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Visual Study of Supersonic Plasma Flow in Constant Area MHD Channel

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The purpose of the present paper is to report the results of visual studies of the supersonic plasma flow in the Faraday tyep MHD generator with constant area channel. The plasma for MHD generator is produced using a shock tube. In order to obtain a clear and sharp image of the supersonic plasma flow in MHD generator channel, the color schlieren method has been employed. The experimental results show clearly shock waves and Prantle-Meyer fans in MHD channel. In the case of the flush mounted electrode channel, the adjusting wave is formed at the end of channel and moves to upstream. The pressure increases smoothly and the flow Mach number decreases from supersonic to subsonic through the adjusting wave. The plasma flow in a channel with protruded electrodes is also investigated, and the characteristics of the multiple shock wave which appear between electrodes are discussed.

1. Introduction

There has been an increasing interest in plasma flows for the technical field in resent years. This is due to the importance of such flows in MHD generator[1], MHD accelerator[2], MHD thruster[3], etc. For a number of these applications, many researchers have studied so far experimentally and theoretically. Especially, the wide variety of research area for MHD generator is studied. The steady gas dynamics in MHD generator was investigated by Louis, et al[4]. Merck and Massee measured pressure distribution in MHD generator channel with steady shock wave[5]. Tsunoda, et al. analyzed second flow in MHD generator[6]. Hara and Umoto calculated gas dynamic in MHD generator on short circuit[7]. However, there are many problems which are not yet resolved in regard to the flow mechanism in a channel with MHD interaction.

The purpose of the present paper is to report the results of visual studies of the supersonic plasma flow in the Faraday type MHD generator with constant area channel. The plasma for MHD generator is produced using a shock tube. In order to have a clear and sharp image of supersonic plasma flow, the color schlieren photographic method has been employed. The gas dynamics and electrical characteristics on a constant area MHD channel are discussed.

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2. Experimental apparatus and procedures

A schematic diagram of shock tube facilities for MHD generator is shown in **Fig. 1**. The experimental apparatus consists of the shock tube, MHD generator, and dump tank. The shock tube consists of the driver chamber (length is 1500 mm, diameter is 97 mm) , the driven tube (length is 3500 mm, diameter is 81 mm) and the stagnation chamber (length is 440 mm, diameter is 76 mm) . The driver chamber is separated from the driven tube by the two diaphragms. The pressure gets down rapidly between these two diaphragms to break these diaphragms. When these diaphragms are broken, the shock wave and supersonic flow are generated. This shock wave propagates into the driven tube and reflects at the end wall of stagnation chamber. Reflected shock wave makes high temperature and pressure plasma.

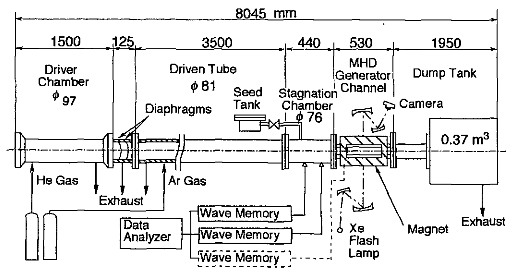

Fig. 1 Schematic diagram of experimental instruments.

The details of MHD generator channel are shown in **Fig. 2**. The MHD generator channel is a Faraday type with the distance between electrode walls is 10 mm and the distance between insulation walls is 20 mm. The electrodes can be protruded h mm away from the electrode wall. The electrode pitch is 10 mm and width is 5 mm. The MHD generator channel has 19 pairs of electrodes and the external load is 10 Ω. The plasma in the stagnation chamber is accelerated to supersonic by vena contracta at the inlet of MHD generator channel[8]. To make clear the influence of protruded electrodes on fluid and electric characteristic, the experiment condition has two electrodes types, namely, all electrodes are flush (h = 0) and all electrodes except 1 st and 19 th are protruded (h = 0.3 mm). The static pressures in the test section are measured at x = 17.5, 67.5, 117.5, 167.5 mm (at 2, 7, 12, 17 th electrode) . The flow is visualized by a schlieren method used Xenon flush lamp as a light source. The magnet is excited to give the field strength 1 T in the test section. The experimental conditions are as follow. The driver chamber is charged with Helium gas at 505 kPa, and the driven tube is charged with Argon gas with vapor of metallic potassium (the seed fraction is 4.1×10^{-5} molar fraction) at 2.6 kPa. The incident shock wave Mach number Ms is 4.1 in the stagnation chamber. The stagnation temperature of the plasma is 4250 K and the stagnation pressure is 350 kPa.

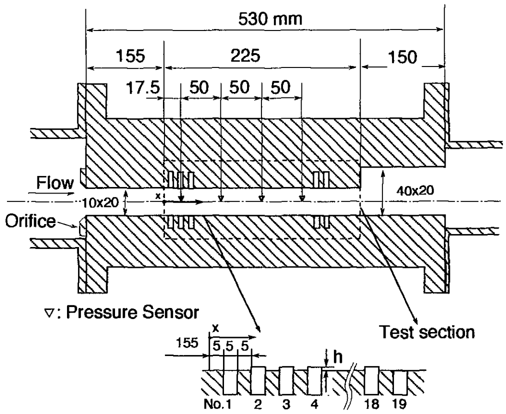

Fig. 2 Details of MHD Generator channel.

3. Results and Discussions

3.1 Flush mounted electrodes

The schlieren photographs and sketch showing the supersonic plasma flow in the test section with flush mounted electrodes are given in **Figs. 3 (a)～(c)**. The magnetic field strenght B and the time t are indicated in each photographs. The time t is measured from the moment when the reflected shock wave impinges on the pressure sensor of stagnation chamber. The original photographs are color ones, in which a homogeneous density region is represented by green and positive and negative gradients of density along the flow direction are represented by red and blue, respectively. The supersonic plasma flows in the direction of right. In **Figs. 3 (a)** and **(b)**, Mach waves from edges of electrodes are observed in supersonic plasma flow.

To make clear the difference between the flows in **Figs. 3**, the flow Mach numbers measured by Mach angles α at the center line of test section are shown in **Fig. 4**. The curves show the theoretical values calculated by applying the steady MHD one-dimensional theory[9] in the case of the friction coefficient $f=0.0004$. The interaction parameter $N=0.015$, which is defined by the ratio of $J\times B$ force and inertial force. In **Fig. 4**, the experimental data of $B=0$T and 1T agree roughly with the theoretical curves of $N=0$ and 0.015, respectively. This means that, when $B=1$T, $J\times B$ force acted in the opposite direction decelerates flow.

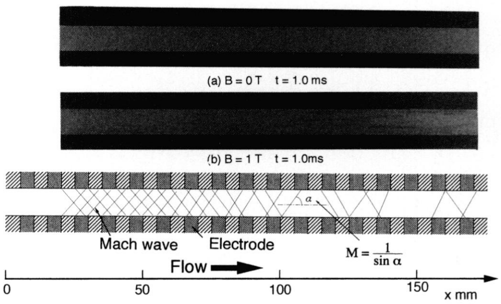

Fig. 3 Schlieren photographs show the flow in the test section. (Flush mounted electrode)

Next, the pressure p/p_2 profiles measured along the test section are shown in **Fig. 5**, where p_2 is pressure at 2nd electrode. **Figure 5** shows that the inflection point of pressure profile indicated by an arrow moves to upstream with time, that is, the head of adjusting wave in the test section moving from downstream to upstream. The flow decelerates from

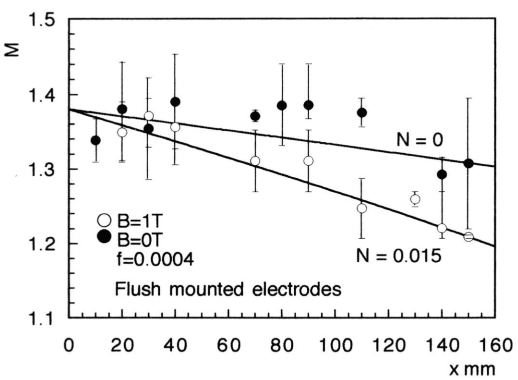

Fig. 4 Mach number along the test section.

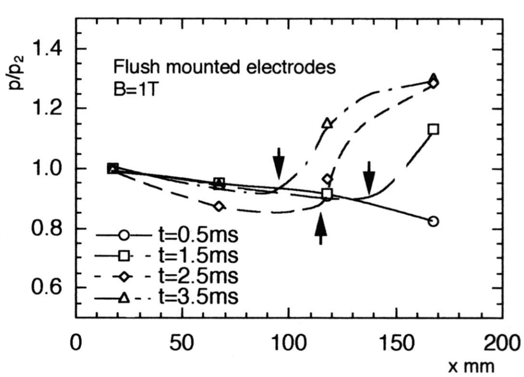

Fig. 5 Pressure profiles along the test section.

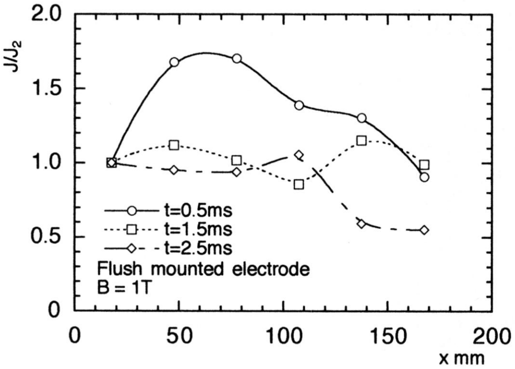

Fig. 6 Current density profiles along the test section.

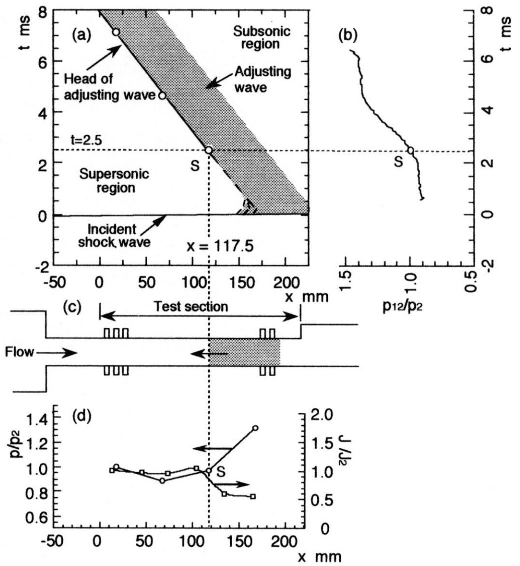

Fig. 7 The wave diagram in the test section.

supersonic to subsonic though the adjusting wave like as a shock system[5] or pseudo-shock[10].

As said before, the flow Mach number is decreased by J × B force which is in proportion to a current density. The current density profile is a very serious problem. **Figure 6** shows the current density J/J_2 profile measured along the test section, where J_2 is current density at 2nd electrode. In **Fig. 6**, the current density is nearly constant after $t = 1.5$ ms along the test section. But at $t = 0.5$ ms, the current density profile has large fluctuation, because the flow is not yet a steady state.

To consider well the gas dynamic characteristics of the MHD plasma flow with flush mounted electrodes, the x-t wave diagram in the test section is shown in **Fig. 7 (a)**. The point S indicates the inflection point, that is the head of the adjusting wave, shown in **Fig. 5** at $x = 117.5$ mm, $t = 2.5$ ms. **Figure 7 (a)** shows that the subsonic region widens from downstream of test section. **Figure 7 (b)** shows pressure profile p_{12}/p_2, where p_{12} is measured pressure at 12 th electrode ($x = 117.5$ mm). The sketch of adjusting wave in test section is shown in **Fig. 7 (c)**. **Figure 7 (d)** shows pressure profile and current density profile at $t = 2.5$ ms. In **Figs. 7 (b)~(d)**, the pressure increases smoothly through the adjusting wave, but the value of current density through one is almost constant. In these figures, when the flow is choked at the end of test section, unsteady compression wave, which we call the adjusting wave, runs upstream so that the flow at the end of test section is maintained sonic.

In order to have a clear image of the adjusting wave, the schlieren photograph is shown in **Fig. 8** at $t = 2.5$ ms. **Figure 8** shows that the flow is clearly supersonic, where many Mach waves are observed, at upstream of head of adjusting wave ($x <$

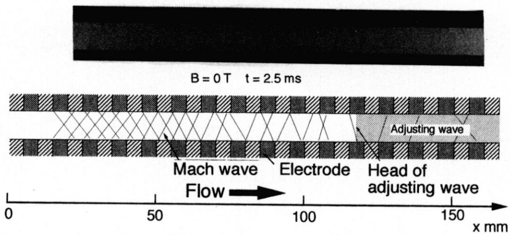

Fig. 8 Schlieren photograph shows the flow in the test section. (Flush mounted electrode)

117.5 mm). On the other hand, at downstream of it (x > 117.5 mm), Mach waves are not clearly observed and sometimes disappear. That means that the adjusting wave propagates intermittently upstream of test section and the flow gradually changes from supersonic to subsonic. To make clear the effect of the adjusting wave on current density profile, the current density profile measured and pressure profile at x = 107.5 mm is shown in **Fig. 9**. In this figure, the left vertical axis is current density ratio J_{11}/J_8, where J_{11} and J_8 are current density at 11 th and 8 th electrode, respectively. The right vertical axis is pressure ratio p_{11}/p_8, where p_{11} and p_8 are pressure at 11 the and 8 th electrode,respectively. Abscissa axis is non-dimensional length $U_p \times t_p/D$ (U_p: propagating velocity of adjusting wave, t_p: time from adjusting wave passes at x = 107.5 mm, D: equivalent diameter of test section, 13.3 mm). Within time of the **Fig. 9**, the adjusting wave doesn't arrive yet at 8th electrode. The pressure p_{11}/p_8 is calculated from p_{12}/p_8 in consideration of adjusting wave velocity. **Figure 9** shows that pressure increases smoothly through the adjusting wave, but the current density is nearly constant without regard to the arrival of adjusting wave. According to the previous paper[8], the current density in the MHD channel cuts off behind the adjusting wave, especially shock wave. In all case of our experiments, the adjusting wave is not shock wave and cut in current density is not observed.

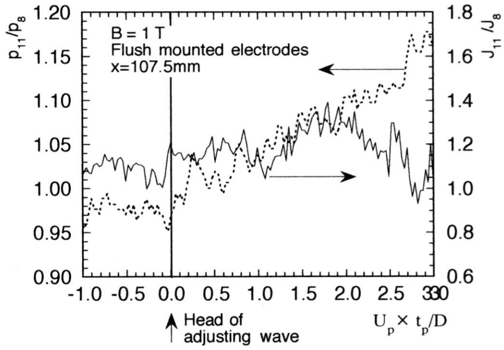

Fig. 9 Current density profile and static pressure profile.

3.2. Protruded electrodes

The schlieren photographs and sketches show plasma flow in the test section with protruded electrodes are given in **Figs. 10 (a) ~ (d)**. The magnetic field strength B and the time t are indicated in each photographs. **Figures 10 (a)** and **(b)** show the multiple choking flow and shock wave are formed in plural location. The flow in the test section has the weak oblique shock waves and Prandtl-Meyer fans from edge of the electrodes inlet, and normal shock wave occurred at electrodes exit. This normal shock wave decelerates flow from supersonic to subsonic. And this subsonic flow

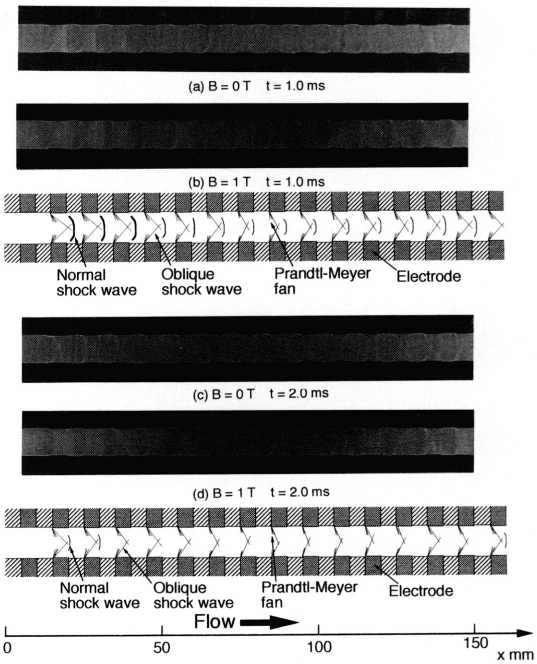

Fig. 10 Schlieren photographs show the flow in the test section. (Protruded electrode)

is accelerated to supersonic by area change, namely protruded electrode. These normal shock wave become weak at downstream area of test section. **Figs. 10 (c)** and **(d)** show the oblique shock waves from the edge of electrodes are observed in the test section. These oblique shock waves are shown clearly at upstream area and downstream area in the test section, but dimly in the middle area.

The flow in test section with protruded electrodes alternately changes from supersonic to subsonic as mention before. It is difficult to know the flow Mach number in subsonic part, but easily to calculate the flow Mach number in supersonic part using Mach angle. To make clear the difference between in the case of B=0T and 1T, the flow Mach number in supersonic part, which we call the local Mach number, is calculated from **Figs. 10 (a)** and **(b)** and is shown in **Fig. 11**. The local Mach number make no difference between results of B=1T and B=0T at upstream area. But, at downstream area in test section, the local Mach number with B=1T is smaller than B=0T. On the whole, **Fig. 11** indicates that the local Mach number take a minimum value at middle area in the test section. This local Mach number profile is supposed to depart from the steady MHD one-dimensional theory because the distance between electrode face and electrode wall (namely, h = 0.3 mm is shown in **Fig. 2**) is large compared with the diameter of test section. This is due to the fact that, the upstream area of the test section is almost supersonic and the Mach number decreases by wall friction because total pressure decreases by wall friction. But the

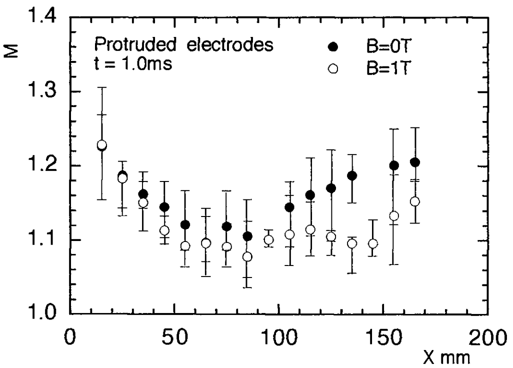

Fig. 11 Local Mach number along the test section.

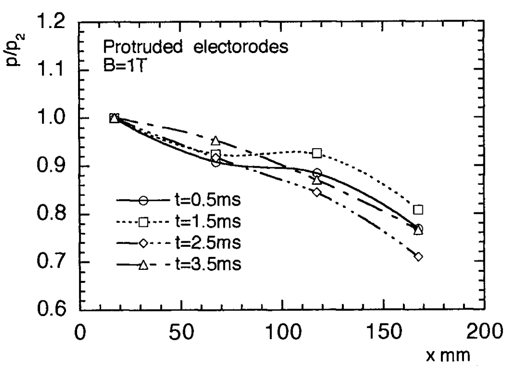

Fig. 12 Pressure profiles along the test section.

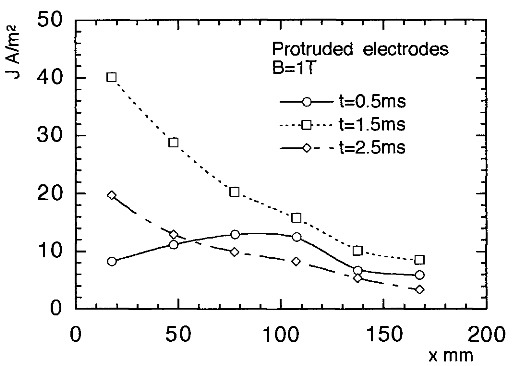

Fig. 13 Current density profiles along the test section.

downstream area in the test section may be almost subsonic. Therefore the Mach number increases by wall friction.

The pressure p/p_2 profiles along the test section are shown **Fig. 12**. Figure shows that the pressure decreases to dwonstream. There is no adjusting wave in the test section with protruded electrodes unlike the flush mounted electrodes.

Figure 13 shows the current density profiles along the test section. The current density profiles is nearly constant at t = 0.5 ms. On the whole, the current density profiles decreases to downstream after t=1.5 ms. This means that flow velocity decrease by wall friction.

4. Conclusions

The supersonic plasma flow in the Faraday type MHD generator with constant area channel have been visualized by the color schlieren method, and the gas dynamics characteristics of supersonic plasma flow in MHD generator channel have been studied experimentally. The results obtained are summarized as follows.

Flush mounted electrode

1) The flow Mach number along the test section with B=1T decreases more than B=0T. Within the scope of this experiment with B = 1T, the interaction parameter is N = 0.015.

2) The adjusting compression wave runs upstream and the flow gradually changes from supersonic to subsonic.

3) The pressure increases smoothly through the adjusting wave but the current density is nearly constant without regard to the arrival of the adjusting wave.

Protruded electrode

The multiple chocking flow and shock wave are formed in plural location. The flow has the normal shock wave occurred at electrodes exit. The normal shock wave decelerates flow from supersonic to subsonic. And this subsonic flow is accelerated to supersonic by protruded electrode.

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