Experiments with a Coaxial Hall Current Plasma Accelerator

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Experiments with a Hall current accelerator using coaxial electrodes and externally applied diverging magnetic fields are reported. The accelerator is operated with mass flows of 0.0164 and 0.0338 g/sec, currents from 300 to 600 amp, and magnetic fields from 1000 to 6000 gauss. The measured values of thrust, specific impulse, power input, and efficiency show an approximately linear increase with increasing magnetic field. The experiments were performed mostly with argon; however, in a few tests, nitrogen and helium were used. The thrusts for the various gases are about the same for given mass flows. However, for argon, and to a lesser degree nitrogen, anomalously high specific impulse is obtained. Possible mechanisms for attaining these results are given. The influence of conditions in the vacuum chamber on operation of the device is, however, also investigated to determine if these desirable results are genuine or based on improper simulation of the space environment.

Nomenclature

B = magnetic flux density, 100 amp in solenoid $\approx$ 1000 gauss at cathode
e = electronic charge
E = electric field
$\dot{m}$ = mass-flow rate
I = current
j = current density
I_{sp} = specific impulse
v = velocity
V = voltage
Z = charge number

Subscripts

r, θ = cylindrical coordinates

Introduction

RECENTLY, very high values of specific impulse have been obtained with continuous coaxial $\mathbf{j} \times \mathbf{B}$ plasma thrusters using self-magnetic fields through j_rB_θ,[1] Hall currents through $j_\theta B_r$,[2] and pressure gradients caused by electrothermal effects (an effect present in both Refs. 1 and 2). Even though much credit for the final application to propulsion belongs to Refs. 1 and 2, it should be pointed out that the devices essentially in the form used in these references[1, 2] were first proposed and discussed for the specific use of continuous plasma propulsion in Ref. 3. The important contributions toward understanding of the current distributions for Hall accelerators[4] are also acknowledged.

In view of the strong interest in re-entry simulation at the NASA Langley Research Center, a coaxial Hall current device was first studied for high mass flows of from 2 to 5 g/sec with the intent of using the combination of magnetic containment with acceleration to reduce wall losses.[5] Measurements of thrust and specific impulse for the accelerator in Ref. 5, with increasingly high magnetic fields, suggested that very efficient performance could be obtained with low mass-flow rates, high power inputs, and suitable magnetic-field strength and shape. Thus, because of the success of the study of Ref. 5 and the high specific impulse of Refs. 1 and 2, an investigation of the low mass-flow rates (about 0.02 g/sec) was included in our program. It should be mentioned also that, in this connection, the low mass-flow-rate/high specific-impulse accelerators also offer hope for solar wind simulators.

The present study differs from that given in Ref. 2 in that Hall currents and their variation with imposed current and magnetic field have been studied, and the product of $I_\theta B_r$ has been related to the variation in thrust. Furthermore, the experiments were performed with argon, nitrogen, and helium, whereas in Ref. 2, mostly experiments with hydrogen and a few with nitrogen were reported. As will be shown in the paper, anomalously high thrust and specific impulse have been found with argon and nitrogen at comparatively low voltages across the electrodes. The results may have important bearing on the understanding of the accelerating mechanism or may cause a careful re-evaluation of the experimental methods for simulating the space environment. Recent personal communications with Cann and John indicate that they have also measured anomalously high specific impulse in argon and nitrogen.

Experiments

The original intent of this paper was to present the results of a theoretical and experimental study of a relatively high mass-flow-rate (2 to 5 g/sec) coaxial plasma accelerator. This study included measurements of arc characteristics, electron temperatures and densities, Hall current densities, thrust and specific impulse, electrode and over-all efficiencies vs the important operating parameters, such as arc current, mass-flow rate and magnetic-field strength. A theoretical analysis performed agreed very well with the experimental results.[6,7] However, as mentioned in the Introduction, the experimental results indicated that efficient operation could be obtained at low mass-flow rates, for example, 0.02 g/sec. The original experiments and the subsequent, low mass-flow-rate experiments were performed mainly with argon as

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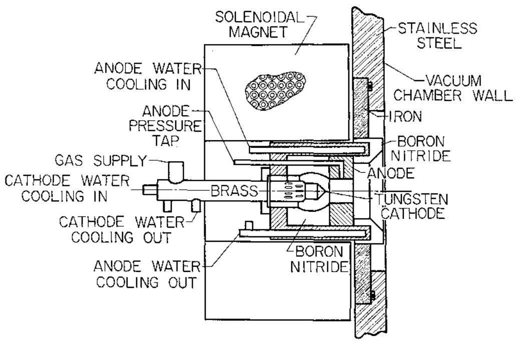

Fig. 1 **Schematic of low mass-flow-rate plasma accelerator configuration.**

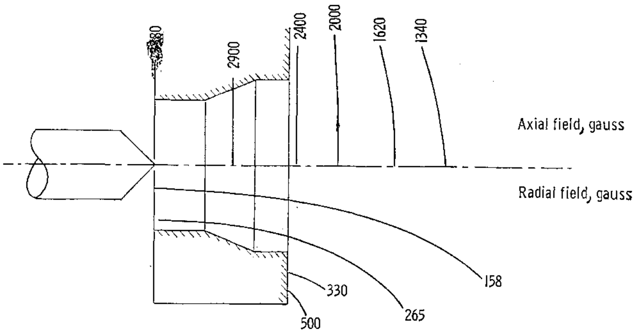

Fig. 2 **Magnetic-field distribution.**

the propellant gas. Also, the original experiments were carried out at low power inputs so that clean plasma diagnostic studies could be made of the important plasma properties, with a simpler cooling system than that used for the present device operating at low mass flows and higher powers.

In view of the rather striking results obtained with the low mass-flow-rate experiments and much higher power inputs, this paper is concerned with the coaxial Hall current plasma accelerator configuration shown schematically in Fig. 1.

In this figure, the annular ring copper anode is shown attached to the outer copper accelerator body, which serves both as a cooling-water jacket and the positive electrical lead. An anode pressure orifice is shown; the orifice is connected to a 0- to 50-mm mercury pressure transducer. A pointed thoriated tungsten cathode is shown attached to the cathode support. This support, as well as being the negative electrical lead, is both the propellant gas inlet duct and cathode water-cooling supply. The insulators shown in the figure are made of boron nitride and teflon. The entire test apparatus was allowed to float electrically in order to eliminate adverse arcing effects.

The external solenoidal magnetic-field coil shown in the figure provides an axial magnetic field in the interior of the electrode region, and a combination of soft iron inserts allow some field shaping in the vicinity of the anode front surface for a fixed position of the external solenoid. The magnetic-field distribution for the accelerator configuration in Fig. 1 is shown in Fig. 2 for a coil current of 300 amp.

The argon mass-flow rate was measured with a Fisher-Porter tri-flat flow meter. The two mass-flow rates used during the tests were 0.0338 and 0.0164 g/sec.

Hall Current Measurements

Reference 5 describes in detail the method that was used here to measure the Hall current signal of the plasma. Essentially, the method consists of placing a search coil around the outside or boundary of the plasma stream. In the present case, the search coil was imbedded in the boron nitride insulator just aft of the anode front surface. The Hall current signal is obtained by crowbarring the plasma arc current into a resister load, thereby obtaining a clean arc shutoff. The collapsing Hall magnetic field then induces an emf in the search coil. The Hall current signal, which was obtained in this manner, is shown in Fig. 3 for three values of arc current and a range of magnetic-field strengths corresponding to the current supplied to the field coil. It is seen that the Hall current signal in arbitrary units increases with arc current and decreases only slightly for a given value of arc current with increasing magnetic-field strength. In order to obtain an absolute value for Hall current in amperes, the following calibration was attempted. A small many-turn coil was placed in the approximate position where the Hall current was thought to be large. By passing current through the calibration coil and interrupting the circuit similar to shutting off the arc, a Hall current signal can be induced in the search coil. If it is assumed that the Hall current exists as a single turn in the plasma, then Hall current in amperes can be measured directly. However, it was found that, for the same number of ampere turns on the calibration coil and for different coil sizes and placement relative to the search coil, significant differences can be noticed in the signal observed by the search coil. This, of course, is necessary information because the effect of changing arc current and magnetic-field strength may alter both the shape and position besides just the magnitude of the Hall current. Such a method, then, for measuring Hall current can give, at best, only an indication of the relative magnitude of Hall current for different experimental values of arc current and magnetic-field strength.

Thrust and Specific-Impulse Measurements

The method by which the thrust of the plasma accelerator was measured involves the use of a target upon which the plasma stream impinges and gives up its normal momentum. The target, described in more detail in Ref. 5, is a 4-in. boron nitride disk, which is connected to a pendulum. The pendulum is supported from a strain-gage resistance bridge, which is calibrated to measure the moment on the disk and pendulum. The strain-gage components are both shielded from the magnetic field by soft iron enclosures and from thermal effects by water-cooling jackets. Calibration of the target pendulum by applying known forces along the thrust axis allows the direct reading of force from the signal obtained from the system during an experimental run. The diameter of the plasma beam impinging on the target disk was of the order of 1 in., whereas the disk diameter was 4 in. The

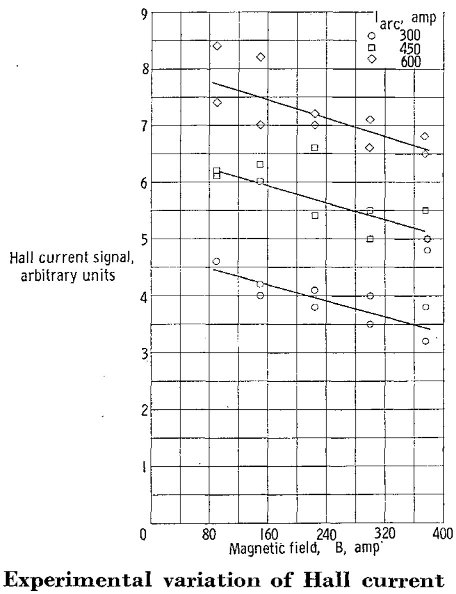

Fig. 3 **Experimental variation of Hall current for $\dot{m}$ = 0.0338 g/sec.**

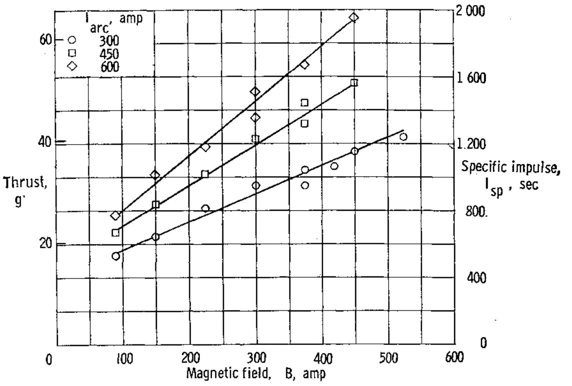

Fig. 4 Experimental thrust data for $\dot{m}$ = 0.0338 g/sec.

thrust target is insulated from electrostatic effects and also from effects caused by bulging currents. As noticed in Ref. 2, these effects could result in arcing to the thrust target if not properly insulated. Such arcing was not noticed in the present experiments since a major effort was made to insulate the thrust balance.

An experimental check was made in an attempt to investigate the possibility of the existence of underpressures on the rear of the target disk. Such an underpressure could give rise to erroneously increased thrust readings. By installing pressure taps both fore and aft of the thrust disk, it was determined that the effect of underpressures was negligible.

Further, it was noticed that a small film of copper from the anode had deposited on the thrust disk, and for this reason the disks were weighed before and after a series of experimental runs. Typically, it was found that the copper deposit on the thrust disk was about 0.039 g for 700 sec of running time. In terms of mass-flow rates, this is about 10^3 times lower than the argon mass-flow rates. The boron nitride disk, after being examined for copper deposition, was investigated for the deposition of cathode material, thoriated tungsten. No appreciable increase in radiation over background could be observed, so it was assumed that the cathode deposition was extremely small. Finally, it should be mentioned that the thrust disk underwent negligible spalling as witnessed by the very smooth appearance of the disk after the experiments.

Thrust measurements were made for two different argon mass-flow rates of 0.0338 and 0.0164 g/sec for three different values of arc current (i.e., 300, 450, and 600 amp) and for a fairly wide range of magnetic-field strengths varying from 1000 to 6000 gauss.

Figure 4 presents the thrust data in grams force for the mass-flow rate of 0.0338 g/sec. The scale on the left of the figure is thrust in grams, and the scale on the far right is specific impulse in seconds calculated by dividing the thrust in grams by the measured mass-flow rate in grams per second times the value of the gravity constant.

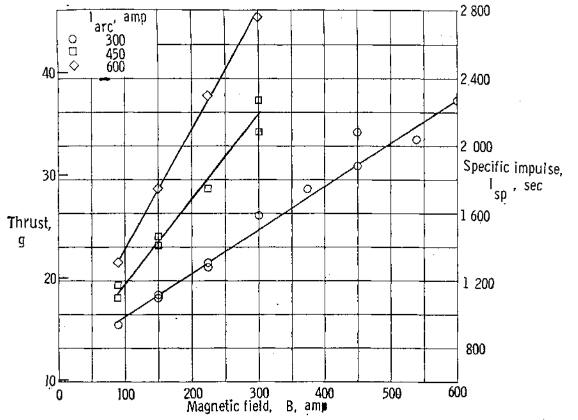

Fig. 5 Experimental thrust data for $\dot{m}$ = 0.0164 g/sec.

Figure 5 shows the same experimental data, however, for the 0.0164-g/sec mass-flow rate.

The measured values of the total power supplied to the arc are shown in Figs. 6 and 7 for the 0.0338- and 0.0164-g/sec mass-flow rates, respectively. In both of the data curves for thrust and power, the best possible fit of a curve was attempted, and in both cases the curves appear, within limits of experimental error, to be linear. With a linear relationship, then, for these two values, a relation for the ratio of the power in motion of the plasma stream to the power supplied to the arc was obtained. This ratio defines the thrust efficiency of the accelerator and is shown in Figs. 8 and 9 for the mass-flow rates of 0.0338 and 0.0164, respectively. The efficiency is shown plotted vs B for three different arc currents. Figures 8 and 9 show that, within experimental error for the range of experimental conditions of the present tests, the efficiency increases linearly with increasing magnetic-field strength.

For reasons discussed later in this paper, the thrust and specific impulse obtained for argon are anomalously high. In an attempt to determine if the experimental results are truly representative of plasma acceleration or are caused by other effects, the thrust experiments were repeated using nitrogen and helium. The results of the nitrogen and helium experiments were interesting since the thrusts obtained were approximately the same level as those of the argon tests; however, the voltages measured across the electrodes were noticeably higher. For example, typical voltages for argon were between 25 and 65 v, for nitrogen between 40 and 80 v, and for helium between 60 and 120 v. The so-called "anomalous" effect discussed was not noticeable either for helium or according to Ref. 2, for hydrogen, another gas of low atomic weight. An effort was made to establish whether or not the high thrust levels could be caused by less glamorous effects, such as thrust augmentation, which occurs when a high-velocity jet exhausts into a still ambient surrounding. This effect is caused by the acceleration of the surrounding low-velocity ambient gas and subsequent mixing in the high-velocity stream, whereby acceleration of entrained mass may cause a thrust increase. Backstreaming of the exhausted gas from the complete tank and from target to the nozzle exit may also contribute to the jet mixing. One should also study the possibility that the presence of elevated exhaust

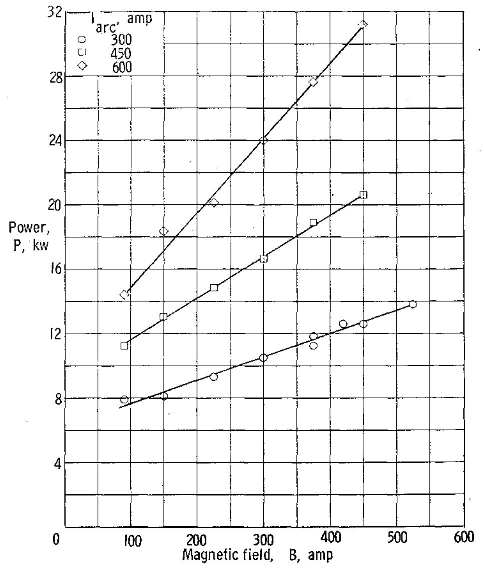

Fig. 6 Experimentally measured power inputs to accelerator, $\dot{m}$ = 0.0338 g/sec.

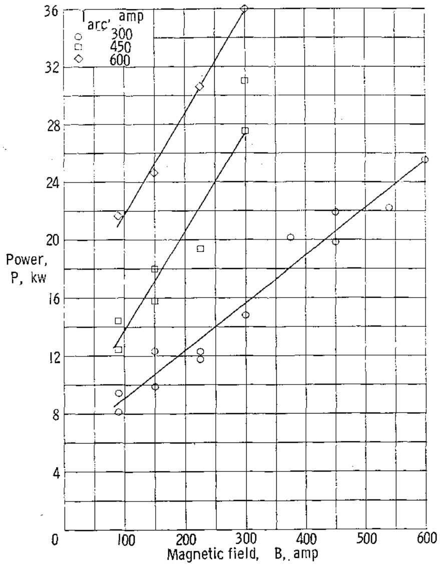

Fig. 7 Experimentally measured power inputs to accelerator, $\dot{m}$ = 0.0164 g/sec.

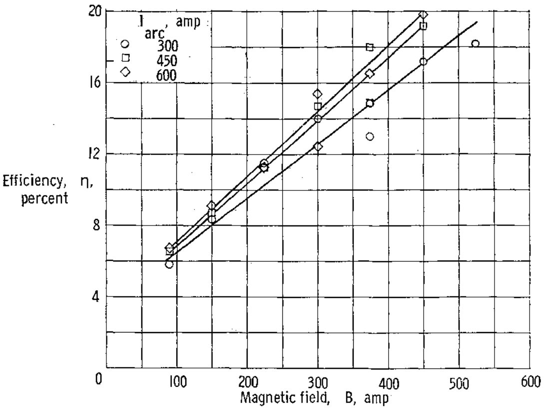

Fig. 8 Accelerator efficiency, $\dot{m}$ = 0.0338 g/sec.

pressures may permit acceleration in a region where it could not occur otherwise. In an attempt to determine the effect of backstreaming from the complete tank and ambient mixing, the following experiments were performed. The experimental apparatus was modified so that, during a test run, two halves of a cylindrical shell could be positioned around the exit stream. The enclosing cylinder is positioned just $\frac{1}{16}$ in. off the nozzle or anode face and $\frac{3}{8}$ in. from the thrust target when enclosing the stream. Also, during these experiments the vacuum chamber back pressure was varied in an attempt to determine the effect of varying the ambient pressure. The results of these experiments are shown in Table 1. In general, the effect of enclosing the stream with the cylinder was negligible except for some runs at high back pressures and power inputs. The effect of possible backstreaming from the thrust target could not be directly determined from this method; however, it is felt that circulation set up because of such backstreaming would have been impeded. The fact that the thrust measurements by G. L. Cann (personal communication) without a thrust target, but by weighing the reaction on the engine, yield similar results is further indication that backstreaming from the thrust target should not be significant.

Table 1 Results of experiments to investigate effect of backstreaming

Arc current, amp	Arc voltage, v	B, amp[a]	$\dot{m}$, g/sec	Thrust without cylinder, g	Thrust with cylinder, g	Vacuum chamber back pressure, μ Hg
300	28	120	0.0338	20.2	20.6	7
450	28	120	0.0338	23.0	23.8	7
600	26	120	0.0338	28.3	28.3	7
300	34	300	0.0338	28.7	32.3	7
450	34	300	0.0338	39.6	42.4	7
600	38	300	0.0338	47.3	46.5	7
300	24	120	0.0338	20.2	20.2	25
450	24	120	0.0338	24.2	24.2	25
600	25	120	0.0338	29.5	29.5	25
300	31	300	0.0338	31.9	33.1	25
450	32	300	0.0338	46.6	42.0	25
600	34	300	0.0338	51.3	50.5	25
300	20	120	0.0338	19.0	21.0	50
450	21	120	0.0338	24.6	25.9	50
600	23	120	0.0338	30.7	32.3	50
300	30	300	0.0338	30.3	39.6	50
450	31	300	0.0338	40.0	48.5	50
600	34	300	0.0338	48.9	51.3	50

[a] 100 amp = 1000-gauss axial field at cathode.

Rather than performing a very detailed analysis of the complicated side effects caused by an insufficient vacuum system, a concentrated effort has been made to reduce these effects by performing experiments with a considerably larger vacuum chamber operating at much lower exhaust pressures. Exhaust pressure of $\frac{1}{2}$-μ Hg about $\frac{2}{100}$-g/sec mass flow in argon have been attained, and the effects of further reduced pressures, mass flows, and mass entrainment are evaluated. The use of argon is beneficial for reduction of mass entrainment. Because of its large atomic weight, a low particle flux and chamber pressure occur for a given mass flow; this effect outweighs the increased rate of mass diffusion of the heavier atom. A comprehensive report of tests at low chamber pressures will be given by Brockmann at a later date.

Finally, the following electrostatic voltage measurements were made. The floating potential of the vacuum tank was monitored during an identical set of experimental conditions in Table 1. It was found that the vacuum tank potential was of the order of 10 v negative to the anode and varied slightly with magnetic-field strength. Also, the test facility was modified in order to measure the potential at any point in the flow stream referenced to the anode; a movable probe was used for that purpose. This probe, at any radial position referenced to the accelerator axis of symmetry, can be moved in and out in the plasma exhaust during a test and obtain the axial voltage gradients. The probe is shielded during both accelerator start-up and shutoff for protection, and the average lifetime of the probe tips (0.040-in. tungsten wire) was about 30 sec. Results of the electrostatic probe measurements have shown that, along the centerline from the position of the probe

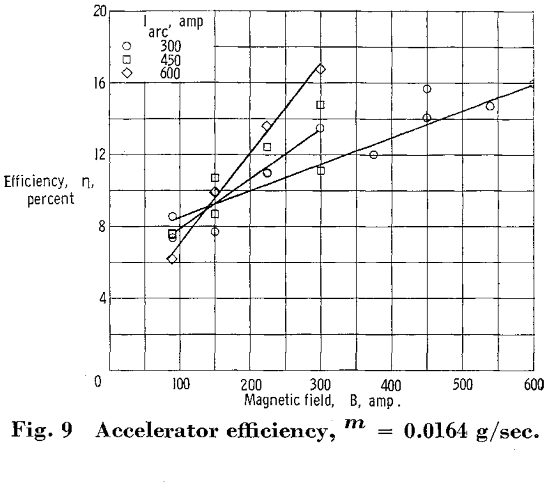

Fig. 9 Accelerator efficiency, m = 0.0164 g/sec.

at rest (6 in. from the cathode) to the cathode, the voltage fall is only about 5 to 8 v depending, of course, upon the arc current and magnetic-field strength. The arc current and magnetic-field strength govern the magnitude of the total voltage drop across the electrodes and the magnitude of the voltages in the plasma exhaust. In all of the cases, though, for high current and high magnetic fields the voltage drop along the axis was very small. However, voltage drops of the order of the drop between the electrodes were shown at small inclinations toward the axis. A detailed study of the variation of potential distributions for various operating conditions has been made and will be reported elsewhere.

Discussion

At first an evaluation is made as to what extent the acceleration could be interpreted in terms of Hall currents interacting with radial magnetic-field components. Other effects are discussed later. It is shown in Fig. 3 that the Hall current increases with current between the electrodes and decreases of the order of 20% with magnetic fields, increasing by 500%. As indicated in Figs. 4 and 5, the thrust varies almost proportionally to the current for the higher magnetic fields, whereas a somewhat smaller, though still appreciable, linear increase is shown with magnetic field. Thus, the $j_\theta B_r$ force/vol caused by Hall currents offers a possible mechanism for plasma acceleration.

The analysis developed in Ref. 8 for variation of Hall current with increasing magnetic field at constant applied current indicates that, for constant collision frequencies between electrons, ions, and neutrals, the Hall current increases to a peak and subsequently decreases. The decrease in Hall current with increasing magnetic field can be explained in terms of ion slip. Experiments with a slightly different device for the high mass flow of 1.8 g/sec in Fig. 10 (which is a partial reproduction of Fig. 49 of Ref. 5) show a more pronounced decrease in Hall current. However, these experiments also show a less pronounced decrease in Hall current with magnetic field at the highest applied current of 300 amp where the ionization is increased. The less pronounced decrease of the Hall current with increased ionization, after the peak has been attained, is also consistent with the theory for ion slip and could account for the smaller decrease for the present low mass-flow experiments at higher power densities. The Hall currents may, however, also be changed by other effects mainly related to the distortion of the exhaust plume and its current distribution with increasing current and magnetic field. These distortions, which can be visually observed, have also been verified by measurements of potentials in the exhaust. Detailed measurements of the current distribution with magnetic probes or with differential electrostatic probes[9] must be performed before the variation of the Hall currents and their distribution can be fully understood and with it the detailed nature of their contribution to the thrust-producing mechanism.

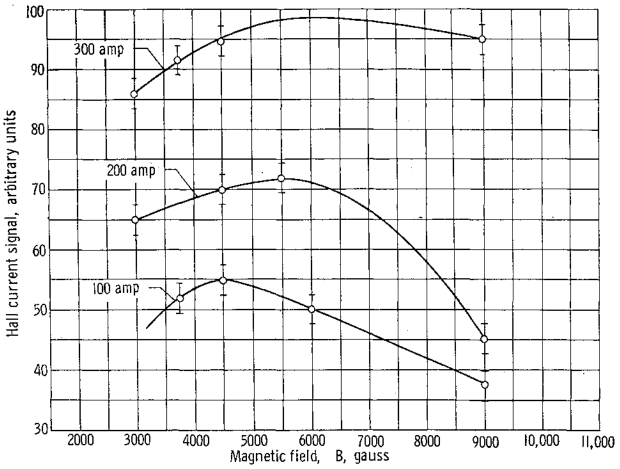

Fig. 10 Experimental variation of Hall current, high mass-flow-rate configuration, $\dot{m} = 1.8$ g/sec.

Evidence of $\mathbf{j} \times \mathbf{B}$ plasma acceleration is also given by the distribution of the potential in the accelerator. As noted in the experimental section, the potential along the axis of the accelerator increases only very slightly above the cathode potential along a distance of about 6 in. beyond the accelerator. The potential distribution at various radii suggests that almost the full applied potential drop is being used for plasma acceleration in a direction somewhat inclined toward the axis. The bulging of the currents beyond the electrode region is evident from this picture. As a result of these current loops, the $j_\theta B_r$ acceleration mechanisms may differ in various regions. This includes the possibilities of acceleration of ions in the presence of azimuthally trapped electrons as well as joint acceleration of ions and electrons caused by built-up axial voltages or by collisions.

The self-magnetic j_rB_θ effects can play a part for the present comparatively low currents only in the neighborhood of the cathode tip where the current densities can be very high. Since the maximum self-magnetic compression should be somewhat behind the cathode tip, it could produce a reverse jet that could bathe the cathode tip. However, at the comparatively low currents more conventional heat-transfer effects rather than self-magnetic effects can already promote stable and efficient cathode operation. The self-magnetic j_rB_θ effects in the region of bulging currents beyond the electrodes should be very small for the present currents.

The effects of pressure gradients caused by electrothermal effects would require extremely high enthalpies or temperatures that do not seem to be available for the experiments at comparatively lower power in argon and nitrogen. This seems true even if the higher nonequilibrium electron temperatures are used in the enthalpy evaluation. Since the axial component of the magnetic field reduces the heat transfer to the wall, however, high temperatures (especially near the cathode) should not be ruled out. Comparative measurements of electromagnetic and electrothermal thrust are required to answer this question in detail. It must be remembered in this connection, however, that even the expansion of plasmas heated by electrothermal means through a magnetic nozzle also will give electromagnetic reactions.

In evaluating the kinetic energy in the plasma stream for high currents and magnetic fields, it was found that the kinetic energy per particle based on $v = \text{thrust}/\dot{m}$ is larger than the potential energy in the applied voltage available for acceleration of a singly ionized particle, i.e.,

$$mv^2/2 > ZeV \qquad \text{for} \qquad Z = 1$$

It must be emphasized that this does not constitute a violation of the first law of thermodynamics for the whole aggregate of particles, since the power in the motion of the plasma stream is smaller than the input power. The possibility of making use of this excess of kinetic energy over the single particle case is, however, of considerable practical interest, and the basic mechanisms, which could produce such excess, must be investigated. Such investigation should also include careful checks as to whether this excess is genuine or is related to increases in thrust caused by effects produced by insufficiently low exhaust pressures in the vacuum chamber.

A few mechanisms are discussed next which could give a genuine increase in velocity above the limit for the singly ionized, single particle approach. Since the excessive energies occur especially for argon, the possibility of multiple ionization of single particles $Z > 1$ must be investigated first. Preliminary spectroscopic studies show intense lines of AIII, i.e., doubly ionized argon, and there are even indications of AIV states in the plasma. However, these single particle effects are not sufficient to explain the excess kinetic energies.

A brief critical review of electromagnetic **j** × **B** acceleration mechanisms capable of providing plasma kinetic energies in excess of the single particle approach is given here, based on a recent talk.[10] The crucial difference between the single particle acceleration and acceleration by **j** × **B** forces/vol is that, in the latter case collective effects, especially those caused by electron currents, can play a vital role. This is the case for **j** × **B** acceleration using segmented electrode pairs distributed along the axis,[11] as well as for single electrode pairs, as in the present coaxial Hall accelerator. In the case of the segmented electrodes, axial Hall potentials in excess of the applied potential across a single electrode pair can build up. For the present single electrode pair, existence of a sufficient number of electron collisions is required, however, if kinetic plasma energies in excess of the applied potential are to be reached; the efficiency of acceleration is thereby decreased. Exact evaluation of the possible role of collisions is difficult for the complicated current paths, and measurements of the latter are in progress to aid in the analysis. Of course in the presence of collisions, random energy is also produced, some of which can be converted, however, in the magnetic nozzle of the present device. In principle there exist other mechanisms for the acceleration of ions in the presence of electrons which depend upon transfer of the energy through oscillations, which require rather special conditions.

The presence of electron currents and collective effects, of course, does not guarantee the attainment of ion (plasma) kinetic energies in excess of the applied voltage across a single electrode pair. An extreme case in point concerns the acceleration of a partially ionized, high-density plasma in an accelerator with plane segmented electrodes. This accelerator is investigated by the magnetohydrodynamics (MHD) section of the Langley Research Center and finds its major application in the field of re-entry simulation. A report on its operating characteristics was also given at the AIAA Fourth Electric Propulsion Conference.[11] In this segmented electrode accelerator, an axial Hall potential much larger than the voltage across a single electrode pair is built up, but the ion kinetic energies do not exceed the potential drop across a single electrode pair since a large number of neutrals must be accelerated. The present propulsion device, however, is capable of efficient operation with high-energy inputs per particle, and this is apparently the reason why it may be possible to attain kinetic energies in excess of the applied voltage for a single electrode pair. The usefulness of the device for electric propulsion also exceeds that of the linear Hall current accelerator where an axial voltage can be directly applied in the presence of a radial magnetic field. The advantages of the present device seem related to the fact that magnetic containment occurs in conjunction with acceleration in the exhaust plume. Because of this special type of acceleration mechanism, and because the assistance gained from electron currents appears to be marginal, the influence of exhaust pressure on entrainment must be further investigated.

Experiments by Electro Optics, Inc. in the NASA Lewis Laboratory giant vacuum chamber indicate that the present type of propulsor works at chamber pressures down to 2.6×10^{-2}-μ Hg at mass flows of the order of 0.001 g/sec. Experiments by Giannini Scientific Corp., Avco-RAD, and our group indicate that engine operation is possible even at zero mass flow. Recent tests by our group ranging down to $\frac{1}{100}$-μ Hg, however, indicate very erratic oscillatory operation except when the engine appears to use cathode material. The tests suggest that, at these low pressures, gas entrainment may not be important, and metal propellants (alkali and others) with cryogenic pumping would be desirable to simulate the very low-pressure space environment.

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