Abstract

Plasma diagnostics and flowfield analysis in quasi-steady MPD channels, almost realizing electromagnetic only blowing acceleration, i.e., one-dimensional flowfield, were made. The discharge current concentrated near the downstream end of the discharge chamber, and particularly the current fractions for molecular gases were much larger than those for monatomic gases regardless of particle weight. However, the current concentration near the inlet, which was expected from the one-dimensional MHD flowfield analysis, was hardly observed. The electron temperature optically measured agreed with that calculated. The axial variation of the velocity inferred from the electron number density measured showed that the plasma was expected to be drastically accelerated only near the outlet, although the analyzed velocity profile had two acceleration zones near the inlet and the outlet.

Introduction

The quasi-steady MPD arcjet is a promising propulsion device which utilizes principally electromagnetic acceleration of the interaction between discharge current of kiloamperes and azimuthal magnetic field induced by the discharge current. Various propellants, such as light gases of H₂ and He, heavy gases of Ar, Xe and SF₆, and waste ones in space stations etc., can be used because the thrust depends only on the discharge current and does not basically on propellant species for electromagnetic acceleration. However, in an MPD discharge chamber, complicated chemical reactions including dissociation and ionization are expected to occur together with the acceleration process. Furthermore, for the acceleration theory of MPD arcjets, there exist two components of electromagnetic force, i.e., the blowing and pumping forces. These forces generate a complicated flowfield in a discharge chamber. Consequently, it has been recognized that the performance characteristics on the discharge voltage, thrust, thrust efficiency and electrode erosion depend on propellant species and electrode geometry[1]–[5].

One or two dimensional analyses of MPD arcjet flowfields have been made by many researchers[6]–[8], in which the electric field is determined by the point of the sonic or the magnetosonic singularity. These calculated results are significant for optimum design of MPD arcjet chambers and for understanding of the discharge feature and the acceleration mechanism.

In the present study, plasma diagnostics and flowfield analysis in quasi-steady MPD channels, almost realizing only electromagnetic blowing acceleration, i.e., one-dimensional flowfield, are carried out to understand plasma feature and acceleration process in an acceleration zone simplified. The discharge current distributions on the electrodes are examined using segmented electrodes. Optical measurement is conducted, and the electron temperatures and the electron number densities are estimated. The experimental results are compared with analytical ones.

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Experimental Apparatus

The coaxial MPD channel MC-1, as shown in Fig.1, is provided with a straight anode 50 mm in diameter and 280 mm deep. The long electrode with a long acceleration zone is expected to almost realize one-dimensional channel flow. The anode made of copper is divided axially into 14 anode parts, each of which is electrically insulated to one another, and the segment No.1 is located outside the discharge chamber. The current entering each anode segment is measured with a Rogowski coil to examine current fractions on the anode, i.e., to infer the current pattern in the interelectrode region. The cylindrical cathode 9.5 mm in diameter and 280 mm long is made of thoriated tungsten. The downstream ends of both electrodes are provided with insulators which prevent current from concentrating on their surfaces and from spreading out of the discharge chamber.

Gases are injected with a cathode slit / anode slit ratio of 50:50 into the discharge chamber through a fast acting valve (FAV) fed from a high pressure reservoir. The rise time and width of the gas pulse, measured with a fast ionization gauge, are 0.5 and 6 msec, respectively. The mass flow rates are controlled by adjustment of the reservoir pressure and the orifice diameter of the FAV. Argon, hydrogen and nitrogen are used as propellants. The mass flow rates are 1.37 g/s for Ar, 0.40 g/s for H₂ and 0.74 g/s for N₂. The mass flow rate for each gas is set up at a corresponding critical current of about 10 kA, which is derived theoretically from the rule of minimum input power or Alfvén's critical ionization velocity.

The main power-supplying pulse forming network is capable of storing 62 kJ at 8 kV, and it delivers a single nonreversing quasisteady current of maximum 27 kA with a pulse width of 0.6 msec. A vacuum tank 0.6 m in diameter and 5.75 m in length, where the MPD channel is fired, is evacuated to some 10⁻³ Pa prior to each discharge.

Discharge current is measured with a Rogowski coil calibrated with a known shunt resistance. Voltage measurement is performed with a current probe (Iwatsu CP-502), which detects the small current bled through a known resistor (10 kΩ) between the electrodes.

Emission spectroscopic measurement is conducted as reliable plasma diagnostics in MPD discharge chambers. Light comes from the plasma through a slit 0.5 mm in width between segments. The emission is collected by a lens and is introduced into a 0.5-m monochromator through an optical fiber. The monochromator of diffraction-grating-type HAMAMATSU C5095 is provided with 150- and 2,400-grooves/mm grating plates, an image intensifier and a 1024-channel diode array detector, achieving spectral resolutions of 0.8 and 0.05 nm, respectively, per detector channel. Electron temperatures and electron number densities are determined using the data. The electron temperature is determined using a relative intensity method of spectral lines, i.e., by means of Boltzmann plotting with ArII or NII spectral lines. The electron density is estimated from the Stark width of hydrogen Hγ line 486.1 nm, in which a mixture of argon or nitrogen and a few percent seed hydrogen is used. Line-of-sight measurement is conducted, and horizontally-average physical properties are calculated directly from the horizontally-integrated spectral intensities measured; i.e., Abel transformations are not carried out.
Experimental Results and Discussion

Current Distribution

Figure 2 shows the current fractions distributed on the segmented anode of MC-1, in which the magnetic Reynolds number is set to about 10. The current fractions on the anode segment No.14 are highest for all gases; i.e., the current concentrates near the downstream end. Furthermore, the current fractions of No.14 for H₂ and N₂ are much higher than those for Ar regardless of particle weight, and in other words for the monatomic gases the current is distributed in the intermediate region of the anode although for the molecular gases the current hardly exit in the region. These are explained from MPD flowfield analyses as follows[7],[8]. The ionization process of molecular gases is slower than that of monatomic ones owing to a time lag due to dissociation process. Therefore, the ionization process of molecular gases starts near the arcjet exit. Also, the current fractions of No.14 decreased with increasing discharge current, and the current is distributed in more upstream segments. Hence, these features on current conduction are found to depend strongly on gas species and discharge current levels[9]–[12].

Electron Temperature and Electron Number

Figures 3 and 4 show the axial variations of the electron temperature for Ar and N₂, respectively, in which the magnetic Reynolds numbers for Ar are about 10 and 20 at 10 and 15 kA, respectively, and for N₂ about 10 and 35 at 10 and 15 kA, respectively. The

Fig.2 Current fractions on anode of MC-1 for Ar, H₂ and N₂ at 10 kA. The magnetic Reynolds numbers are set to about 10.

Fig.3 Axial variations of electron temperature for Ar. The magnetic Reynolds numbers for Ar are about 10 and 20 at 10 and 15 kA, respectively.
Fig. 4  Axial variations of electron temperature for N₂. The magnetic Reynolds numbers for N₂ are about 10 and 35 at 10 and 15 kA, respectively.

Fig. 5  Axial variations of electron number density for Ar. The magnetic Reynolds numbers for Ar are about 10 and 20 at 10 and 15 kA, respectively.

Experimental errors are within 0.2 eV for Ar and within 0.3 eV for N₂. The electron temperatures for both gases are axially kept about 1.2–1.4 eV regardless of discharge currents. Since the profiles hardly depend on radial positions, the flowfields in the MPD channel used are expected to be nearly one-dimensional ones.

Figure 5 shows the axial variations of the electron number density for Ar. The profiles have peaks at an axial position of about 20 cm. As shown in Fig.6, the electron number density for N₂ has the characteristic as well as that for Ar although the peak location moves upstream. This characteristic is related closely to dissociation and ionization processes and acceleration process in the channel. The electron densities for Ar and N₂ range from $2 \times 10^{14}$ to $3 \times 10^{15}$ cm$^{-3}$. 
Flowfield Analysis

The present analysis is carried out using a popular one-dimensional MHD flow model[13]. Particularly, we assume as follows: (1) the gas flows between parallel electrodes; (2) the flow, electric field and magnetic field are perpendicular to one another; (3) the magnetic field is induced by the discharge current; (4) viscosity, heat conduction, convection and radiation, and Hall effect are neglected; (5) the electron temperature and the translational temperature of heavy particle species are considered; (6) the velocities for all species are same; (7) non-equilibrium dissociation and ionization are considered; (8) The electric field is determined from the singularity of the sonic point. The length and width of the electrode channel are 28 and 3.7 cm. and the gap between the electrodes is 2 cm. The mass flow rates are same as those for the experiments.

Calculation Results and Discussion

Figures 7–10 show the axial variations of the current density, temperatures, number densities, degrees of dissociation and ionization and velocity for Ar and N₂ at 10 kA, respectively. The sonic points for both gases exist just near the inlet. The electron temperature at the sonic point for Ar is 15,000 K, the heavy species temperature 600 K, the degree of ionization 0.0038, and electric field 610 V/m. The physical values for N₂ are 18,300 K, 700 K, 0.0035 and 1038 V/m, respectively, and the degree of dissociation is 0.005.

The calculated current distributions show that the current concentrates near the inlet and outlet. For Ar, there is conduction of small current in the intermediate region as well as the current distributions measured as shown in Fig. 2 although current hardly flows for N₂. The current concentration near the

Fig. 6 Axial variations of electron number density for N₂. The magnetic Reynolds numbers for N₂ are about 10 and 35 at 10 and 15 kA, respectively.

Fig. 7 Calculated current fractions of MC-1 for Ar and N₂ at 10 kA. The magnetic Reynolds numbers are set to about 10.
Fig. 8 Calculated axial variations of physical properties for Ar at 10 kA with Rm=10.

Fig. 9 Calculated axial variations of physical properties for N\textsubscript{2} at 10 kA with Rm=10.
inlet disagrees with the current patterns measured. This is expected to be because of neglect of electron diffusion in the calculation model and because of measurement of current patterns on the anode, i.e., not on the cathode. Also, a three fluid model of electrons, ions and neutral particles needs to be used near the inlet. Furthermore, since the experimental MPD channel as shown in Fig.1 has the anode segment No.1 and floating electrodes outside the main discharge zone, the current concentration near the inlet is expected to relax.

As shown in Figs.8(a) and 9(a), the electron temperatures are about 1-1.5 eV in the intermediate region of the channel as well as those measured as shown in Figs.3 and 4 although there exist drastic increases near the inlet and outlet because of current concentration. The degrees of dissociation and ionization, as shown in Figs.8(c) and 9(c), agree with the electron temperatures.

In the particle number densities shown in Figs.8(b) and 9(b), the electron densities increase intensively near the inlet, and they are almost kept constants in the intermediate region of the channel. These profiles disagree with those measured as shown in Figs.5(a) and 6(a). Furthermore, the electron densities calculated for N\textsubscript{2} are much lower than those measured. This is due to the current concentration near the inlet. For the calculations the plasma generated near the inlet is accelerated extremely just near it and near the outlet owing to current concentration, as shown in Fig.10. However, in the experimental MPD channel the gas is gradually ionized through the channel, and the plasma generated is expected to be drastically accelerated only near the outlet. The velocity roughly inferred from the electron density measured shows this feature of acceleration. Consequently, the analyzed current concentration near the inlet causes the difference of the acceleration process, that is, the large differences of the velocity and the degrees of the chemical reactions which are related to the difference of the electron number density.

**Current Distributions of MPD channel MC-II**

The coaxial MPD channel MC-II, as shown in Fig.11, is designed so that the experimental results approaches the analytical ones. The anode has a length of 200 mm. and the inner diameter of 50 mm is same as that of MC-I. The cathode is 26 mm in diameter. The gap between the electrodes is 12 mm. and it is about half of that of MC-I. MC-II is not provided with floating electrodes, and gas is injected uniformly from the upstream end of the discharge chamber. Current distributions on the electrodes can be measured with the segmented anode and cathode.

Figures 12 and 13 show the current distributions on the anode and cathode of MC-II for
Ar and N\textsubscript{2}. The current fraction on the anode intensively increases downstream; however, that on the cathode gradually increases except for Ar at high magnetic Reynolds numbers. The current fractions on the cathode for Ar at high magnetic Reynolds numbers slightly increase near the inlet compared with those in the intermediate region of the cathode. Since the current pattern on the anode is slightly different from that on the cathode, a little axial current flows in the arc channel. However, we can recognize the above experimental results with MC-I even by using MC-II.

**Conclusions**

Plasma diagnostics and flowfield analysis in the quasi-steady MPD channels, almost realizing only electromagnetic blowing acceleration, i.e., one-dimensional flowfield, were made. The discharge current concentrated near the downstream end, and particularly the current fractions for molecular gases were much larger than those for monatomic gases regardless of particle weight. However, the current concentration near the inlet, which was
expected from the one-dimensional MHD flowfield analysis, was hardly observed. The
electron temperatures for Ar and N\textsubscript{2} optically measured were axially kept about 1.2–1.4 eV
regardless of discharge currents. The electron temperature measured agreed with that
calculated. The electron number densities for both gases ranged from $2 \times 10^{14}$ to $3 \times 10^{15}$
cm\textsuperscript{-3}. The axial variation of the velocity inferred from the electron number density measured
showed that the plasma was drastically accelerated only near the outlet of the channel.
although the analyzed velocity profile had two acceleration zones near the inlet and the
outlet.

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