Gas Phase and Surface Phenomena in Seeded Plasmas

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This paper deals with some experiments conducted with low-temperature seeded plasmas at atmospheric pressure. Results of the experiments indicated two modes of steady, stable current conduction between the electrodes. A thermionic process was found to be the mechanism for current emission under all conditions and the effects of potassium adsorption on electrode surfaces was found to be important. A quantitative comparison between the observed voltage-current characteristics and two current conduction theories is presented. This comparison indicated that both Joule heating and nonequilibrium heating of electrons must be considered in understanding the current conduction phenomena. Electrode heat transfer was also studied and analysis of the data indicated that an important heat transfer mechanism was the penetration of the surface work function barrier as electrons entered or left the surface.

Nomenclature

A = electron emission constant [60.2 amp/(cm²°K)]
$\bar{c}_e$ = mean thermal velocity of electrons
e = charge of electron, base of natural logarithms
I = total electrode current
J = current density
k = Boltzmann's constant
n_a = number density of argon atoms
n_e = number density of electrons
n_k = number density of potassium atoms
Q_a = collision cross section electron-argon
Q_k = collision cross section electron-potassium
T_a = argon temperature
T_w = wall temperature
V = electrode voltage
θ_n = fractional coverage of surface with adsorbed potassium
μ_a = neutral flux of potassium atoms impinging on cathode
ν_e = electron emission flux
σ = electrical conductivity
Φ_s = sheath potential
ϕ = surface work function

I. Introduction

IN recent years, a large number of fluid flow systems have been proposed which utilize the interaction of electromagnetic forces with an ionized gas. A number of these devices is concerned with one of two problems: 1) acceleration of the gas with a view to producing a propulsive thrust, and 2) the direct conversion of thermal energy to an electrical form.

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In order that any of these systems operate efficiently, it is necessary that the gas have a high electrical conductivity. Since the gases proposed for use in such devices are usually products of combustion (of hydrocarbon air mixtures) or noble gases, it is evident that very high working temperatures are necessary to insure the degree of ionization required to achieve a high conductivity.

In order to keep the gas temperature within tolerable limits and yet maintain an adequate electrical conductivity, the gas is often "seeded" by injecting a small amount of some material such as cesium or potassium. Such materials ionize readily at relatively low temperatures, and thus can be used to give high conductivity at temperatures as low as 2000°K. However, in addition to changing the properties of the bulk of the gas, conditions at the electrode surfaces are also affected since these materials tend to coat the electrodes.

In view of the complexity of the general problem, a series of experiments were conducted to study various surface and gas-phase processes that have important influences on the performance of generators or accelerators using a seeded plasma as the working fluid. The problems investigated include current conduction through the plasma proper, several surface phenomena associated with the adsorption of potassium on the electrodes, the emission of currents from hot electrodes, and heat-transfer rates to the electrodes.

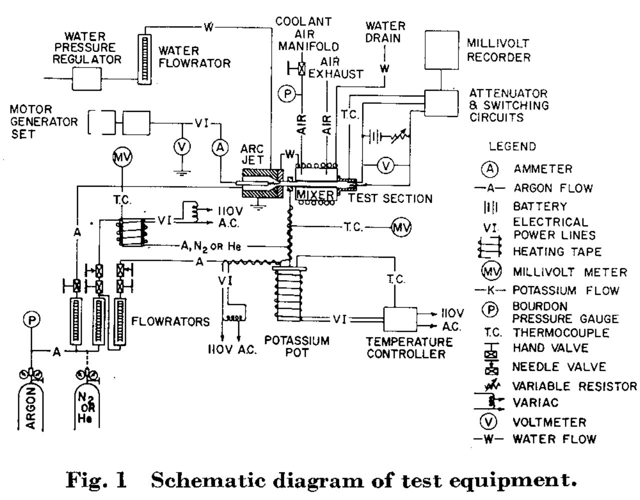

Fig. 1 Schematic diagram of test equipment.

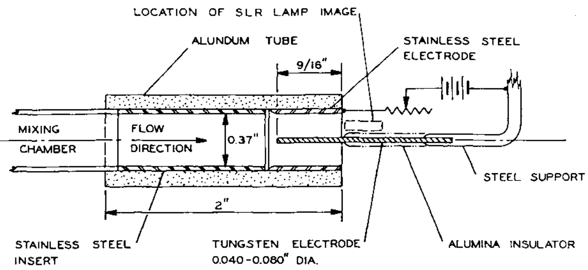

Fig. 2 Coaxial electrode test section.

II. Experimental Method of Investigation

A simple, steady-state experiment was set up to study some of the aforementioned effects associated with current conduction and surface phenomena in a seeded plasma. The plasma utilized was composed of a mixture of argon gas and potassium vapor, and in order to simplify the experiments, no magnetic field was applied.

The plasma ranged in temperature from approximately 1200° to 2700°K, with a static pressure of 1 atm in all cases. Values of the seed concentration n_k/n_a ranged between zero and 1.2×10^{-2}, and, under typical operating conditions, the electron density was on the order of 10^{14} electrons/cm^3.

A conventional arcjet was used to heat the argon, and potassium seed material was injected by passing a small flow of argon through a bath of liquid potassium and mixing this with the main, heated argon stream. This mixture then passed through a chamber in which the flow equilibrated to a more or less uniform, homogeneous fluid. Finally, the resulting "seeded plasma" passed through an appropriate test section. A schematic diagram of the apparatus is depicted in Fig. 1.

Figures 2 and 3 show several of the test sections that were employed in these experiments. The physical measurements that were obtained during the test runs included the following: voltage and current passing through the arcjet, temperature rise in the arcjet cooling water, argon flow rates, test section voltage, current and electrode temperatures. Table 1 lists the magnitudes of some of the operating parameters of the complete system.

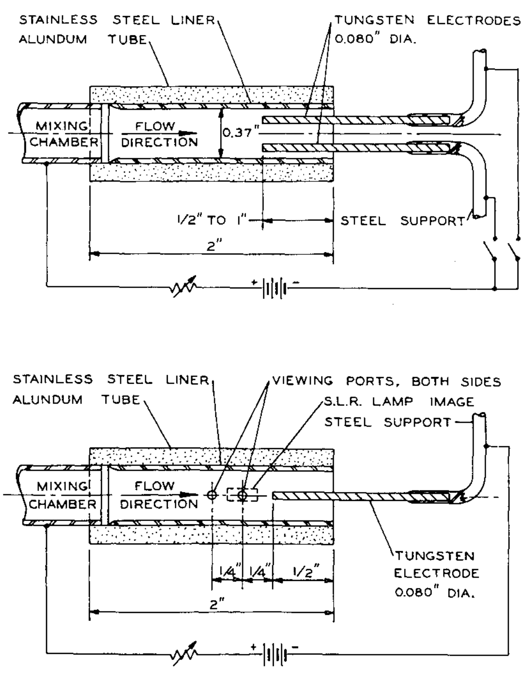

Fig. 3 Axial geometry test section.

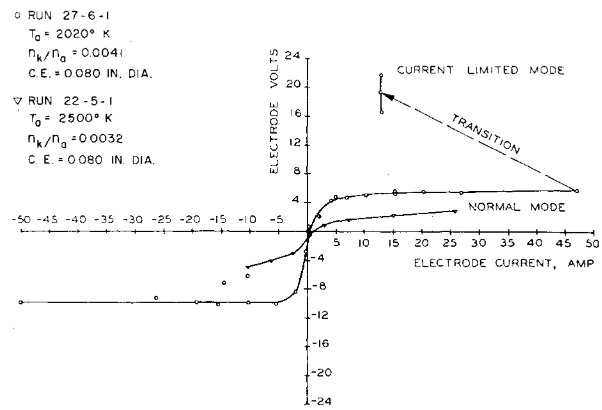

Fig. 4 Voltage current characteristics.

III. Experimental Results

A selection of typical experimental results is compiled in this section for ease of reference and to provide an over-all picture of the various phenomena observed during the investigation. The data will be presented here unaccompanied by any attempt at explanation, and discussion of the implications of these results will follow in subsequent sections.

A. General Characteristics of the Observed Phenomena

Figure 4 shows a typical voltage-current curve obtained from the coaxial electrode arrangement that is depicted in Fig. 2. Two modes of operation were found to exist for steady current conduction and are indicated in this figure. As noted in Fig. 4, these two modes will be referred to as the normal mode and the current limited mode. An unstable transition phenomenon was found to occur when the test section passed from one mode of operation to the other.

Figure 5 indicates the change in center electrode temperature for both the normal mode and the current limited mode. With the center electrode negative, the center electrode temperature decreases slightly with increasing current, and then may increase again as the maximum normal mode current is approached. Upon transition to the current limited mode, the electrode temperature increases by a large amount (up to

Table 1 Arcjet and test section operating conditions

Parameter	Arcjet	Test section
Main argon flow rate	2.23 g/sec	2.23 g/sec
Potassium pot argon flow rate	...	0–0.5 g/sec
Potassium flow rate	...	0–0.3 g/sec
Voltage	60–90 v	0–±24 v
Current	30–120 amp	0–±50 amp
Arc power	2.7–8.0 kw	...
Mean argon temperature	1200–2700°K	1200–2700°K
Argon pressure	1 atm	1 atm
Potassium pressure	...	0–0.013 atm
Potassium pot temperature	...	475–520°C
Mean flow velocity	~400 fps	~(400 fps)
Mach number	~0.1	~(0.1)
Wall temperature	330–700°C	750–1100°C
Electrode temperature	...	1000–2500°C
Mean flow stay time	$\sim 1.2 \times 10^{-3}$ sec	$\sim(10^{-4}$ sec)
Electron-electron equilibration time	$\sim 10^{-10}$ sec	$\sim(10^{-10}$ sec)
Electron-neutral equilibration time	$\sim 10^{-6}$ sec	$\sim(10^{-6}$ sec)
Electrode drift time (electrons)	...	10^{-6} sec
Viscous Reynolds number (L = 1 cm)	...	$\sim(10^4)$

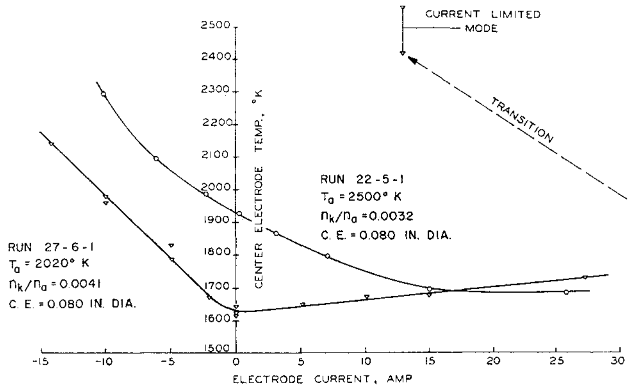

Fig. 5 Center electrode temperature vs electrode current (coaxial geometry).

700°C in some cases). With reversed polarity (center electrode positive), the electrode temperature continuously increases with increasing current. At sufficiently high reversed currents, the wire temperature may even exceed the initial bulk temperature of the gas.

B. Normal Mode Phenomena

Under normal mode operation, the external resistance of the electric circuit was varied, and the resulting test section voltages and currents were recorded. It was found that the electrode voltage changed from zero to about +6, −16 v, whereas the current ranged upward from zero to ±50 amps. Figures 4 and 6 show typical data of this type.

The maximum currents obtained with 0.080-in.-diam center electrodes resulted in maximum current densities of approximately 80 amp/cm^2. However, with an electrode of 0.020-in. diam, it was possible to obtain maximum current densities in excess of 230 amp/cm^2 at the electrode surface.

Some impurities were present in the plasma, and the question arises as to the reliability of the data and its reproducibility. An indication of the reproducibility of the data is given in Fig. 6 in which three runs are depicted. The runs were made under identical operating conditions on three separate days. Special care was taken to eliminate impurities in the aforementioned runs.

1. *Seed concentration tests*

Figure 7 shows the results of varying the potassium seed concentration for the coaxial geometries when the current density was very small. It is interesting to note that changing the electrode geometries produced essentially the same result (within the experimental scatter) for the optimum value of

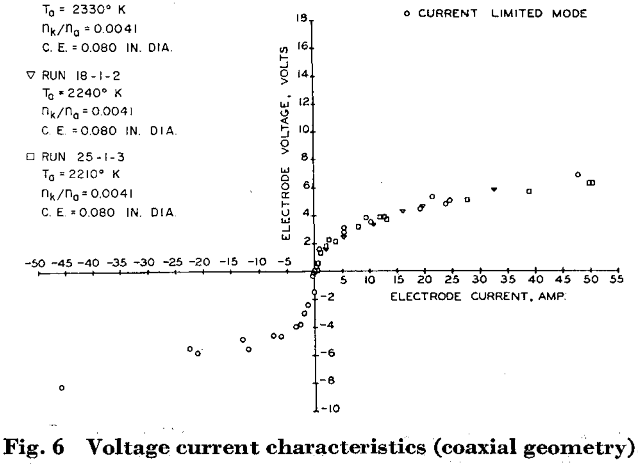

Fig. 6 Voltage current characteristics (coaxial geometry).

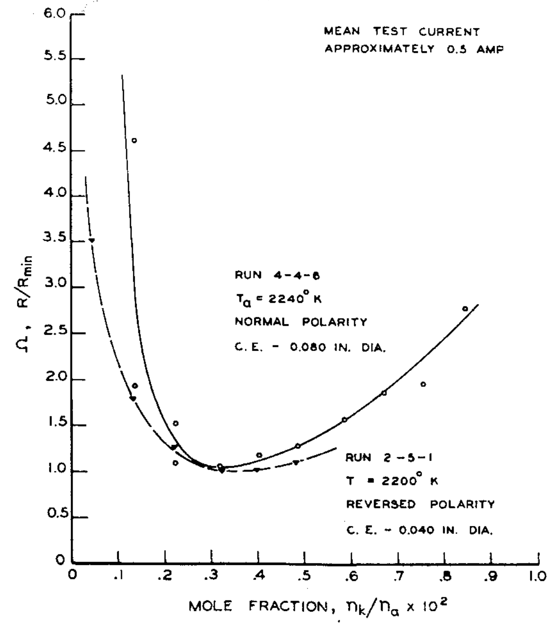

Fig. 7 Nondimensional resistance vs potassium seed fraction (coaxial geometry).

$n_k/n_a \sim 0.003$. Changing the inner electrode diameter from 0.040 to 0.080 in. did not affect the location of the resistance minimum in any regular way.

In all, there were 16 tests performed at temperatures ranging from 1200° to 2500°K with the purpose of finding the seed concentration corresponding to the maximum conductivity. The average value of all tests was $n_k/n_a = 0.0032$, with a variation from 0.002 to 0.0049.

2. *Effects of electrode geometry*

The general shape of the *V-I* curves obtained with the three different test-section geometries was the same in all three cases. The transition phenomenon was noted with all three geometries.

Besides investigating the effect of size, shape, and location of the electrodes as mentioned previously, the effect of varying the electron-emitting area was investigated in the following manner. A simple experiment was performed with the axial geometry in which two "center electrodes" could be individually switched into the circuit (see Fig. 3). With the system in the normal mode and both electrodes initially conducting, one of the electrodes was open circuited; the total current decreased by less than 5%. Alternating the two electrodes into and out of the circuit produced identical results, i.e., a slight reduction in the current with one electrode as compared with the case of two electrodes conducting. Approximately the same percentage decrease in the current was observed at 2.5, 6, and 12 amp/cm^2.

C. Transition Phenomena

It was found quantitatively that the maximum normal mode current that occurred just prior to transition increased monotonically with increasing seed concentration.

Transition to the current-limited mode could also be precipitated from normal operating conditions merely by reducing the potassium concentration. A return to the normal mode could then be accomplished by sufficiently increasing the seed fraction. A typical variation in the current caused by this large variation in n_k/n_a is given in Fig. 8.

Reduction of the cathode surface area was another means of inducing transition to the current limited mode. This effect was observed in the aforementioned switching experiments. In one particular set of such experiments, about 20 amp were

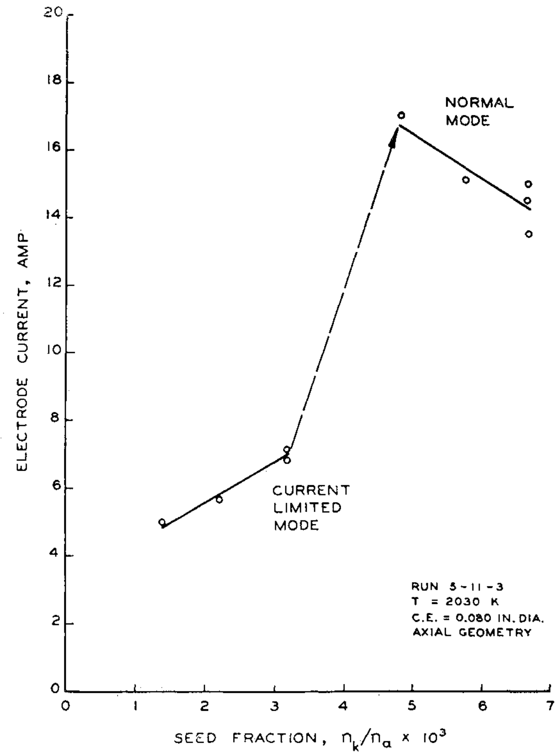

Fig. 8 Electrode current vs potassium seed fraction.

being conducted by the two electrodes in the normal mode. Switching one electrode out resulted in the remaining electrode passing into the current limited mode, and the current thus was reduced to approximately half the initial value. This behavior was observed whenever the two cathodes were conducting a current close to the magnitude of the maximum normal mode current.

D. Current Limited Mode Phenomena

1. Effect of electrode geometry and surface area

Transition to a current-limited mode was found to occur with all electrode geometries. However, the magnitudes of the currents were different for each of the three geometries, even though the initial gas properties may have been the same. It should be noted here that the effective cathode emitting area was different for each of the three forementioned configurations.

The effect of changing the emitting surface area during operation in the current limited mode was accomplished by means of the switching experiment as described previously and depicted in Fig. 3. With the electrodes initially operating in the current-limited mode, open circuiting one electrode resulted in a 50% (±5%) decrease in the total current. This effect was independent of which electrode maintained the current. Alternate switching of the electrodes produced the same 50% reduction in the total current.

2. Effect of seed concentration and impurities

The magnitude of the current obtained in this limited mode was a monotonic increasing function of the seed fraction of potassium. Simultaneously, the cathode temperature increased monotonically with seed concentration. It was noted that in this mode the electrode is hotter near the downstream end of the test section than at the tip.

The addition of foreign diluent gases such as helium or nitrogen did not affect the magnitude of the currents in this mode if all other parameters were held constant. Similarly, the effect of teflon contamination (from insulators) had no influence on the current.

IV. Discussion of Results

A. Potential Distribution in the Plasma

Before interpreting the results of voltage-current measurements in any plasma experiment, it is necessary to ascertain the relative magnitudes of the voltage drops across the gaseous conductor and those across gas-surface sheaths.

If thermionic emission from the potassium-coated tungsten is greater than the current, then the sheath potentials should be on the order of kT_w. In contrast, with arc-like emission, the sheath voltage drops should be on the order of the ionization potential of the gas or surface material, which amounts to several volts in the present experiments. The general shape of the experimental voltage-current intercept indicates that the sheath voltages are small. This suggests that thermionic emission may be adequate to account for the observed current densities.

The magnitude of the thermionic current emitted by a hot surface is given by the Richardson-Dushman equation

$$J = AT_w{}^2 e^{-\phi/kT_w} \tag{1}$$

In the case of a vacuum diode, this is the magnitude of the maximum current that may be drawn if the applied potential is maintained sufficiently low. At higher applied voltages, the Schottky effect becomes important, and the current continues to increase slightly with the applied voltage.

In the present experiments, all parameters in Eq. (1) can be easily determined except the parameter ϕ, which is the work function of the emitting surface. This parameter is extremely sensitive to surface conditions and is very strongly affected by the presence of adsorbed layers. Unfortunately, not much is known quantitatively concerning the effects on the value of ϕ of a layer or layers of potassium on a tungsten surface. Fortunately, however, a great deal of work has been carried out by Langmuir et al.[1] with cesium layers adsorbed on tungsten, and at this point, it is of interest to review some of his results.

For the purposes at hand, the pertinent material from Langmuir's work is summarized in Fig. 9.[1] In this figure, the

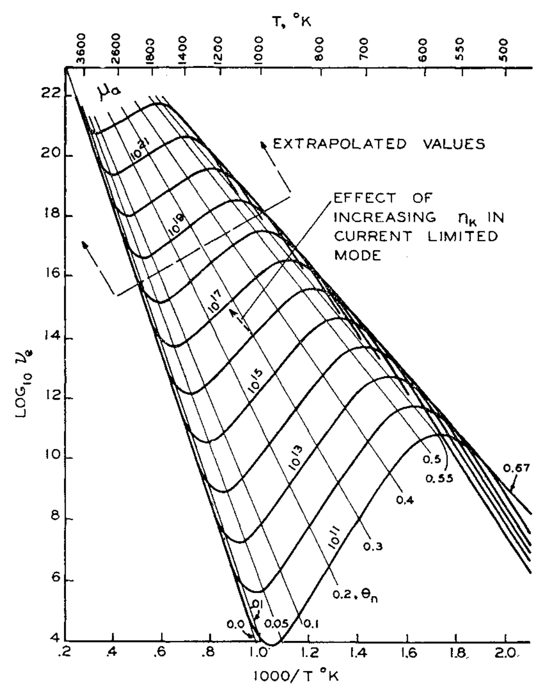

Fig. 9 Logarithm of thermionically emitted electron flux density (cm^{-2} sec^{-1}) vs reciprocal of surface temperature.

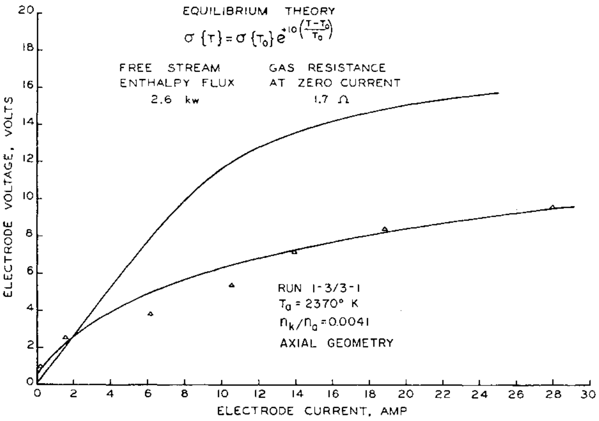

Fig. 10 Theoretical and experimental voltage-current characteristics (axial geometry).

number of electrons emitted per unit time per unit surface area (ν_e) is plotted against the reciprocal of the surface temperature. The lines that are indicated as different values of θ_n refer to loci along which the fractional coverage of the surface by adsorbed cesium is a constant. In particular, the line with $\theta_n = 0$ gives the emission from a bare tungsten surface. As a larger fraction of the surface is coated with the cesium, the effective work function changes from that of pure tungsten to the value expected for pure cesium.

The various values of μ_a refer to the rate at which cesium atoms strike the surface per unit time per unit area. It is readily seen that, if T_w is held constant, then increasing μ_a results in an increased fractional coverage (θ_n) and a larger emission current ν_e. However, if μ_a is held constant and the temperature is increased, the emission current actually decreases over a wide range of θ_n values. Extrapolation of the data in Fig. 9 to values of $\mu_a = 10^{20}$, which were encountered in these experiments, indicated that currents comparable to those observed experimentally could be obtained.

At present, no data for electron emission from potassium-coated tungsten is available in the range of parameters for the experiments described here. However, extrapolation of Killian's[2] data by five orders of magnitude indicates that current densities of at least 10 amp/cm² are possible. The shape of the potassium-tungsten curves is similar to the cesium-tungsten case. However, the line of maximum emission in the former situation nearly coincides with the $\theta_n = 0.4$ line in Fig. 9. Because of the immensity of the forementioned extrapolation, it is quite possible that a large error exists in the estimated value of the emission current.

Space does not permit discussion of several other factors that also lend support to the idea of small thermionic-sheath potentials for the case of the normal mode. A detailed discussion of these points may be found in Ref. 3.

The view adopted here in regard to the sheath potentials is completely different from that presented by Ralph.[4] In his seeded plasma experiments, the electrode voltage had to be raised to a relatively large "striking voltage" (3–8 v) prior to the onset of current conduction. With conduction occurring between the electrodes, the electrode voltage decreased to approximately 2 v and remained relatively constant, independent of electrode spacing and magnitude of the current, for fixed values of the seed concentration. Thus, Ralph correctly concluded that in his experiments the electrode voltage drop appears primarily across electrode sheaths.

The voltage-current curves presented here have zero "striking voltage." Furthermore, a smooth, continual rise of the V-I curve and a similarity of the positive and negative portions of the V-I curve are found in these experiments. Thus, the shape of the observed voltage-current curves is interpreted in terms of the dominance of bulk gas phase phenomena rather than sheath phenomena.

The question now arises as to the reason for the discrepancy between the results of Ralph and those reported here. A tentative explanation may be found by considering the recent work of Kerrebrock and Hoffman.[5] The voltage-current characteristics of Ref. 5 are somewhat similar in appearance to Ralph's data except for the large difference between the initial "striking voltage" and subsequent decrease in electrode voltage with the onset of current conduction. Kerrebrock and Hoffman found essentially no abrupt sheath potential drop at very low currents ($J < 0.10$ amp/cm²). They also noted an increase and then a decrease in sheath potentials as the electrode current is steadily increased. At the largest current densities ($J = 2.48$ amp/cm²) their total sheath potential drops were approximately 25% of the electrode voltage. In view of the forementioned observation, the relative importance of the sheath potentials is expected to decrease with increasing current density.

All of the experiments considered previously utilized an argon gas with potassium seeding at a bulk pressure of approximately 1 atm. However, Ralph's data was taken at 1100°K, Kerrebrock and Hoffman's at 1590°K, and Zukoski and Pinchak's at 2000–2500°K. Viewed in this manner, the combined data indicate the predominance of sheath phenomena at low gas temperatures and their reduction in importance as the gas temperature is raised.

As a result of the preceding considerations, the view adopted here will be one to assume that thermionic emission is sufficient to account for the observed currents in all modes of operation. In the normal mode, the circuit current is always less than or equal to the thermionic limited value, and sheath potentials are of the order of one kT_w. In the current limited case, circuit current is equal to the thermionic limited value, and sheath potentials are on the order of 10 v.

B. Effect of Gas Phase Phenomena

1. *Dependence of the gas conductivity on the seed fraction*

In the limit of small currents in the gas, it is permissible to assume that the conductivity may be computed accurately by perturbation techniques such as employed in Ref. 6.

Assuming the ionization level to be given by the Saha equation, and neglecting the effect of the Spitzer conductivity,[7] it is possible to find the optimum value of the seed concentration n_k for the case of constant plasma temperature:

$$n_k/n_a|_{\text{opt}} = \bar{Q}_a/\bar{Q}_k \tag{2}$$

A reasonable estimate of the values of $n_k/n_a|_{\text{opt}}$ is 0.0023, based on $\bar{Q}_k = 4.20 \times 10^{-14}$ cm² and $\bar{Q}_a = 1.0 \times 10^{-16}$ cm² (Ref. 8). This is to be compared with the average experimental value of 0.003. In view of the great degree of uncertainty in the value of the average momentum cross sections under the low temperature conditions of these experiments, this may be considered very good agreement. The values of the cross sections used in the preceding estimate were obtained by using the appropriate average value of scattering cross sections.[8]

2. *Low current conductivity*

As will be shown later in this section, at low current densities the nonequilibrium conduction effects become less important.

Table 2 Comparison of conductivity at low currents with equilibrium theory

Run	T_a	n_k/n_a	σ_{exp}, mho/cm	σ_{theory},[a] mho/cm
22-5-1	2500°K	0.0032	0.36	0.78
9-5-3	2360	0.0032	0.14	0.54
25-1-3	2210	0.0041	0.10	0.23
8-2/3-1	1780	0.0041	0.057	0.010

[a] Based on $Q_a = 1.0 \times 10^{-16}$ cm², $Q_k = 420 \times 10^{-16}$ cm².

Thus, it is appropriate to compare the experimental conductivity values obtained at low currents with the values computed by the equilibrium model. These values are given below in Table 2.

The results shown in Table 2 indicate that computed values of σ are three to four times the experimental values, with the exception of the low temperature (1780°K) run. In view of the uncertainties in cross sections and gas properties, the disagreement between theoretical and experimental values is not unexpected.

3. *Interpretation of nonlinear voltage current curves*

a) Equilibrium theory of current conduction: Inspection of the pertinent equations indicates that the electron density, and thus the conductivity, are strong functions of the gas temperature. This fact suggests that at least part of the apparent increase in conductivity observed with increasing current may be due to Joule heating of the gas as it flows through the test section. The magnitude of the effect of Joule heating has been examined analytically and the results are given in detail in Ref. 3. Figure 10 presents a comparison of a typical experimental run and the corresponding theoretical curve based on the conditions of the actual test run. The agreement between the curves is only qualitatively satisfactory. Although some of these differences may be due to the simplifying assumptions made in the theory, it is clear that agreement with experiment is not completely satisfactory. However, it is evident that simple equilibrium heating effects are quite important for the range of currents, voltages, and gas enthalpy fluxes used in these experiments. These effects must be properly accounted for in any complete theory.

b) Nonequilibrium theory of current conduction: While at the California Institute of Technology, Jack L. Kerrebrock developed the theory of nonequilibrium current conduction in seeded plasmas.[9] Qualitatively, the nonequilibrium conduction theory can be considered in the following manner. The electrons fall through the electric field and obtain energy from it. They then proceed to lose this extra energy by means of relatively inefficient, elastic collisions. As a result, the mean energy of the electrons continues to increase until the rate of energy loss and the rate of energy gain from the field are equalized. The result of the elevated electron temperature is to produce a greater degree of ionization, which in turn provides more conduction electrons, which increases the conductivity. The quantitative relations that form the basis of this current conduction theory will not be presented here, but are given in detail in Refs. 3 and 9. Comparison of slopes of the voltage-current plots with those of the theory show that the experimental values are about 30 to 50% too low. This agreement is excellent in view of the facts that the effect of Joule heating is to reduce the slope, and the cross section data are questionable.

c) Some comments on the two current-conduction models: A further insight as to the current conduction mechanism can be gained by examining the relative magnitudes of the mean electron drift velocities and the mean random velocities. This is equivalent to comparing the directed current density J to the random current flux $(en_e\bar{c}_e/4)$. If the equilibrium theory as well as the nonequilibrium theory is to be valid, then it is necessary that the directed current density be much less than the current density due to the random flux.

Table 3 indicates that only the nonequilibrium theory is self-consistent in that it permits $J_{\text{rand}} \gg J_{\text{dir}}$ for the magnitudes of J_{dir} observed in the experiments which were as large as 50–250 amp/cm². Although this simple comparison is not sufficient to validate the nonequilibrium theory, it still serves to indicate that the equilibrium theory by itself cannot furnish a complete picture of the process.

A series of experiments were performed with the purpose of "directly" measuring the elevated electron temperature predicted by Kerrebrock's nonequilibrium theory by use of the line reversal technique. Under the conditions of these experiments, the temperature measured by sodium line reversal techniques is essentially the electron temperature. Details concerning this procedure may be found in Ref. 3. Elevated temperatures were observed but were 300° to 400°K lower than the theoretical temperatures.

C. Transition Process

This section will consist of a discussion of the mechanism of transition to the current-limited mode. Consider the case of the electrodes initially operating in the normal mode; when the external resistance is reduced, the current increases until the thermionically limited current is reached. When the maximum possible current is being drawn from the cathode, the voltage drop across the bulk of the plasma cannot increase further. As a result, an additional increment in the applied voltage must appear across the sheath formed adjacent to the cathode surface.

The emitted electrons, which have been accelerated by the sheath potential, are then thermalized by elastic collisions with the atoms and electrons in a region near the cathode. Now the thermalization of the electrons constitutes an energy source near the cathode, which results in the heating of the cathode. In turn, this increased cathode temperature produces a reduction of the fractional surface coverage of potassium. This results in an increased work function ϕ and a reduction in the thermionic current as indicated by Eq. (1).[1]

The resulting decrease in the current produces a further increase in the sheath potential and thus an increase in the energy of the emitted electrons, which are accelerated by the sheath potential Φ_s. In the energy range from 1 to 10 ev, the cross section of the elastic electron-argon collision rapidly increases. Thus the heating effect increases with increasing sheath potential, because the strength of the heating source Φ_s is increased, and simultaneously the effective distance of the heating source from the cathode is reduced. This interaction then continues to increase the cathode temperature until other competing mechanisms are sufficient to limit the temperature increase.

Radiation from the wire, which increases as T_w^4, and the cooling effect on the cathode of passing the electrons through the work function barrier both produce a heat flux out of the cathode. When the forementioned heating and cooling effects reach a balance, a new stable operating condition is achieved. Space does not permit a quantitative discussion of this phenomenon; this may be found in Ref. 3.

D. Current-Limited Mode

When operating in the current-limited mode, the data suggest that the magnitude of the current is determined by the rate of thermionic emission of electrons from the cathode surface. This statement is supported by several experimental observations.

The vertical slope of the upper portion of the V-I curve in Fig. 4 shows that the current is independent of the applied voltage. The addition of foreign diluent gases and the presence of teflon contamination did not alter the magnitude

Table 3 Random electron current densities for equilibrium and nonequilibrium conduction

Gas temperature, °K	$J_{\text{rand}}{}^a$ (equilibrium), amp/cm²	$J_{\text{rand}}{}^a$ (nonequilibrium), amp/cm²
1800	1.53	1010
2000	6.72	1100
2250	29.9	1150
2500	100	1200

[a] $n_k/n_a = 0.004$, based on $J_{\text{dir}} = 10$ amp/cm².

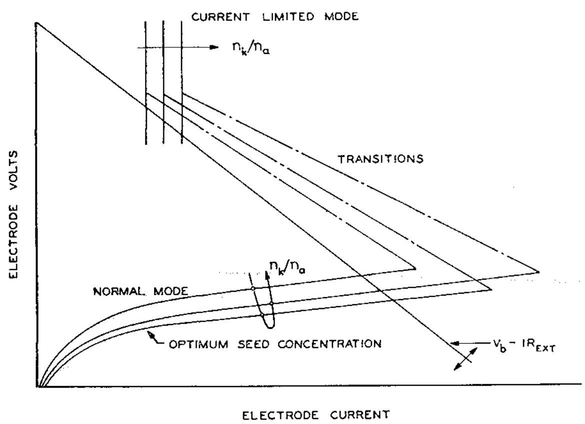

Fig. 11 Schematic voltage-current characteristics.

of the current obtained in this second mode. With an electrode system operating at a thermionic limit, a reduction in the electron emitting area will result in a proportional decrease in the current passing between the electrodes. The previously discussed "electrode switching" experiments, performed under conditions of current-limited mode operation, showed this dependence. And finally, increasing n_k/n_a produces a monotonic increase in current as would be expected, since for this region an increase in surface coverage of potassium will reduce the work function and hence increase the thermionic current.

In view of the preceding discussion concerning surface effects and the previous considerations of normal mode operation, it is now possible to properly explain the experimentally observed current variation shown in Fig. 8. Figure 11 is a schematic diagram of the V-I characteristics obtained when n_k/n_a is varied with all other parameters fixed. The spacing of the curves in the normal mode indicates the dependence of gas conductance on n_k/n_a and the existence of a maximum conductivity in the gas. Increasing (n_k/n_a) produces a larger maximum normal mode current, since increasing n_k for a given T_w should tend to produce an increased fractional potassium coverage with a resulting increase in the maximum thermionic current. In the current limited mode, the current increases with n_k for the same reason and is independent of gas phase phenomena.

E. Electrode Heat Transfer

When an electron is emitted from a surface, it moves into a region of higher potential energy by virtue of its having overcome the attractive image forces.[10] In a steady-state condition, this emitted electron is replaced by an electron conducted in from the external circuit. The replacement electron possesses a mean energy that is approximately equal to the Fermi energy. As a result, the metal must lose an amount of energy equal to $e\phi$ for each emitted electron when the sheath potentials are neglected. The reverse process occurs when the electron enters the surface and the material is heated.

Examination of experimentally determined heat-transfer coefficients,[3] indicates that they increase by a factor of 2 or 3 when a current density of 30 amp/cm^2 is used. This change shows that the Joule heating of the thermal boundary has an appreciable influence on the heat-transfer rate to the wall. However, it should be emphasized that the well-known, but sometimes overlooked, heating or cooling effect of the passage of electrons through the surface work function barrier can be of equal or greater importance when the temperature difference between gas and wall is not great.

F. Conclusions

Two modes of steady current conduction have been found for current flow between high-temperature electrodes in a potassium-seeded argon plasma. In the first, or normal, mode, the conduction phenomena are dominated by gas phase effects. The conduction in the second, or current-limited, mode is determined primarily by surface effects.

It should be stressed that, in both modes of conduction, electron emission from the cathode is apparently by the thermionic process. In the first mode, the current density at the electrode surface is less than the thermionic limit, and cathode sheath potentials are less than a few kT_w. In the second mode, the current density is equal to the thermionic limit, and sheath potentials are orders of magnitude greater than kT_w.

The transition between the two modes is produced by the increase in heat transfer associated with the sheath potentials, which may be large when the current is thermionically limited. Although the abrupt change in voltage which occurs at transition is a result of the use of uncooled electrodes in these experiments, both modes would still exist for constant temperature electrodes.

Interpretation of voltage-current data for the normal mode indicates that both Joule heating and the nonequilibrium heating of electrons must be taken into account to explain the high conductivity values that were experimentally observed. The data obtained during the transition process and in current limited mode operation agrees well with the behavior anticipated in view of Langmuir's work concerning surface adsorption of alkali metals on tungsten.

Heat-transfer phenomena are strongly influenced by electron cooling or heating effects. In the normal mode, the most important term appears to be the energy loss or gain associated with motion of electrons through the surface work function barrier. In the current-limited mode, the dominant factor is the thermalization of emitted electrons, which have been accelerated by the large cathode sheath potentials.

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