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The Magnetoplasmadynamic Arcjet

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Abstract—The Magnetoplasmadynamic Arcjet. The optimum thrusters for interplanetary space missions should provide a combination of high specific impulse and high thrust density. The first electric thruster to show promise of this combination, the so-called magnetoplasmadynamic arcjet, evolved from the conventional electrothermal arcjet operated in a very low mass flow, high power regime. The diffusion of the arc attachment point over the cathode, which occurs at low arc chamber pressures, enables currents up to 3000 amps to be drawn, producing specific impulse values comparable to the ion engine at thrust densities three orders of magnitude greater. Many variations of this thruster now exist, both with and without externally applied magnetic fields, but little understanding of the relative importance of self-magnetic field, external magnetic field, and pure electrothermal thrust components over the complete spectrum of operation has yet been achieved.

Analytical models of the magnetoplasmadynamic arcjet range from application of $\mathbf{J} \times \mathbf{B}$ body forces in a continuum flow, to collisionless orbit theories of ionized gases in the prevailing electric and magnetic fields. Better definition of the proper model for analysis awaits determination of the physical properties within the exhaust plume—an extremely difficult task due to the hostile environment. Because of this problem, only a few productive diagnostic studies have been performed, and these have been for exhaust plume conditions far from the most intense.

Recent experiments with pulsed plasma thrusters have revealed a stabilization of the exhaust plume current pattern in a configuration closely resembling the magnetoplasmadynamic arcjet, raising the possibility of utilizing transient probing techniques to provide diagnostic information in operating regimes inaccessible to steady state probing.

Translated abstracts appear at the end of this article.

I. Introduction

DURING the past several years, consideration of more and more ambitious space missions requiring progressively higher specific impulse propulsion systems has fostered the development of a variety of electric propulsion concepts. Initially, emphasis was concentrated primarily on the attainment of high propellant exhaust speeds at high electrical conversion efficiencies, with little concern about the low thrust densities characteristic of devices of this family. It is clear, however, that if electric propulsion is to assume a major role in prime propulsion for deep space missions, thrusters combining high specific impulse with reasonably high thrust capabilities must be developed. This article is a review of the early stages of development of the first electric thruster to show promise of this combination.

The potential capability of this new thruster is perhaps best illustrated by casting it on a diagram displaying the specific impulse and thrust density attainable with various familiar propulsion devices (Fig. 1). In the upper left corner, we find the conventional chemical rockets of high thrust but low specific impulse; in the lower right corner reside the electrostatic ion engines and the less well developed pulsed plasma thrusters which provide very high specific impulse, but low mean thrust density. Our interest here is in the accessability of the upper right domain where both specific impulse and thrust may be optimized for given missions.

The solid core nuclear thermal rocket takes a step in this direction in providing specific impulses up to 800 sec at thrust densities comparable with chemical rockets. Projections for the proposed liquid and gas core nuclear rockets extrapolate further into the desired domain. Operational electrothermal systems, such as the arcjet and resistojet provide specific impulses comparable with the nuclear rockets, at one or two orders of magnitude less thrust density.

The desired domain of high specific impulse and substantial thrust density was first attained in the laboratory by a class of steady-flow electromagnetic plasma thrusters wherein an externally applied magnetic field acted upon currents driven through

an ionized propellant stream to provide the desired acceleration. Data from laboratory tests of these devices included thrust densities of 10 lb/in^2 at specific impulses from 2000 to 3000 sec [1], but was attended with such severe material erosion problems, and involved such massive auxiliary equipment for cooling, magnetic field generation, and preionization of the gas flow, that little space propulsion application could be visualized.

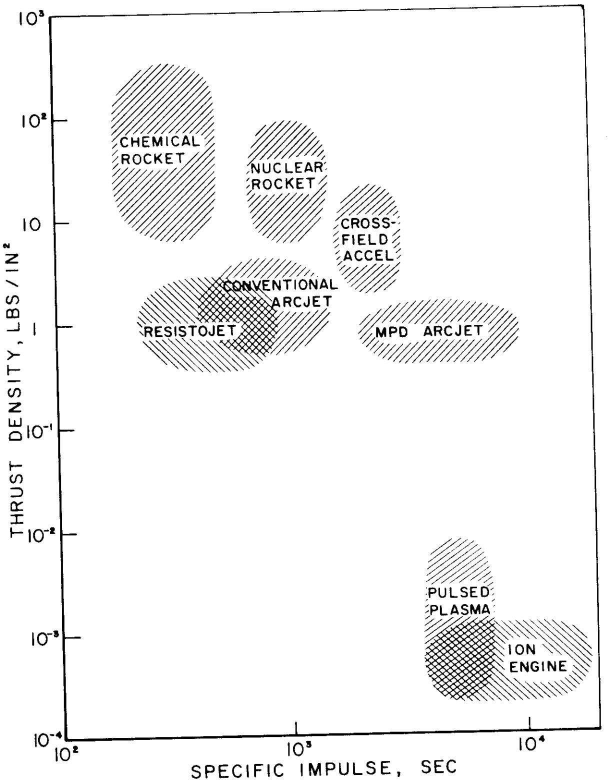

FIG. 1. Specific impulse and thrust density of various propulsion devices.

Prior to 1964, then, no feasible candidate for a space thruster capable of operation in the desired range of Fig. 1 existed. At this time, however, experimentalists stumbled upon a thruster concept which combined certain elements of both the electrothermal and electromagnetic thrust mechanisms, to produce better performance than either mechanism alone. The capability of this thruster, which has generally become designated as the magnetoplasmadynamic or MPD arcjet, has yet to be precisely catalogued. However, recent experiments indicate its operating regime to be approximately that shown in Fig. 1, i.e. specific impulse comparable to that of the ion engine but thrust density values at least three orders of magnitude greater. In the following review of the early development of this thruster, it will become clear that this performance improvement is accompanied by unique problems which have lead to substantial data discrepancies, to an absence of definitive diagnostic experiments, and to a consequent lack of analytical formulation. Nevertheless, the magnitude of the initial performance increase of the MPD arcjet over other electric propulsion schemes is sufficient to warrant the expenditure of considerable effort in order to resolve these problems.

II. Early Observations

The MPD arcjet was a by-product of experimental efforts to extend the operating regime of the conventional thermal arcjet, a device that itself was being developed to exceed the specific impulse level of chemical rockets by circumventing the limitation imposed by the energy content of the combustible propellants. Typical of the variety of conventional arcjets is the radiation-cooled thruster shown in Fig. 2 [2]. In this engine, an arc is struck between the

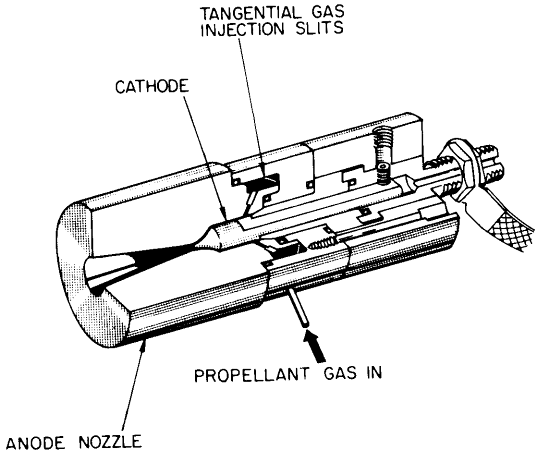

FIG. 2. 30 kW radiation-cooled arcjet engine. (*Courtesy of Avco Corp.*)

central cathode and the diverging anode nozzle, and is constrained to pass through the short constrictor channel. The tangentially injected propellant is heated by both the arc and the thruster walls and in turn stabilizes the arc filament while maintaining the thruster walls at a tolerable temperature. The specific impulse for this 30 kW engine ranges from 1000 to 1500 sec for hydrogen propellant with an overall energy conversion efficiency of up to 45 per cent. The upper value on specific impulse attainable in this device and in others like it is established by the thermal limitations of the tungsten electrodes, and of the other material surfaces. Yet, there is considerable motivation to operate thrusters of this class at

substantially greater power density, since any additional energy input beyond that required to ionize and dissociate the propellant will go directly into random thermal modes of the gas which can be readily converted to kinetic energy in the nozzle. However, attempts to operate in these higher power regimes were accompanied by frequent burnouts at the anode attachment of the arc filament, and the arcjet concept seemed fundamentally confined to specific impulses below 2000 sec.

Then, in late 1963, Ducati reported a remarkable change in the operating range of a hydrogen arcjet [3]. Namely, that by drastically reducing the mass flow and hence the chamber pressure, the arc could be caused to diffuse over the cathode surface, and to extend far out into the exhaust stream, in which configuration the arc current could be increased to 3000 A or more with no noticeable structural damage. Operating under these conditions, a luminous exhaust plume was observed to blossom out into a large ball behind the nozzle as illustrated in Fig. 3, and the thruster performance could be increased to the level shown in Fig. 4, attaining efficiencies of nearly 50 per cent at a specific impulse of 10,000 sec.

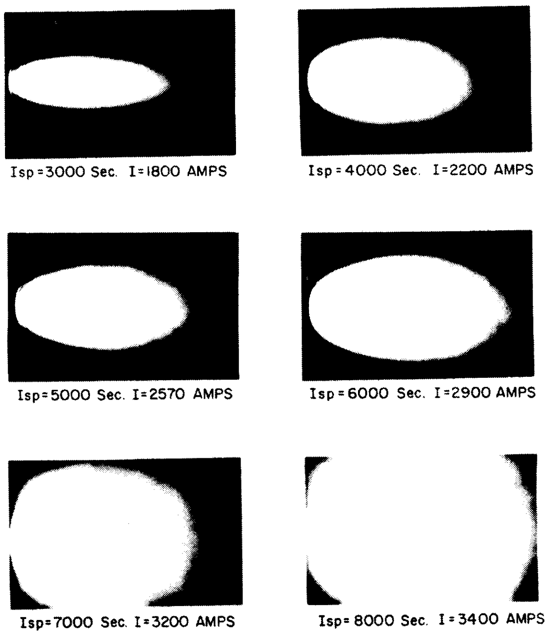

FIG. 3. Hydrogen MPD arcjet at various current levels. (*Courtesy of Giannini Scientific Corp.*)

In order for a purely thermal expansion to produce velocities of such magnitude, stagnation temperatures of the order of 100,000°K would be required. Since this seems substantially beyond the thermal limitations of the thruster, it may be surmised that the large arc current generates a magnetic field of sufficient intensity to react on the current pattern itself, and thus to produce a substantial electromagnetic thrust component. Hence, contrary to the discouraging predictions of the early plasma propulsion experiments, Ducati had constructed a steady electromagnetic accelerator which required no external magnet, no preionization equipment, and no gas-seeding system, and which operated with negligible electrode erosion.

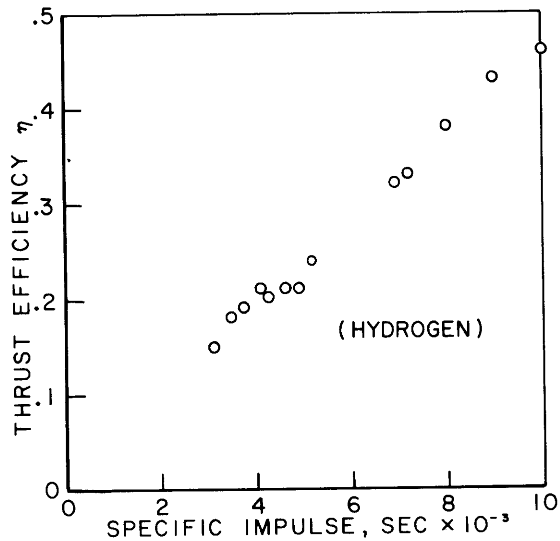

FIG. 4. Magnetoplasmadynamic thruster efficiency variation with specific impulse [3].

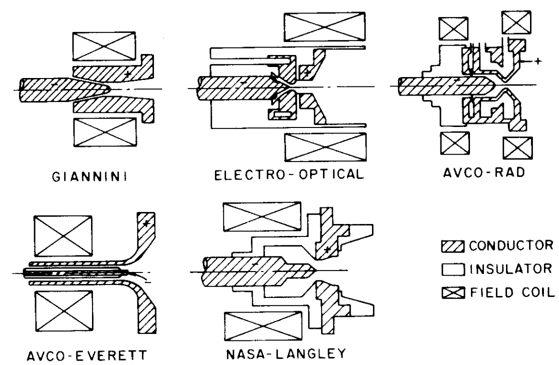

FIG. 5. Various MPD thruster configurations.

Immediately following Ducati's report, several laboratories undertook a sequence of rather empirical confirmatory experiments in which thruster geometry, propellant type, mass flow rate, and power level were varied [4–7]. External magnetic fields were also added to diffuse further the anode arc attachment, resulting in additional performance improvements. In retrospect, some hints of the high performance capability could be identified from much earlier experiments on

steady electromagnetic thrusters of the 'Hall-Current' class [8, 9]. Typical of the many configurations which were found capable of operating in this high specific impulse domain are the five thrusters shown schematically in Fig. 5. These geometries cover a wide range in both degree of throat constriction and magnitude and configuration of the externally applied magnetic field. However, since each of these thrusters is capable of a performance level at least equal to that of Ducati's, each should logically be regarded as a type of MPD arcjet.

III. Mechanisms

From the operation of these different thruster configurations over a wide range of conditions, it is apparent that a variety of mechanisms contribute to the total thrust: (1) a self-field contribution arises from the interaction of the current with its self-induced magnetic field. The resulting thrust component clearly varies with the square of the arc current and becomes significant for currents greater than approximately 1000 A. This contribution can be further subdivided into an axial component and a radially inward component, the latter being counterbalanced by a radial pressure gradient which, when integrated over the cathode face, also produces an axial force. (2) The arc current interacts with the external magnetic field to produce (a) an azimuthal current which can further interact with the applied magnetic field to yield axial forces and (b) a bulk azimuthal motion of the plasma in which the rotational kinetic energy can be exchanged for axial kinetic energy by expansion in a nozzle. (3) Some electrothermal thrust contribution must remain as a vestige of the original function of the arcjet accelerator.

Beyond the initial identification of these mechanisms, and the general observation that their relative importance is a sensitive function of the particular operating conditions and electrode geometry, little specific correlation of performance with physical phenomenology has been achieved. One example of this level of confusion is shown in Fig. 6 which displays cumulative data of absolute thrust variation with arc current. In the data of this figure almost every parameter including geometry has varied to some degree, e.g. external field strength covers the range from 0 to 5 kG, the mass flow for six different propellants varies from .1 to 300 mg/sec, and the tank back pressure ranges from 7 μ to 500 μ. Clearly no general conclusion regarding the dependence of thrust on arc current can be deduced from this scattered data, except that an increase in arc current produces an increase in thrust.

In the process of accumulating the data shown in Fig. 6, a second remarkable property of the MPD arcjet was revealed when the propellant flow to an operating thruster was inadvertently shut off. Instead of extinguishing, or precipitating severe structural

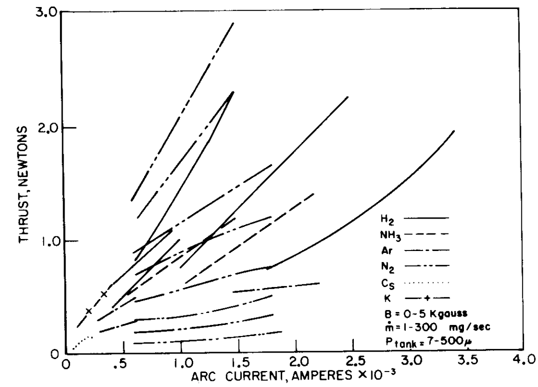

FIG. 6. MPD thrust variation with arc current [23].

damage, the arc continued to produce significant thrust and continued to develop an extended, luminous plume [10]. This observation understandably cast serious doubts on the validity of the original high performance levels reported and placed a premium on its immediate explanation. Subsequent tests showed that for cathode diameters less than approximately $\frac{1}{4}$ in., the arc discharge could be sustained by vaporization of the electrode material alone. For larger diameter cathodes, however, negligible erosion was found, yet stable operation with no incoming gas flow could be maintained indefinitely [11]. It was suspected that this latter mode was fostered by a recirculating of the residual exhaust gases in the vacuum test chamber back through the arc and plume. In some cases, it was observed that current loops in the plume were completed through the metallic vacuum tank walls [12, 13].

In order to minimize the effects of ingestive recirculation of the exhaust gases and current loops in the environmental chamber, an MPD thruster has been operated in the large vacuum facility at the National Aeronautics and Space Administration's Lewis Research Laboratory [14]. Specifically, this vacuum tank is 15 ft in diameter by 65 ft long and is equipped with a liquid nitrogen cooled wall and twenty 32-in. diffusion pumps making it one of the few vessels of its size capable of maintaining a vacuum of 10^{-2} μ at characteristic MPD arcjet flow rates. The thruster used in the test is identical to the one shown in Fig. 7 except that it has a solid cathode rather than the pressure tap in the tip as shown in the figure. The magnetic field was varied between 600 and 1400 G.

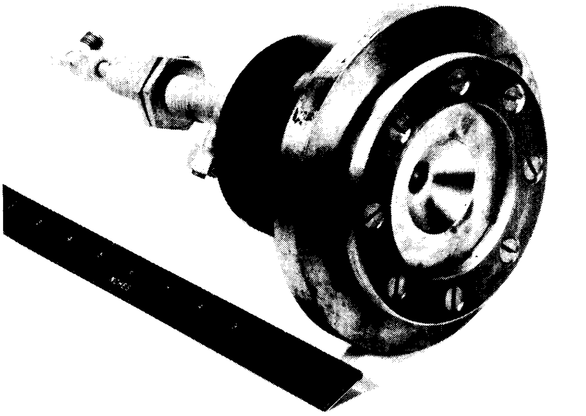

FIG. 7. MPD arcjet producing data in Fig. 8. (*Courtesy of Avco Corp.*)

The efficiency–specific impulse curve for this thruster obtained in this facility using hydrogen propellant is shown in Fig. 8. The solid line in the figure represents the average of performance data recorded in a vacuum tank 3 ft in diameter at a backpressure of 200 μ. The small circles are performance data recorded in the large facility at approximately the same backpressure as in the smaller tank indicating that at this pressure, the smaller tank does not appear to prejudice the data. As the ambient pressure is lowered by three orders of magnitude, it is observed

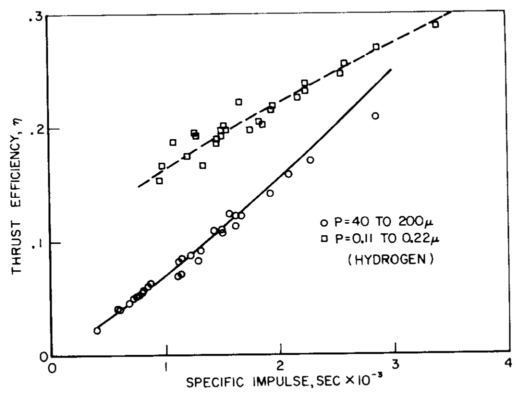

FIG. 8. MPD arcjet performance with various tank pressures [14].

that the thrust monotonically increases, and consequently the thruster performance increases as shown by the square data points and the dashed average line through them. Hence, within the geometrical and environmental capabilities of this large vacuum facility, the original high performance of the MPD arcjet with a low propellant flow rate has been sustained.

IV. Models

Several physical models have been proposed for the MPD arcjet. Because of the paucity of diagnostic experiments in the exhaust plume, these models invoke a variety of assumptions with a consequent wide range of predictions and limitations. Selection of the most pertinent model awaits better determination of the physical parameters of interest in the exhaust plume—a difficult task due to the extremely hostile environment.

The main distinction among the models is between the continuum or magnetogasdynamic point of view and the free particle or gaskinetic approach. Since the actual process probably involves some aspects of both of these mechanics it is useful to examine each separately. In the continuum representation, the crossing of the radial and axial current components with the azimuthal self magnetic field produces axial forces as discussed previously. In addition, either the radial or axial component of an external magnetic field when crossed with the proper current component can produce an electromagnetic swirling of the gas. Finally, allowing tensor conductivity effects, various Hall interactions can be present, such as the crossing of an azimuthal Hall current component with the radial component of an external field to produce an axial force.

For the purely self-field contributions, it has been shown that the total electromagnetic thrust for uniform current density over the cathode end surface varies as

$$F = \frac{\mu J^2}{4\pi}\left(\frac{3}{4} + \ln\frac{r_a}{r_c}\right)$$

where J is the total arc current (A), μ the magnetic susceptibility (m.k.s.), and r_a and r_c the radii of arc attachment on anode and cathode respectively [15]. Note that this thrust component is independent of the detailed pattern of the arc, and independent of the mass flow rate to the extent that the mass flow does not alter the total arc current or the effective radii of arc attachment on the cathode and anode surfaces. To this extent, then, the exhaust velocity should scale inversely with the mass flow rate if the acceleration conforms with the postulated mechanism.

Although the magnetogasdynamic model of the MPD arc makes no reference to gas properties, it assumes a continuum interaction in the manner in which it invokes the **J** × **B** body force. However, since the large arc currents and high exhaust velocities are favored by low gas pressures in the arc chamber, some particle mean free paths and gyro radii may become comparable with the chamber dimensions.

The extreme case of completely collisionless current conduction and particle acceleration forms the basis for the second proposed model for the MPD arc [16]. In this model, sufficient collisions are allowed to ionize the incoming propellant near the anode. The ions thus created are accelerated radially inward by the electric field without further collisions and are subsequently deflected axially outward by the azimuthal self-magnetic field until they join an axial stream of electrons emitted from the cathode. Hence, the thruster basically acts as an electrostatic ion accelerator with space charge neutralization provided by the cathode electron beam.

This model predicts certain correlations of its terminal properties which differ from the continuum case. First, the current is directly limited by the mass flow since only ions carry the radial current, i.e.

$$J \leqslant \frac{\dot{m}e}{M_+}$$

for single ionization, where M_+ is the ion mass and e the electronic charge. Second, the ion gyro radius must be of the order of the radial position in order to negotiate the turn from the radial to the axial direction, i.e.

$$r_g^+ (r) = \frac{M_+ V_+}{eB} = \frac{2\pi r M_+ V_+}{\mu e J} \leqslant r.$$

This criterion is most severe when the ions have attained nearly their full exhaust velocity, $V_+ = u$, from the E field so that this velocity is bounded in terms of J:

$$u \leqslant \frac{\mu e J}{2\pi M_+}$$

The exhaust velocity is also limited by the available potential drop across the electrodes, ϕ:

$$u \leqslant \left(\frac{2\phi e}{M_+}\right)^{\frac{1}{2}}.$$

Appropriate combinations of these relations, using the equalities, predicts an arc voltage that varies as J^2, a thrust that varies as J^2, and an exhaust speed proportional to J and inversely proportional to M_+. The essential distinction between these predictions and those of the magnetogasdynamic model thus stem from the specific coupling of arc current to mass flow and to exhaust speed which are not demanded by the latter.

The validity of the particle model clearly hinges on the collisionless assumption, one which may be unreasonable for much of the domain over which the MPD arc is observed to function. However, two features of it are more generally relevant and provide some insight into two prominent aspects of the arc operation. The first relates to the ability of the cathode to withstand the extremely high current densities, of the order of 10^9 A/m^2. Normally, concentrations of current this intense will rapidly erode a cathode surface by ion bombardment, but here the strong magnetic field near the cathode tip can deflect the incoming ions sufficiently to protect the cathode from excessive heating. Because of the inverse dependence of the magnetic field on the radius, this magnetic protection of the cathode can prevail at far higher particle densities than could be allowed for application of a purely collisionless theory throughout the arc chamber.

The second instructive contribution of the collisionless approach concerns the coupling of arc current to mass flow rate which may be relevant to the 'zero mass flow' operation reported earlier. If the device is operated in a regime where ions alone carry the current and the mass flow is then reduced, the arc would be starved for current carriers, and the current would tend to decrease. However, if the current were forcibly maintained at its previous level by the external circuit, the arc would be obliged to obtain current carrying particles from other than the inlet mass flow, e.g. from the electrode surface material, or by recirculating a fraction of the exhaust plume. Thus, while this model may not describe the higher mass flow domain of MPD arc operation, it may establish the lower mass flow limit before recirculation or electrode consumption begins.

The gap between the continuum and collisionless approaches can be bridged by incorporating collisional effects in the particle orbit mechanics, a formidable task if done precisely. However, qualitative patterns of current and thrust densities can be predicted from examination of the electron and ion Hall

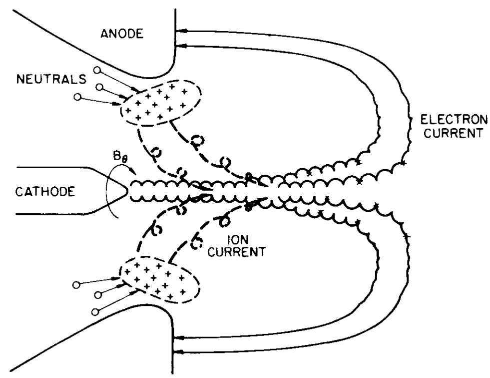

FIG. 9. Schematic ion and electron trajectories in an MPD arcjet.

parameters and their respective gyro radii over the arc chamber and plume regions [17]. This approach requires some initial estimates, presumably based on experimental data, of the patterns of the various gas properties which determine the Hall parameters and gyro radii, namely the degree of ionization, the electron number density, the electron and heavy particle temperatures, and the magnetic field. When applied to a typical example of a hydrogen MPD arc of sufficient current density to dissociate and ionize all of the gas in the current carrying region and with no external magnetic field, this technique suggests the following picture of the current conduction process (Fig. 9):

(1) Electrons emitted from the cathode find themselves in a high Hall parameter region and consequently follow a cross-field drift which is here axial due to the azimuthal magnetic field and primarily radial electric field. As the electron temperature decreases in the drift away from the nozzle exit plane, so does the electron Hall parameter, whereby the electron enters a collision-dominated region which allows radial motion and migration back to the anode. This latter scalar conduction region provides a **J** × **B** force like that in an elementary cross-field accelerator, but which here is directed everywhere outward from the exhaust plume.

(2) Very near the cathode tip, the ion gyro radius can be sufficiently small to allow the ions also to lapse into a cross-field axial drift, thereby contributing a thrust determined by the mass flow concentrated in the jet and the local drift velocity, E/B.

(3) The intermediate radial and axial positions are distinguished by a predominantly electron Hall current and ion scalar current yielding a radial acceleration of the ions by the electric field. This manifests itself as an axial force due to the increased gasdynamic pressure on the cathode surface.

In a similar fashion, the effect of an external magnetic field on the arc operation can be displayed by this technique (Fig. 10). For a predominantly axial external magnetic field which is everywhere much stronger than the self-induced magnetic field, electrons emitted from the cathode again encounter a high Hall parameter region and accordingly drift in the **E** × **B** direction which is now azimuthal. The component of the electric field parallel to the magnetic field superimposes an axial motion on the azimuthal rotation until the electron moves far enough downstream to allow a collision dominated radial migration across the **B** lines back to the anode. As the electron approaches the anode however, it again enters a region of high Hall parameter due to the external field and

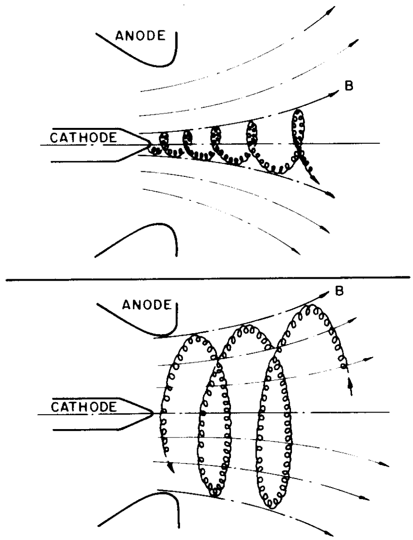

FIG. 10. Schematic electron trajectories near the cathode and anode of an MPD arcjet with an external magnetic field.

lapses into another spiraling trajectory like that found near the cathode.

For realistic operating conditions, the ion gyro radii near the cathode and anode may be much smaller than the electrode gap, predicating spiraling ion trajectories in these regions very much like those of the electrons. In this case, since the direction of the **E** × **B** drift is the same for both ions and electrons, this hybrid model predicts no net Hall current, but only a swirling of the gas as a whole in these anode and cathode plasma funnels.

It should be noted that most of the phenomenological traits displayed in the experimental operation of these devices can be qualitatively rationalized by the procedure briefly outlined above. Plume protraction, ambient gas ingestion, arc swirling, cathode protection, and the gross aspects of the current density distribution all follow logically from its self-consistent application under the prevailing conditions. The extent to which it can provide quantitative information of these phenomena clearly rests on the accuracy with which the appropriate parameters can be determined over the range of interest.

It is important to realize that none of the previous models includes an electrothermal thrust contribution which, as has been mentioned previously, is a strong possibility considering the evolution of the MPD arc. At first glance, the electrothermal contribution might seem to be minor in a thruster producing exhaust velocities up to 10^5 m/sec because of the excessive gas temperatures which would be required. However, a characteristic feature of the previous models has been the displacement of the collision

dominated regime downstream from the material electrodes due to the large self-induced or external magnetic fields. In this way, the arc may now be able to sustain much higher currents and gas temperatures in this 'ohmic' region than if the latter were in direct contact with the electrodes. The extreme point of view would be to regard the device as still an electrothermal arc, with the hottest portion of the gas constrained away from the electrodes and the exhaust stream expanding in a magnetic nozzle established by the field pattern. In the last analysis however, the distinction between electrothermal and electromagnetic acceleration processes becomes rather academic in an environment as complex as this. On an atomic scale, this distinction relates to the ability of the particles to randomize the energy imparted to them by the electromagnetic fields, over the dimensions available in the device. Effective randomization is evident in the collisional regions of the arc, but in the free orbit drifting regimes and in the effectively collisionless motion of the ions, the criterion for thermalization is less clear. This postulated electrothermal component is important from the standpoint of the overall efficiency of the arc. Were only electromagnetic effects producing the gas acceleration, all Joule heating of the gas would be regarded as an energy loss. If on the other hand, the device retains some of its electrothermal heritage and can redirect a significant portion of this randomized energy into streaming energy, the overall efficiency will benefit accordingly. In the limit, only some radiation and electrode losses would detract from its performance, and its efficiency can be extremely high.

V. Illuminating Tests

As has been indicated previously, analytical and experimental efforts on the MPD arcjet are not yet to the point of being complementary since few conclusions can be drawn from the postulated models regarding interparameter dependence, and diagnostic experiments to provide inputs for complete models have been limited by the extremely hostile testing environment. A few illuminating experiments, both phenomenological and diagnostic, have been conducted however.

One enlightening phenomenological test has been the demonstration of entrainment and recirculation of the exhaust gases when the ambient pressure is relatively high (20–1000 μ) [11]. In this experiment, the MPD arc is operated on nitrogen propellant while hydrogen is bled into the vacuum tank through an auxiliary port. At the outset, the color of the exhaust plume is the characteristic blue of atomic nitrogen, but as the nitrogen flow rate is steadily lowered, the downstream portion of the exhaust plume displays the characteristic red hue of atomic hydrogen indicating that hydrogen is becoming entrained in that region. This effect progresses upstream through the plume, until, with no nitrogen propellant flowing through the thruster, the entire exhaust is bright red back into the electrode gap, indicating that the arc is being sustained solely by the entrained hydrogen gas.

In this zero-mass-flow operating condition of the arcjet, the recirculation of the gases in the exhaust plume region can be demonstrated by lowering a thin tungsten wafer to various radial positions in the plume. In the intermediate and outer radial positions, the wafer deflects upstream indicating a movement of the gases in this region toward the nozzle exit. Upon lowering the wafer further into the center of the exhaust plume, it deflects strongly downstream indicating the presence of a high velocity core of gas in the conventional direction.

Two separate determinations of the distribution of current density in the arc and plume have been made with conflicting results. The first of these employed a water-cooled Hall effect transducer on an argon MPD arc operating at a total current of 400 A, an external magnetic field of 1.5 kG, and a backpressure of the order of 100 μ [18]. The second effort employed a similar technique on an MPD arc using argon, ammonia, and nitrogen with roughly the same external field and backpressure, but a total current of 1000 A [19]. The results agree qualitatively on the radial dependence of axial current density which is strongly peaked in the center near the exit plane and broadens smoothly as axial distance from the exit plane increases. The disagreement arises in connection with the axial decay of axial current as shown in Fig. 11. Here, it is seen that the higher current data decays axially faster than the lower current data, a trend which conflicts with the observation of higher

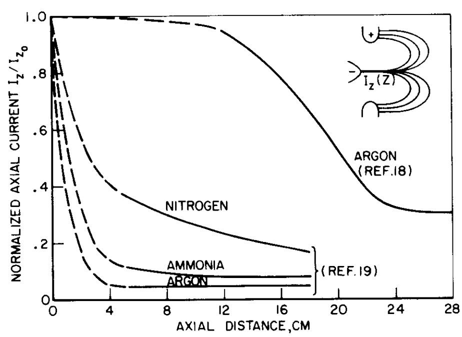

FIG. 11. Experimental axial current variation with axial distance.

currents producing a greater plume extension, assuming that the highly luminous regions can be associated with regions of high current density. For example, 12 cm downstream of the thruster exit plane, the low current arc still passes some 95 per cent of total current out along the axis, while the high current arcs maintain less than 25 per cent out to this dimension.

The distribution of electron number density and electron temperature in an exhaust plume has been studied using a Langmuir probe swung through the plume and spectroscopic techniques [20]. This MPD arcjet operated with argon propellant at a power level of up to 50 kW, with no external magnetic field, and a backpressure from 100 to 500 μ. The results are shown in Fig. 12. It is observed that the electron

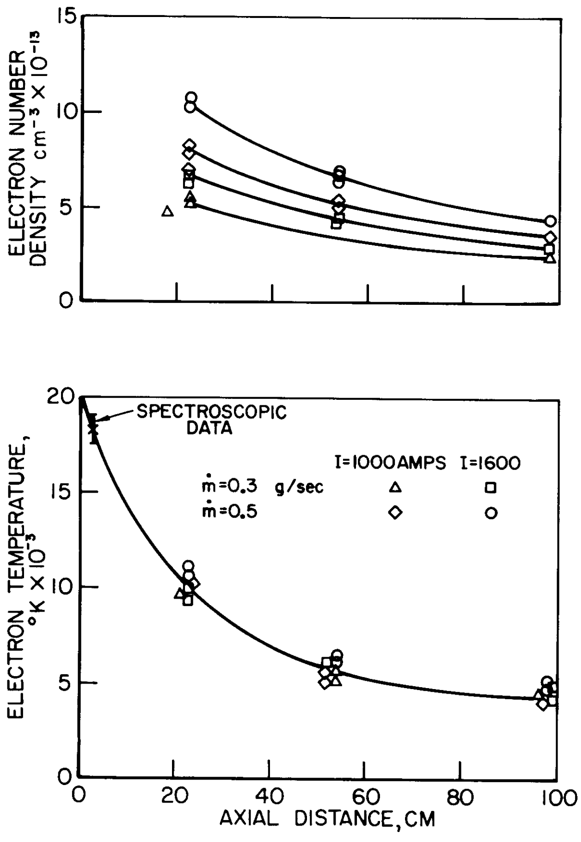

FIG. 12. Axial profiles of electron number density and electron temperature [20].

number density decreases slowly in moving downstream from a value of $1–2 \times 10^{14}/\text{cm}^3$ at the nozzle exit plane. There is a slight dependence on mass flow and current level. The electron temperature appears to fall exponentially downstream with little or no dependence on mass flow rate and current level. Both the electron number density and the electron temperature show a fairly flat radial variation.

With these isolated exceptions, little definitive experimental data on the structure of an MPD arc exists. Clearly, more sophisticated and detailed diagnostics must be accomplished before any significant generalizations can be drawn or new models proposed. It is especially important that techniques be developed for probing the exhaust plume under the most intense conditions of low back pressure and high current, where the magnetoplasmadynamic effects will be paramount.

VI. Correlations with Pulsed Experiments

Magnetoplasmadynamic space thrusters of ultimate interest may consume some 1–10 MW of electrical power, i.e. involve currents of 10,000 to 100,000 A. The electromagnetic processes which dominate such thrusters could differ significantly from those observed in the 100 to 1000 A devices currently under study, yet steady operation of a 10 MW arcjet in the laboratory to identify such differences seems formidable indeed. There thus is valid interest in the transient simulation of the operation of such high power devices, where the arc would last long enough to achieve the essential characteristics of a steady device, and permit suitable diagnostic measurements on its properties, but not so long as to pose intolerable power supply, cooling, or gas handling problems.

Experiments based on this concept are currently in progress, wherein a large capacitor bank assembled in a low inductance transmission line sequence delivers a $10^4–10^5$ A pulse of $10^{-5}–10^{-4}$ sec duration to an MPD electrode configuration of 4 in. anode orifice [21]. Following an inception period of a few microseconds, the arc is found to stabilize itself for the duration of the pulse into a fixed pattern which is felt to embody the essential characteristics of the steady MPD arc at this power level. One possible reservation concerns the attainment of prolific thermionic emission from the cathode on this time scale, a point which is being checked by observation of the electrode voltage profile in time, and by comparison of data with and without the cathode artificially heated [22]. Figure 13 displays early results on the current density distribution in a pulsed arc which uses a cold flat disc cathode, rather than the conventional conical tip. The observed patterns are found qualitatively to resemble the current density profiles in the lower power steady MPD arcs insofar as axial protraction into the plume, and radial blooming are concerned, but it has not yet been possible to examine the subtler aspects of the patterns, particularly the details of the anode and cathode fall regions.

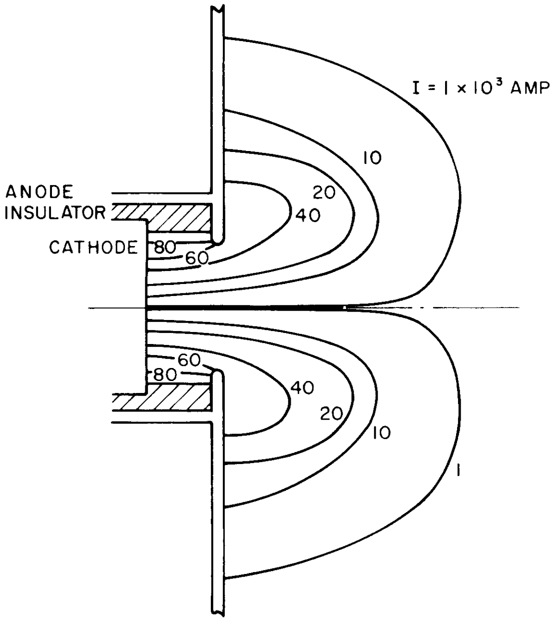

FIG. 13. Stabilized enclosed current contours in the exhaust of a pulsed plasma thruster.

VII. Concluding Remarks

The somewhat vague and sketchy presentation of this topic is indicative of its present state of understanding. While it is evident that the magnetoplasmadynamic arc is a device which fortuitously embodies intensities and geometries of current, electric and magnetic fields which circumvent several of the classical limitations of conventional electromagnetic and electrothermal accelerators, it is far from clear how it is capable of violating several previously accepted limitations on arc accelerator operation. In the extremely high current densities it extracts from its electrodes, in the apparently excessive gas temperatures within the arc, and in its preference for a low pressure, low mass flow mode of operation, the MPD arc is a renegade in its class. Yet, this irregularity may be a portent of the situation ultimately to prevail in the entire field of prime plasma propulsion. Namely, that the acceleration of a high temperature, highly ionized, nonuniform and nonequilibrium working fluid by the interaction of large, interwoven electric and magnetic fields will not prosper under the simple superposition of conventional gasdynamic and electric arc technologies, but will demand a new spectrum of engineering techniques yet to be developed.

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Résumé—L'Arc Réacteur Magnetoplasmadynamique. Les dispositifs de poussée optimum pour des missions dans l'espace interplanétaire doivent être en mesure de produire une combinaison d'impulsion spécifique élevée et d'intensité de poussée élevée. Le premier dispositif de poussée électrique qui ait démontré les possibilités de cette combinaison, connu sous le nom d'arc réacteur magnétoplasmadynamique, fut développé à partir de l'arc réacteur électrothermique conventionnel fonctionnant dans un écoulement de masse réduit, avec une puissance élevée. La diffusion du point d'attache de l'arc sur la cathode, qui a lieu à des pressions réduites dans la cuve de l'arc, permet d'obtenir des courants allant jusqu'à 3000 ampères, produisant des valeurs d'impulsion spécifique comparables au moteur à ions à des intensités de poussée supérieures dans la mesure de trois ordres de grandeur. De nombreuses variations de ce dispositif de poussée existent maintenant, aussi bien avec que sans champs magnétiques à application extérieure, mais on n'a obtenu qu'une compréhension réduite de l'importance relative, du champ automagnétique, du champ magnétique extérieur et de la poussée électrothermique pure par l'effet de leurs composantes tout au long du spectre de fonctionnement complet.

Des maquettes analytiques de l'arc réacteur magnétoplasmadynamique s'étendent de l'application de forces **J** × **B** dans un écoulement de masse continue, à des théories d'orbite sans collision pour des gaz ionisés dans les champs électriques et magnétiques. Une meilleure définition de la maquette convenant à l'analyse nécessite d'établir les propriétés physiques de l'intérieur du panache d'échappement—tâche extrêmement difficile par suite du milieu hostile. En raison de ce problème, seulement quelques études donnant un diagnostic productif ont été exécutées, et celles-ci ont eu trait à des conditions de panache d'échappement très éloignées des plus intenses.

Des expériences récentes avec des dispositifs de poussée à plasma ont révélé une stabilisation de la configuration de courant dans le panache d'échappement en une configuration ressemblant de très près à l'arc réacteur magnétoplasmadynamique, présentant la possibilité d'utiliser des techniques de sondage transitoire pour fournir des renseignements sur des régimes en fonctionnement ne pouvant être soumis à un sondage dans un état stable.

Zusammenfassung—Der magnetoplasmadynamische Plasmabrenner. Die günstigsten Schubantriebe für den interplanetaren Raumflug vereinigen in sich hohe Werte des spezifischen Impulses mit hohen Schubdichten. Die ersten elektrischen Schubantriebe die in dieser Richtung Versprechen zeigen, sind die sogenannten Magnetoplasmadynamischen Plasmabrenner, eine Weiterentwicklung der üblichen elektrothermalen Plasmabrenner die bei geringem Massendurchsatz und hoher Leistung betrieben werden. Diffusion des Bogenansatzpunktes über die Kathode, die bei geringen Bokenkammerdrucken stattfindet ermöglicht den Betrieb mit bis zu 3000 Ampere, dies ergibt spezifische Impulse, die mit denen des Ionen-Antriebes vergleichbar sind, und Schubdichten die um drei Grössenordnungen höher sind. Es gibt verschiedene Arten dieser Schubantriebe, sowohl mit wie ohne äussere Magnetfelder; aber ein Verständnis der relativen Bedeutung von Eigenfeld, angewandtem äusserem Feld, sowie der rein elektrothermalen Schubkomponenten über den gesammten Wirkungsbereich wurde bisher nicht erzielt.

Analytische Modelle des Magnetoplasmadynamischen Plasmabrenners rangieren von der Anwendung der **J** × **B** Körperkräfte auf eine Kontinuierliche Strömung bis zu Theorien der Bahnen zusammenstosslose Teilchen in ionisierten Gasen in elektrischen und magnetsichen Feldern. Eine bessere Definition des passenden Modells für eine Analyse setzt eine Bestimmung der physikalischen Eigenschaften des austretenden Plasma strahles voraus—was wegen der ungünstigen Umgebung im Plasmastrahl keine einfache Aufgabe ist. Wegen dieser Schwierigkeit, wurden bisher nur wenige diagnostische Untersuchungen gemacht, und diese nur für nicht besonders intensive Plasmastrohl Bedingungen. Versuche die kürzlich mit pulsierenden Schubantrieben gemacht wurden zeigten eine Stabilisierung der stromdichte Verteilung im ausgestossenen Plasmastrahl in einer Form, die der des Magnetoplasmadynamischen Plasmabrenners sehr ähnlich ist, was die Möglichkeit eröffnet durch diagnostische Kurzzeit-Methoden Versuchsergebnisse zu erhalten die unter Dauerbetriebs-Bedingungen nicht zugänglich sind.