Electrode conduction processes in air plasmas

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Using an electrically driven shock tube with initial pressures of 0·1 to 1·0 mm Hg and shock speeds of about Mach 12 to 15, the resistance of an air plasma between two parallel probes has been measured by two different techniques and the results compared. In one, external voltages of from 0 to 100 V were applied to the probes and in the other, electromagnetically induced voltages of from 0 to 25 V were produced by the plasma's motion in a magnetic field of up to 3500 G. In either case the resistance was found to decrease as the current flow increased and was consistent with the equilibrium electronic conductivity of the air plasma at high current densities.

1. Introduction

The electrical conductivity of gases at very high temperatures can conveniently be studied using a shock-tube technique (Wright 1961). Both pressure-driven (diaphragm type) and electrically driven shock tubes can provide transient conditions in which the heated gas approximates to thermal equilibrium. Spectroscopic techniques are normally used to measure temperatures and the plasma motion can be investigated with photographic and electrical techniques.

To measure the conductivity of the gas, indirect rather than direct methods have been mostly used, to avoid the surface-resistance and boundary-layer effects associated with probes. For example, Lin, Resler & Kantrowitz (1955), working with argon in a combustion-driven shock tube, applied potentials between an insulated probe and the shock-tube wall and found that conductivity increased exponentially with temperature. However, the values were very much smaller than the theoretical values and indirect methods were therefore adopted in which the moving plasma deflected a magnetic field.

With a similar technique, Lamb & Lin (1957) studied the electrical conductivity of air at equilibrium temperatures from 3500 to 6200 °K and densities of the order of 0·01 N.T.P. Their results indicated that the ionization process built up quickly behind the shock front, and the measured conductivities agreed well (figure 1) with calculated values based on the equilibrium degree of ionization.

Recently Valentin (1961) has repeated these measurements in air and compared the results with those obtained by applying static voltages to parallel electrodes in the conducting gas. The short duration of the shock-heated gas process precludes the possibility of the electrodes becoming heated and in this case the question arises as to whether the conductivity can be controlled by the electron motion without thermionic emission from the cathode. Satisfactory agreement was obtained (figure 1) by Valentin from which it was concluded that the 'electronic' conductivity was possible with cold electrodes.

A similar conclusion was reached by Pain & Smy (1961) for argon in a combustion-driven shock tube. In this case, however, the voltage-producing current flow was self-induced in the plasma by its motion in a magnetic field, and the plasma resistance was found to be a function of the current density present. On the other

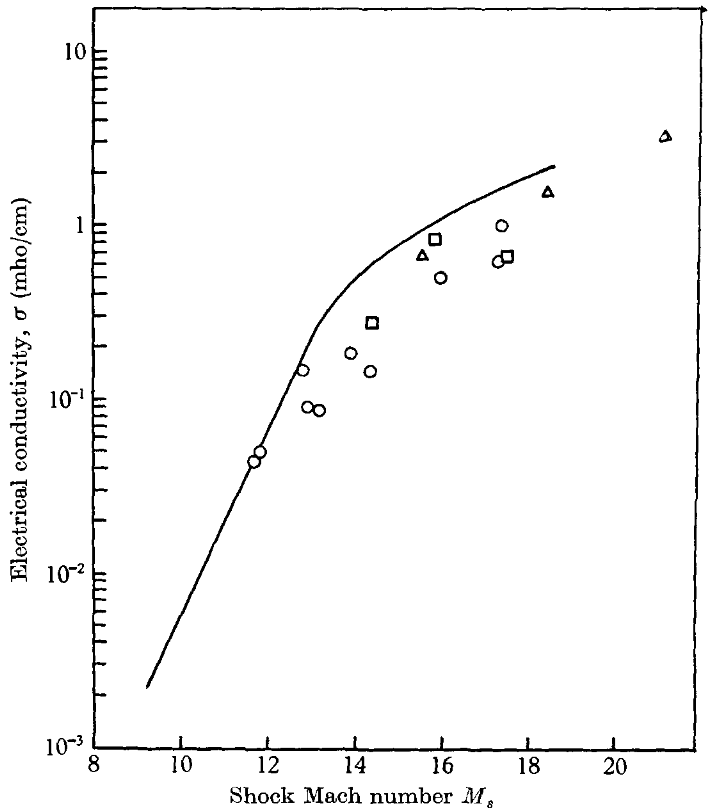


FIGURE 1. Electrical conductivity of shock-heated air. M_s is the shock Mach number, referred to the sound speed of the undisturbed gas ahead of the shock wave, which is approximately $3{\cdot}4 \times 10^4$ cm/sec for air at room temperature. ——, Lamb & Lin (1957), experiment and theory. Valentin (1961): □, magnetic; ○, 15 mm electrodes; △, 1 mm electrodes. $p_0 = 1$ mm Hg.

hand, Sakuntala, von Engel & Fowler (1960), using hydrogen in an electrically driven shock tube found no dependence on the magnitude of the current flowing and that the resistance between the probes was independent of probe area, separation and surface condition. The conductivity of the plasma was one hundredth of its electronic value and agreed well with its ionic value. Nagamatsu & Sheer (1961) have recently also obtained a constant plasma resistance for air in a combustion-driven shock tube, the voltage between the two probes being self-induced by the plasma motion. The conductivity was approximately one-fifth of the theoretical electronic value and an ionic flow model was suggested as a partial explanation for this reduced value.

The experiments reported here have been carried out in air with an electrically driven shock tube, and results are described principally for the same initial conditions as Lamb & Lin (1957) and Valentin (1961). The current flow between two parallel probes was measured both for external voltages applied to the probes and for voltages electromagnetically induced between the probes due to the plasma's motion and the results compared. In either case the resistance between the probes was found to depend on the magnitude of the current flowing and to decrease with increased current density. For an initial air pressure of 1 mm Hg the resistances obtained with the 'applied' test were consistently less than those for the 'induced' test, although at lower initial pressures (e.g. 0·15 mm Hg) the 'applied' resistances were found to exceed the 'induced' resistances. Possible explanations for this are discussed later. The plasma 'conductivity' indicated from these resistances approached the equilibrium electronic values (for totally enclosed paths) as the current density increased and greatly exceeded these values for applied voltage tests at very high current densities where equilibrium no longer applied.

Thus conflicting experimental evidence is now available for cold metallic probes in plasmas produced both by mechanically and electrically driven shocks, and a satisfactory theory is required to reconcile the results and also to provide a reasonable description of the physical processes occurring. Such considerations are of considerable importance in the field of magnetohydrodynamic power generation where greatly increased electrode life could be expected if low electrode temperatures can be combined with high electrical conductivity in the plasma. To obtain overall current flow equivalent to the 'electronic' conductivity of the gas, it is clearly necessary to have available a source of electrons near, or at, the cathode, and it is suggested that a possible mechanism may be secondary collision ionization processes due to high electric field gradients local to the cathode.

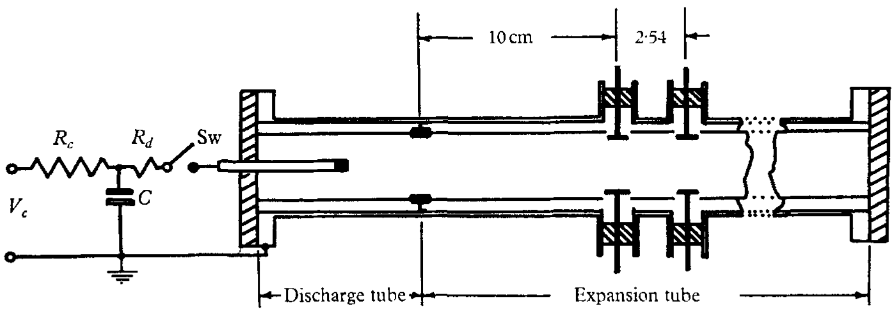
2. Apparatus and experimental method

The apparatus used is shown in figure 2 and is basically similar to that used by Sakuntala, Clotfelter, Edwards & Fowler (1959). The outer vacuum vessel, however, was made of brass and provided a co-axial return path for the condenser discharge current. The length of the discharge path could be varied to optimize the shock energy for a given initial pressure in the tube and condenser energy. Probe stations were located at 2·54 cm intervals, commencing 10 cm from the annular ring electrode.

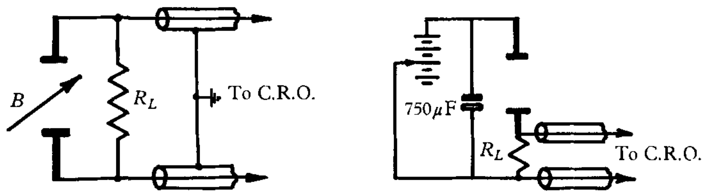
The storage condensers used varied in capacitance from 4 to 32 μF, and were charged to voltages from 2 to 5 kV. As far as possible critically damped current pulses were used (frequencies from 25 to 50 kc/s) to avoid multiple shocks and to reduce electrical interference in the probe circuits. Switching was accomplished with either a mechanically operated (atmospheric pressure) mercury switch or an electrically triggered ignitron. At certain initial pressures and voltages it was found to be convenient to use relaxation switching with the discharge tube itself acting as the switch.

Initial pressures of operation have varied from 1 to 0·1 mm Hg, giving plasma flow velocities of up to 10^6 cm/sec. Fresh ambient conditions at the beginning of each shock were ensured by operating with continuous pumping against a steady air input-leak of about 1 mm Hg/min. Pressures were read on an Edwards bridge-type Pirani gauge mounted at the discharge tube.

Probe-measuring circuits are shown in figure 2. The probes consisted of parallel plane disks of diameter from 0·15 to 0·5 cm, with separations of from 1·0 to 1·5 cm (the inside diameter of the glass expansion tube). All probe stems and



C, main storage condenser; R_c, R_d, charging and damping resistances; Sw, switch; V_c, high-voltage across condenser.



(*a*) Induced voltage tests. (*b*) Applied voltage tests.

FIGURE 2. Apparatus and probe measuring circuits.

surfaces, except the working areas, were insulated with Araldite. Similar carbon-film resistances were used for both applied and induced voltage tests. For both cases, the resistance between the probes R_{pr} is given by

$$R_{pr} = R_L\{(E/V) - 1\},$$

where R_L is the load resistance, E the open circuit induced or applied voltage, and V the voltage across R_L during probe current. In the case of the applied voltage tests, a 750 μF condenser in parallel with the battery maintained a constant-voltage source up to the largest currents drawn.

Interference and pick-up in the probe circuits were satisfactorily reduced to a minimum by the use of differential amplifiers on the oscilloscope and by careful attention to earthing. Most records were taken with a Tektronik Type 502 dual-beam cathode ray oscilloscope triggered from the main condenser discharge current.

3. Results

Typical results for current flow at the first set of probes under air conditions of $p_0 = 1$ mm Hg and a condenser energy of 110 J are shown in the oscillograms of figures 3 and 4. It is seen that, in contrast with pressure-driven shock tubes, the duration of high-temperature plasma flow is relatively short and uniform conditions only exist for several microseconds. The flow velocity is also found to decrease rapidly along the expansion tube.

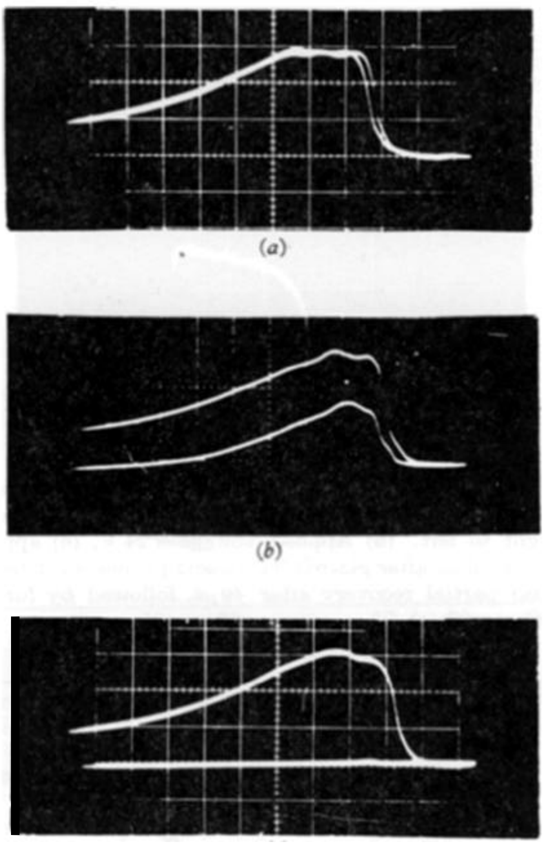
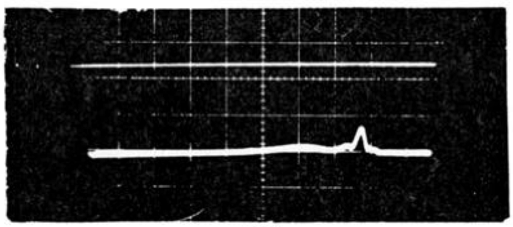


FIGURE 3. Double-probe induced-voltage tests. p_0 = 1 mm Hg, C = 24 μF, V_c = 3 kV, 0·15 cm-diam. probes, 1·15 cm apart; B = 3500 G. Scales: 5 V/division, 2·5 p/division. Time reads from right to left. (a) Both probes open-circuited, (h) one set of probes loaded, R_L = 330 Ω, (c) one set of probes short-circuited.

(a) Induced-voltage tests

The peak open-circuit voltage was found to be independent of the probe material, surface area or condition and was equal and opposite for a reversal of magnetic-field direction. As the magnitude of the induced voltage also satisfied the expression $E = Bud$ V, for variable flux density B, and probe separation d (*see,* for example, figure 5), it was used to estimate the flow velocity u of the plasma. For example, with an initial pressure of 1 mm Hg, B = 3500G and d = 1·15 cm,

$C = 24\ \mu F$ and $V_c = 3$ kV, the induced voltage was 15 V, corresponding to a flow velocity of $0{\cdot}37 \times 10^6$ cm/sec. As a check this can be compared with the voltage induced at the second set of probes of 11·5 V ($0{\cdot}29 \times 10^6$ cm/sec) and the average velocity as obtained from the measured time interval between arrival of the shock front at the two stations ($t = 6{\cdot}5\ \mu s$, $u_{av} = 0{\cdot}39 \times 10^6$ cm/sec, $M_{av} = 11{\cdot}5$).



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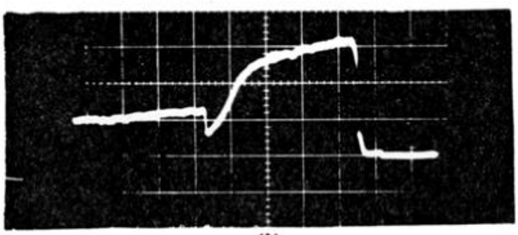


(*b*)

FIGURE 4. Applied-voltage tests. Voltage across $R_L = 10\ \Omega$; $p_0 = 1$ mm Hg, $C = 24\ \mu F$, $V_c = 3$ kV, 0·15 cm-diam. probes, 1·15 cm apart. Scales: 10 V/division, 10 μs/division. Time reads from right to left. (a) Applied voltage = 24 V, (b) applied voltage = 46 V (note duration of current flow after plasma has passed probes, evidence of a self-sustained breakdown-note also partial recovery after 40 μs, followed by further breakdown as voltage builds up across probes).

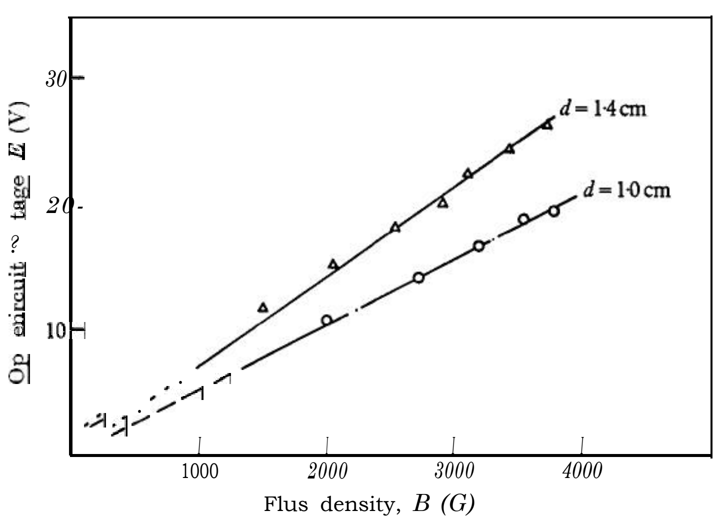


FIGURE 5. Open-circuit induced voltage at first set of probes. $p_0 = 0{\cdot}15$ mm Hg $C = 24\ \mu F$, $V_c = 3$ kV, 0·15 cm-diam. probes.

A particle flow velocity of $0{\cdot}37 \times 10^6$ cm/sec at the first probes corresponds to a shock-front velocity there of approximately Mach 12·5.

From the reduced peak voltage with various load resistances, R_{pr} can be calculated and plotted against the average current density at the probe surface (figure 6). It should be noted that the accuracy of this measurement is a maximum when the open-circuit voltage is approximately halved (i.e. under 'matched' conditions). Thus for a wide range of current densities at a given shock condition

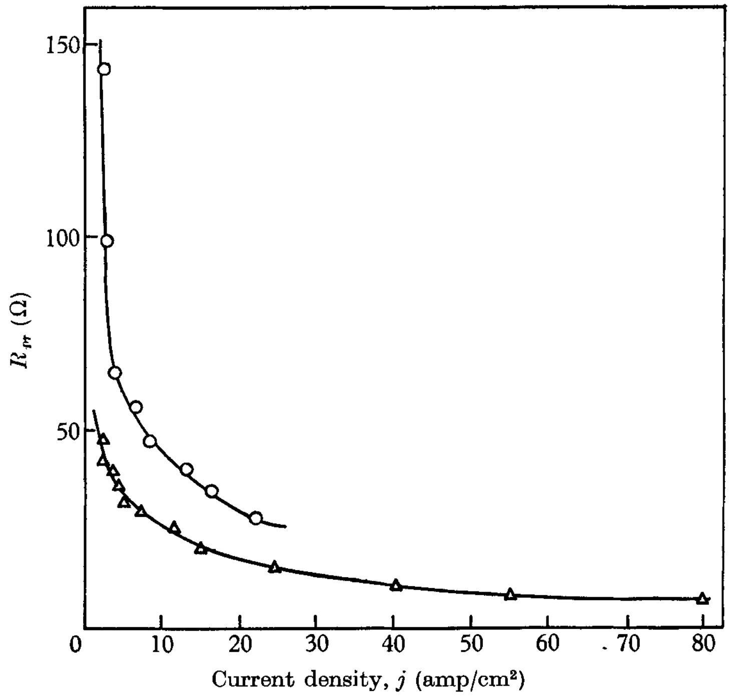


FIGURE 6. Resistance between probes, R_{pr}, as a function of current density, j. $p_0 = 1$ mm Hg, $C = 24\,\mu$F, $V_c = 3$ kV, 0·15 cm-diam probes, 1·4 cm apart. ○, Induced-voltage tests; △, applied-voltage tests.

it is advantageous to vary the induced voltage by varying B. Points on the induced-voltage curve in figure 6 were obtained both by varying R_L at constant B and also with variable values of B, indicating that the conductivity is a scalar quantity (see later discussions).

A further possible source of error in these measurements is that open-circuit and loaded probe voltages are being compared for different shocks which, although similar, may differ slightly. A technique of using two parallel sets of probes in a plane transverse to plasma flow permits the simultaneous measurement of open-circuit and loaded voltage for the one shock. Records obtained in this way are as shown in figure 3. This 'double-probe' technique also has useful advantages when comparing probe surface conditions (as discussed later), and can provide a more accurate measurement of shock-front velocity when turned longitudinally in the shock tube.

(b) *Applied-voltage tests*

Typical oscillograms for applied voltage tests are shown in figure 4. In this case the current density can be simply varied over a wide range of values, although for maximum accuracy (as before) R_L should be adjusted approximately to equal R_{pr}. At sufficiently high current densities secondary collision processes were observed to produce current multiplication throughout the plasma and spark breakdown (figure 4(*b*)). This was confirmed by microscopic examination of gold-plated probes after removal from the expansion tube.

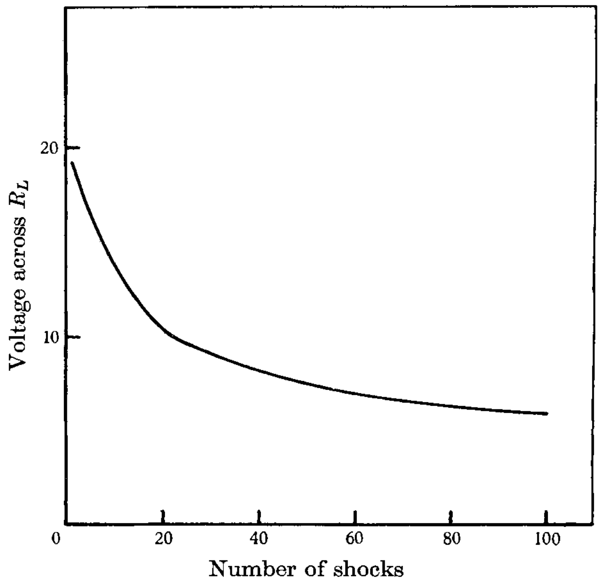
Values of R_{pr} as a function of the current density at the probes are plotted in figure 6 for comparison with the induced-voltage results. Normally in both induced- and applied-voltage tests the probes were allowed to float in electrostatic potential with respect to the discharge tube. With applied voltages the effect of 'earthing' a probe under certain conditions significantly altered the results. It was found that these were associated with the longer-duration shocks in which axial conducting paths were created between the probe and the annular discharge electrode. This effect disappeared with shorter 'slugs' of moving plasma, and does not arise in the case of induced voltages because of the different field configurations.

Although, as stated earlier, at lower initial pressures the relative disposition of the induced and applied R_{pr}-curves varied, in all cases the value of R_{pr} was found to decrease with increasing current density as shown typically in figure 6.

(c) *Probe surface condition*

To examine for the presence of surface resistances, the variation of R_{pr} with time and/or the number of shocks was observed using both applied and induced tests with a constant load resistance R_L. It was found in both cases that R_{pr} increased with the number of shocks to which the probes were exposed at a rate determined by the initial pressure or shock speed (i.e. the equilibrium shock temperature). Typical results are shown in figure 7 for induced-voltage tests at an initial pressure of 0·15 mm Hg. The open-circuit voltage was 21 V and was constant independent of the number of shocks. The voltage V across the load resistance, however, decreased with the number of shocks as shown in figure 7 (*a*). Due to the nature of the test, R_{pr} was thus not measured at a constant-current density, but is a function both of this and the number of shocks (see figure 7 (*b*)). At a constant current density, R_{pr} would have increased less rapidly. Similar results were obtained for applied tests and the same shock energy. The double-probe technique provided a useful means of confirming this behaviour, by permitting one pair of probes to be re-cleaned and allowing a direct comparison (for the same shock) of a new and an 'aged' pair of probes.

The rate of variation of R_{pr} was found to be greatly reduced for an initial air pressure of 1 mm Hg and showed no significant change over 100 shocks. For this reason most readings were taken at this higher initial pressure to remove one of the variables. Even so, points on curves such as figure 6 were obtained at random rather than with steadily increasing or decreasing current density and with alternate applied and induced tests to ensure that probe surface conditions were identical. An attempt to differentiate between the results for nickel, gold and brass electrodes was unsuccessful, all electrode materials showing the same general behaviour as above.



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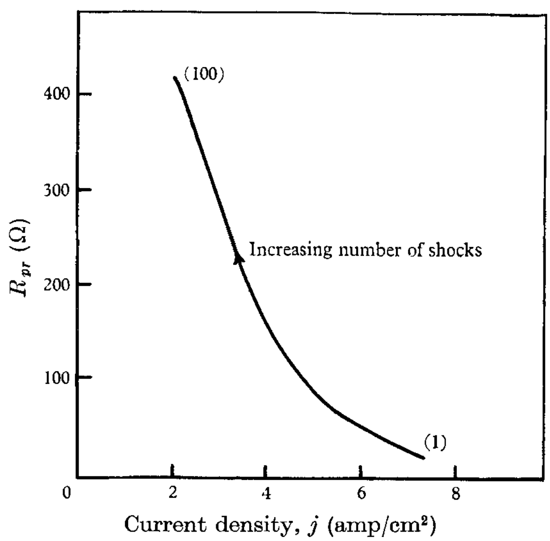

(*b*)

FIGURE 7. Variation of R_{pr} with number of shocks occurring (induced-voltage tests). $p_0 = 0{\cdot}15$ mm Hg, $C = 24\,\mu$F, $V_c = 3$ kV, 0·15 cm-diam. probes, 1·4 cm apart. (*a*) Voltage across constant $R_L = 150\ \Omega$; (*b*) R_{pr} as a function of j.

4. Discussion

The general shape of the R_{pr} current-density curves is characteristic of many contact resistance phenomena (for example, the contact surface resistance of a carbon brush and commutator). In the present case, the resistance is made up of two components: first, the contact resistance due to the plasma-to-electrode conduction process, and secondly, the plasma resistance proper. As will be shown the first component, i.e. the contact resistance, appears to be mainly responsible for the overall variation in R_{pr}, since here the plasma itself remains largely unaltered in nature by the current flowing through it (at least for small voltage gradients). At the same time the results of § 3 (*c*) indicate that an explanation for the contact resistance is not to be sought in the formation of non-linear resistance films on the surfaces of the probes due either to oxidation or to deposition of metallic vapour from the main discharge electrodes.

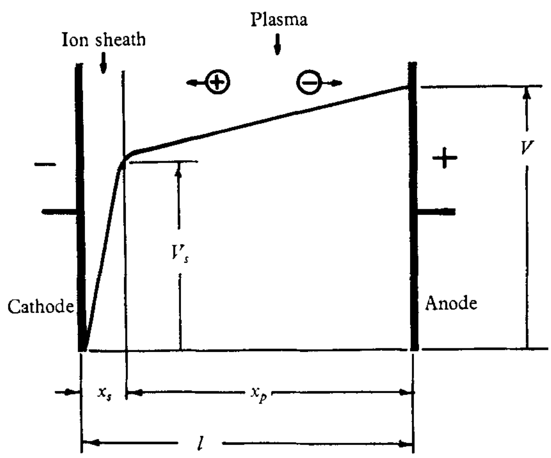

FIGURE 8. General case of a voltage applied to the probes.

Consider first the applied-voltage tests, in which (prior to the arrival of the plasma) a uniform potential gradient will exist between the probes (neglecting fringing). Since the redistribution time for the charges is small compared to the time that the plasma is present between the probes, we can neglect the translational motion of the plasma in the applied-voltage tests and consider the analogous case of a step function of voltage suddenly applied to the cold probes with the plasma present. Due to their much higher mobility, the electrons can arrive at the anode more rapidly than the positive ions can drift to the cathode and thus a positive space charge sheath will be created close to the cathode (figure 8). A steady state will result in which the potential gradient across the plasma is reduced and thus also the electron drift velocity.

For the plasma region, regardless of the magnitude of the current flowing, we must have a current density j_p, given by

$$j_p = j_e + j_i,$$

where j_e is the electron current density and j_i the ion current density. Because of the relatively large electron mobility we have approximately

$$j_p \approx j_e \approx (e^2 N_{ep} \tau_{ep}/m_e) E_p = \sigma_e E_p,$$

where e is the electronic charge, N_{ep} the number density of electrons in the plasma, τ_{ep} the electron collision period, m_e the mass of an electron, σ_e the 'electronic' conductivity of plasma and E_p the voltage gradient in the plasma (assumed constant). Also the potential V is determined by the integral over the gradient E along path l as

$$V = \int E\,dl \approx E_p x_p + V_s \approx E_p l + V_s,$$

where V_s = voltage drop across sheath, since $x_p \approx l$.

Thus

$$R_{pr} = \frac{V}{I} = \frac{1}{A}\left(\frac{l}{\sigma_e} + \frac{V_s}{j_s}\right),$$

since $j_s = j_p$ = external load current per unit area of the probes, neglecting fringing effects.

The resistance between the probes will approach that corresponding to 'electronic' current flow either for a constant voltage drop across the sheath and increasing current density or for reduced sheath voltage drops (e.g. with an electron emitting cathode). At very small currents with cold probes almost all the voltage drop will be across the sheath.

To explain the apparent electron emission from a cold cathode in argon, Pain & Smy (1961) have calculated the sheath voltage gradient to be of the order of 10^5 V/cm and suggest ion bombardment as the source of electron emission. An alternative suggestion is that collision ionization of neutral molecules can be produced by electrons accelerated in this field producing a virtual cathode very close to the physical cathode. The positive ions so produced have then only very short distances to drift to the cathode to provide current continuity around the external circuit. Ultimately, as the applied voltage is increased, the Townsend ionization extends into the whole plasma region, giving spark breakdown (see figure 4 (*b*)). For an initial pressure of 1 mm Hg and a shock speed of Mach 12·5, such breakdown was observed for average applied field gradients as low as 35 V/cm.

A considerably more complex situation exists for the case where the voltage on the probes is electromagnetically induced by the plasma's motion, although the variation of R_{pr} with current density is found to be almost identical in nature. As before the space between the probes is occupied principally by a plasma, together with a positive ion sheath which now is adjacent to the positive electrode. However, regardless of the magnitude of the current flowing, the resultant potential difference across the plasma region is zero, since the induced field is exactly balanced by the ohmic voltage drop due to the collisions occurring. Evidence for this is seen in figure 3 (*c*), where an extreme case is shown of one pair of probes short-circuited (i.e. maximum current flowing of about 1 amp) alongside an open-circuited pair (E = 15 V) with negligible interference between the plasma paths. If, however, instead of allowing both probe circuits to 'float' in potential, the positive electrodes were joined together, a large degree of interference was observed, and the potential across the unloaded probes fell to about one-half of its original value.

In the plasma region, as before, the contribution of ion flow to the total current will be negligible compared to that of the electron flow, but the higher electron mobility will result in positive ion sheaths being formed. As the current density is increased by the connexion of smaller load resistances R_L to the electrodes, the greater electron mobility will increase the thickness of the ion sheath and result in electrode and sheath processes as described for the applied-voltage case. Since, however, the terminal voltage will now be falling with increasing load, a smaller overall effect will be produced.

In the above discussion, no mention has been made of the effects of fringing on the geometry of the conducting paths. Various investigators have made different assumptions in this regard. Pain & Smy (1961) used a conducting path based on an applied-voltage test in an electrolytic solution to obtain the conductivity during induced-voltage operation. On the other hand, Sakuntala, Von Engel & Fowler (1960) and Nagamatsu & Sheer (1961) have assumed a cylindrical conducting path between the probes, equal in area to the probe area. Rosa (1961) used applied-voltage tests with small diameter probes in a moving argon plasma (seeded with potassium carbonate) to estimate its conductivity (incidentally, observing sheath voltage drops for the case of hot electrodes), but does not describe the assumptions made as to the conducting path geometry.

Since the present tests were carried out with relatively small diameter probes (0·15–0·5 cm) spaced well apart (1·0–1·5 cm) the effects of fringing could be considerable. This is particularly true of the 0·15 cm diameter probes which were preferred to the 0·5 cm probes in these experiments because of the sharply decreasing shock energy along the tube and the 'averaging' effects of the larger probes. To investigate the maximum fringing effect possible, a series of tests were carried out with the same geometry as the shock tube using weak electrolytic solutions. It was found that the 'geometric factor' relating the resistance of the confined parallel path to that of the free-fringing path with applied voltages could be as large as 10, for 0·15 cm-diam. probes spaced 1·5 cm apart. In the case of the air plasma between the probes and applied voltages of up to 100 V, say, the charge density on the electrodes will be negligible compared to the charge density in the volume between the probes, and so the fringing effect would be less than that associated with the electrostatic field distribution prior to the arrival of the plasma. Nevertheless, due to this effect alone, one would expect for the applied-voltage tests resistances less than those with induced-voltage tests. Fringing for induced-voltage tests should be very small.

Thus when comparing the results of the applied and the induced tests two principal effects can explain the relative differences in R_{pr} observed for a given current flow: (*a*) different electrode sheath effects for the two conditions, and (*b*) different geometry of conducting paths. Two further considerations can arise in the case of the induced-voltage tests which could influence the magnitude of R_{pr}. These are: (*c*) variation in flux density B, due to the load current (armature reaction effect), and (*d*) variation in σ_e (and σ_i) with flux density B (for $\omega_e \tau_e$ or $\omega_i \tau_i$ of the order of unity).

Order-of-magnitude calculations, together with simple experiments as confirmation, were carried out and demonstrated that only (*a*) and (*b*) above were significant factors in these tests. At high current densities the effect of (*b*) should predominate whilst at low current densities the effects of (*a*) should be the more important.

5. Conclusions

The results obtained for the resistance between two probes in a moving air plasma indicate some of the difficulties of interpreting from probe measurements the 'conductivity' of the plasma itself. The results quoted in figure 1 for the equilibrium 'electronic' conductivity of an air plasma give a value of 0·1 mho/cm for a shock speed of Mach 12·5. This is consistent with the minimum overall resistance observed for the same conditions in the electrically driven shock tube, provided a suitable geometric factor is allowed for fringing. A mechanism of secondary ionization in the positive ion sheath is suggested as an explanation of how such high conductivities can be obtained with cold probes.

The results are in agreement with those of Pain & Smy (1961) who also observed variable resistance between the probes at different current densities. Further work is proceeding to compare the results in air with those for other gases, and to elucidate further the interesting electrode-to-plasma conduction processes.

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