Effect of Applied Magnetic Fields on Physical Processes in an MPD Arcjet

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An experimental investigation was conducted to investigate the physical processes involved in a conventional MPD arc thruster with strong applied magnetic fields. Operating characteristics such as the reaction force which acts on the electrode assembly, and the magnetic coil were evaluated for the case of solid and hollow cathode operation. The changes of current distributions at cathode surface and anode surface with applied magnetic fields were also examined. Using these results the physical processes involved in such a thruster were discussed.

Introduction

THE main purpose of this experimental investigation is to understand the physical processes involved near the cathode of a conventional MPD arcjet with applied magnetic fields. Interest in such processes derives from a desire to achieve logical guidelines for the design of an optimum electric thruster of this type for space applications.[1-6] In the early stage of the investigations, understanding of MPD processes had been limited to inferences made from various terminal properties such as discharge voltage, discharge current, thrust, etc. supplemented by some optical measurements, but this situation is improved, at least in the case of high-power, large-scale MPD arcjets without applied magnetic fields, by detailed measurements within the discharge region under quasisteady operation.[7,8]

We had obtained some information on the physical processes in a conventional MPD arcjet (solid and hollow cathode) with applied magnetic field, by measuring the reaction forces on electrode assembly and the magnetic coil (T_{ea} and T_{mc}) separately, and the pressures at typical points in the arcjet.[9] (T_{ea} is related to the aerodynamic and self-magnetic acceleration and T_{mc}, the acceleration due to magnetic nozzle formed by the applied magnetic field.) In the present investigation, the experiment extended the range of applied magnetic fields considerably, and the changes of current distributions with increasing applied magnetic fields on the surfaces of the cathode and anode were examined, using a divided cathode and an anode furnished with small electrodes.

Apparatus and Experimental Procedure

Figure 1 shows the MPD arc thruster used. The nozzle-shaped anode (copper) has a throat diam of 10 mm. As shown in the figure, three types of cathode, solid cathode, divided cathode, and hollow cathode (tungsten) were used. In the case of the solid and divided cathode, propellant was supplied through the port at the wall of arc chamber and in the case of the hollow cathode, through the port at the cathode tip. The arcjet was operated in the steady mode generally, though in the case of the divided cathode it was operated in the quasisteady mode. The anode was surrounded by a 360 turn solenoidal coil (19.5 cm o.d., 8 cm i.d. and 7 cm in length), which produced an essentially axial slowly diverging magnetic field in the electrode region.

Argon was used as the propellant and the background pressure was maintained at about 5×10^{-2} torr. In the present experiments, discharge current (I) was varied from 300 to 1500 A and propellant mass flow rate ($\dot{m}$), from 15 to 75 mg/sec, at applied magnetic field (B), measured at cathode tip, up to about 4000 gauss.

The electrode assembly was mounted on a parallelogram-pendulum thrust stand, and the electrical power for the arc was brought onto the stand through mercury pots. Deflection of the stand was sensed by a linear differential transformer. The total reaction force (thrust), T_t, was measured, mounting the magnetic coil on electrode assembly. The reaction force which acts on the electrode assembly, T_{ea}, was measured, attaching the magnetic coil to the coil holder connected rigidly with a vacuum tank. In this case, the interaction force between current passing through the electrode assembly and applied magnetic field was excluded, evaluating it by reversing the direction of magnetic field. To check this technique, the interaction force was also measured at some operating points, using an electrode assembly in which the cathode is shorted to the anode. Using T_t and T_{ea}, the reaction force which acts on the magnetic coil, T_{mc}, can be obtained from $T_{mc} = T_t - T_{ea}$.

The current distribution on the cathode was examined, using the divided cathode, divided into central and outer parts, and operating the arcjet in quasisteady mode (operation time 1 ~ 3 msec). The current distribution on the anode surface was evaluated by furnishing electrically-insulated small electrodes (Fig. 2) on it. These electrodes were endurable in steady operation of the arcjet, and they were also used for the detection of rotating spokes.

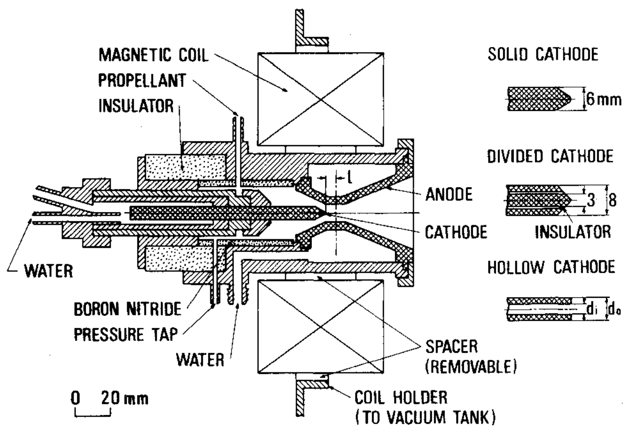

Fig. 1 MPD arcjet and cathode used.

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Results and Discussion

Figure 3 shows the behavior of the total reaction force (T_t) and the reaction force on the electrode assembly (T_{ea}) versus the applied magnetic field (B) for the case of 6-mm-diam solid cathode ($\dot{m} = 30$ mg/sec), where the reaction force on the magnetic coil (T_{mc}) is given as $T_{mc} = T_t - T_{ea}$. It is seen in the figure that the increase of T_t, with increasing B, results from the increase of both T_{mc} and T_{ea}, although T_{ea} shows the tendency of saturation for large values of B. (Similar experimental results are also obtained in the case of $\dot{m} = 15$ and 60 mg/sec, although at a larger mass flow rate the increase of T_{ea} with increasing B becomes small.) In Fig. 4 it is shown that the increase of T_{ea} with increasing B is suppressed by furnishing a pressure tap (3mm diam) at the cathode tip, although the increase of T_{mc} is not influenced. (It is reported in Ref. 10, for the case of large discharge current under a weak applied magnetic field, that some decrease of the thrust is caused by furnishing a pressure tap to cathode tip). In this experiment it is confirmed that the values of T_t and T_{ea} (and hence T_{mc}) and the tendency of their variations with increasing B are not influenced with the change of distance l, ranging from 3 to 9 mm l is the axial distance between the middle point of the nozzle throat and the cathode tip; Fig. 1). In the scope of this experiment, it is also confirmed that rotating spokes do not occur.

The results of the experiment on the current distribution at cathode surface, obtained by using the divided cathode, are shown in Figs. 5 and 6. As described previously, in this case the arcjet was operated in quasisteady mode, and the distance 1 was held at 5 mm. In Fig. 5 it is shown that the fraction of current to the central part of the cathode (I_c/I) increases with increasing I and $\dot{m}$, and in Fig. 6, that the mean current density in the central part of the cathode, J_c, increases with increasing B, so far as rotating spokes do not occur. (In the present investigation, rotating spokes were observed sometimes in the case of quasisteady operation, though they were not, in the case of steady operation. Such a tendency coincides with the experimental result[11] showing that in the case of low temperature cathode, rotating spokes occur more easily. In this experiment, using such a divided cathode as shown in Fig. 1, when rotating spokes occurred, it was seen that the current to its central part becomes zero.) In this experiment it was noticed that the distance l influences to some extent on the current distribution at cathode surface; when l is increased, J_c increases, although the tendency of the change of current distribution with B is not altered.

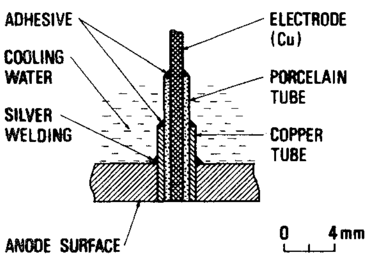

Fig. 2 Electrode attached to anode surface.

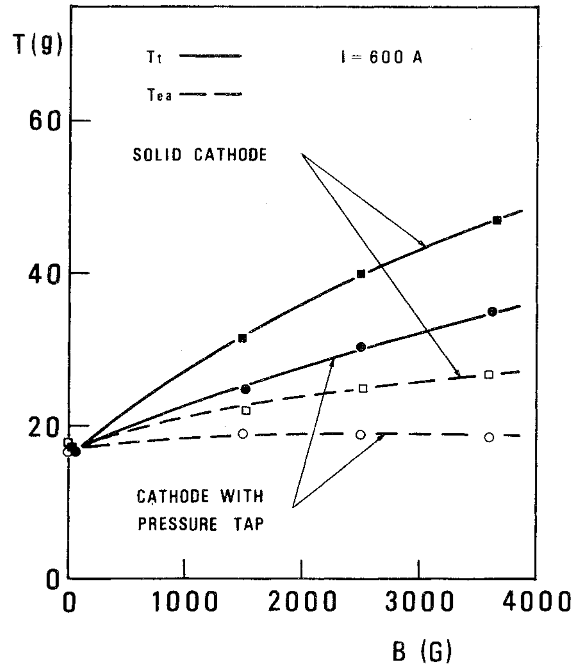

Fig. 4 Effect of cathode pressure tap on reaction forces ($\dot{m} = 30$ mg/sec).

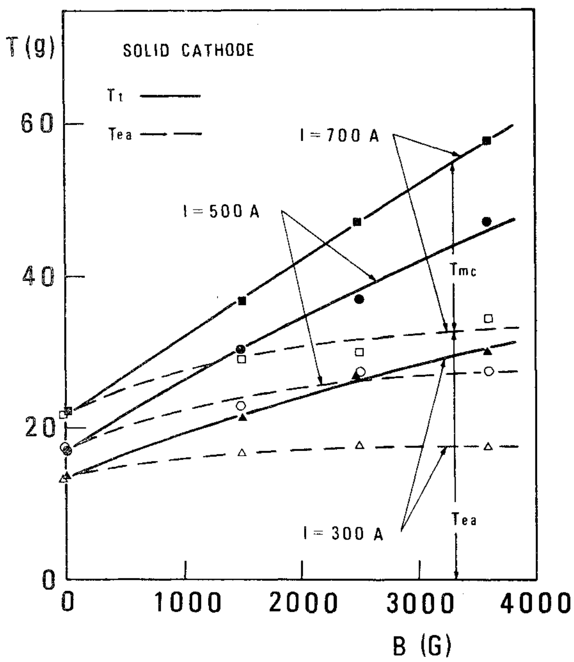

Fig. 3 T_t and T_{ea} vs applied magnetic field ($\dot{m} = 30$ mg/sec), $T_t = T_{ea} + T_{mc}$: total reaction force (or thrust), T_{ea}: reaction force on electrode assembly, T_{mc}: reaction force on magnetic coil.

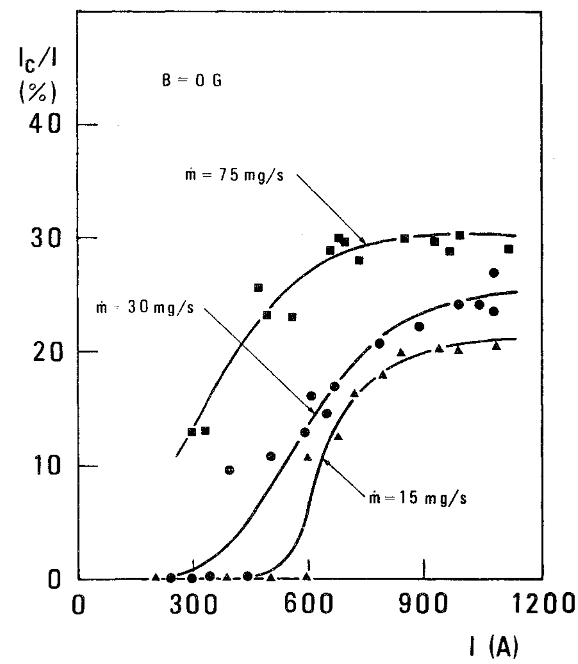

Fig. 5 I_c/I vs I, I: discharge current, I_c: current to the central part of cathode.

The experimental results, that the increase of T_{ea} with increasing B is suppressed by furnishing a pressure tap to cathode tip (Fig. 4) and that J_c increases with increasing B (Fig. 6), suggest that the increase of T_{ea} in the case of solid cathode, with increasing B, is related to the increase of blowing force $[(\mu I^2/4\pi)\ln(r_a/r_c)]$, caused by the decrease of effective cathode radius, r_c. It can be shown, furthermore, that the order of increase of T_{ea} with increasing B, shown in Fig. 3, corresponds to the increase of blowing force, calculated assuming a reasonable change in r_c. Figure 7 shows a typical example of experimental results on the change of current distribution at anode surface with applied magnetic fields, measured in steady operation free from rotating spokes. The examination of these experimental results showed that the increase of effective anode radius, r_a, with increasing B, is not large enough to change blowing force noticeably, in the present experimental conditions.

In the case of experiments using hollow cathodes, T_{ea} increases almost linearly in the whole range of magnetic fields applied (Fig. 8). At present, we do not have enough information to explain the mechanism of the increase of T_{ea} in this case, but it must be noticed here that the values of T_{ea} in this case are larger than that in the case of solid cathode for the small values of I and B (Fig. 4). The thrust efficiency in the case of hollow cathode was generally higher than that in the case of solid cathode for the same values of I and B, although the discharge voltage in the case of the former was higher than that in the case of latter. (For example, in the case of $I=600\ A$, $B=3600$ gauss and $\dot{m}=30$ mg/sec, the values of thrust efficiency were 39% for the hollow cathode with $d_0=6$ or 8 mm and $d_i=3$ mm, and 25%, for the solid cathode of 6 mm diam. The thrust efficiency does not include the power of

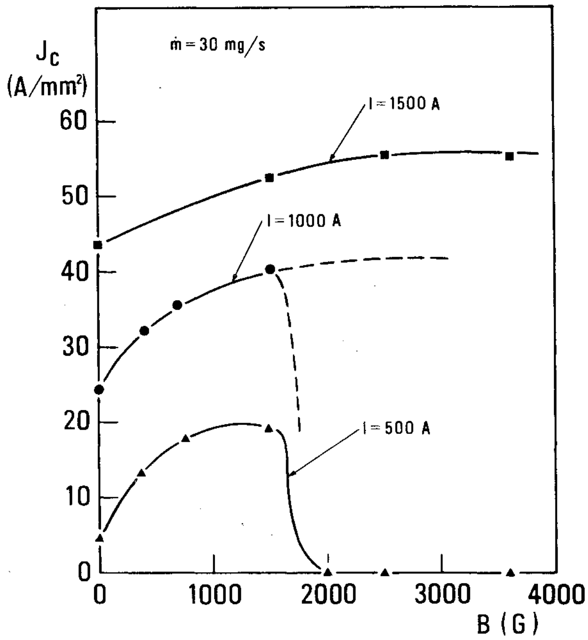

Fig. 6 J_c vs applied magnetic field, J_c: mean current density in the central part of cathode.

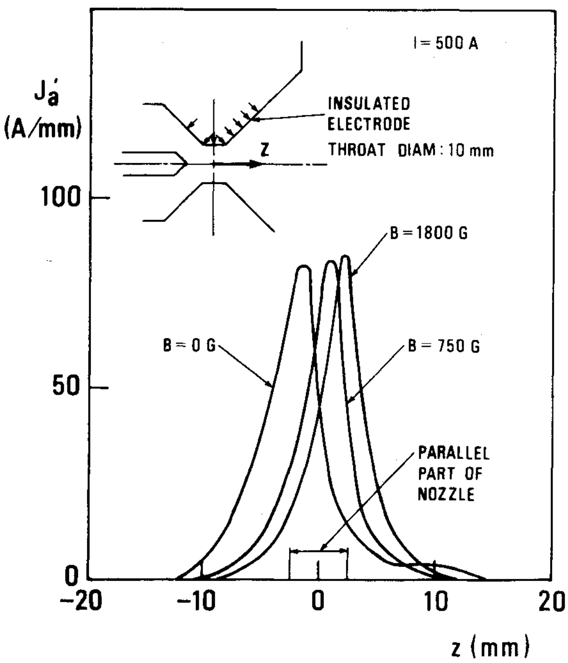

Fig. 7 Change of current distribution on anode surface with applied magnetic field ($\dot{m}=30$ mg/sec), J_a': current in unit axial length of anode surface, arrow mark: axial position where insulated electrode was furnished.

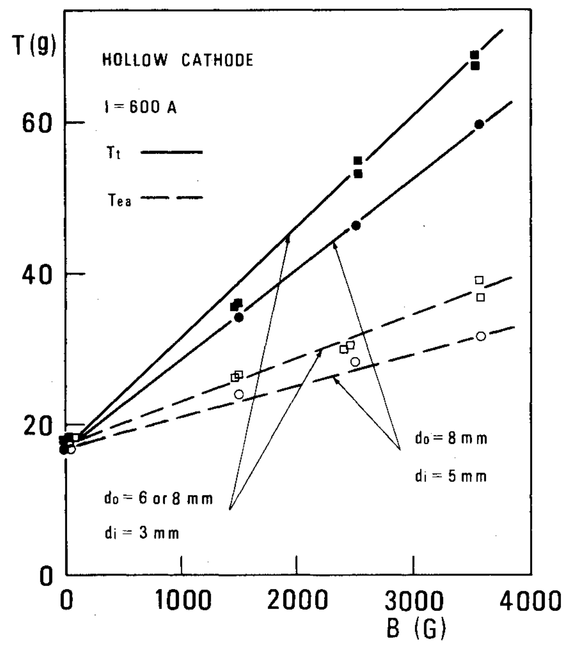

Fig. 8 T_t and T_{ea} vs applied magnetic field ($\dot{m}=30$ mg/sec), d_o and d_i: outer and inner diameter of hollow cathode.

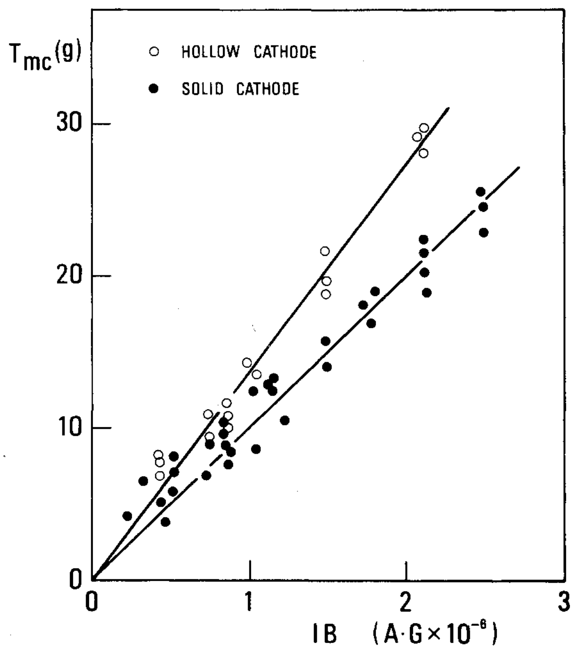

Fig. 9 T_{mc} vs IB (I: 150 ~ 700 A, B: 0 ~ 3600 gauss and $\dot{m}$: 15 ~ 60 mg/sec).

the magnetic coil, and it must be noticed that at the background pressure of 5×10^{-2} torr used in this experiment, entrainment of propellant may seriously affect the measured value of thrust and hence the surmised value of thrust efficiency.)

It is suggested experimentally in Ref. 12 that for a constant value of I, T_{mc} increases linearly with increasing B, and it is shown experimentally in Refs. 13 and 14 that the increase of thrust with magnetic field, $T_t - T_t(B=0)$, can be expressed as a linear function of IB. In the present investigation it was shown experimentally that T_{mc} can be expressed as a function of IB and increases linearly with IB, and that the value of it in the case of hollow cathode is larger than that in the case of solid cathode (Fig. 9). (In Ref. 15 the thrust production mechanisms by an applied magnetic field are described, and in Ref. 2, for the contribution of rotational motion, a linear increase of T_{mc} with increasing IB is predicted.) The quantity, $T_t - T_t$ $(B=0)$, is not a fundamental one, when physical processes in arcjets are considered, but the quantity, T_{mc}, is directly related to the acceleration due to magnetic nozzle formed by the applied magnetic field. In the present investigation, the following result is also obtained. If the background pressure is increased up to the level of 1 torr, the contribution of T_{mc} on T_t becomes negligible ($T_t \approx T_{ea}$). Also the degree of increase of T_{ea} with increasing B is not influenced so much by the increased background pressure.

Conclusions

The experimental results show that the increase of total reaction force (or thrust), with increasing B (applied magnetic field), results from the increase of both T_{ea} (reaction force on electrode assembly) and T_{mc} (reaction force on magnetic coil), and that T_{ea} in the case of solid cathode shows the tendency of saturation for large values of B, but T_{ea} in the case of hollow cathode increases almost linearly in the range of the present experiment and it is larger than that in the case of solid cathode. It was confirmed that the increase of T_{ea} with increasing B in the case of the solid cathode can be explained as the increase of blowing force caused by the decrease of r_c (effective cathode radius), although the mechanism of increase of T_{ea} in the case of hollow cathode is not clear at present.

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