EXPERIMENTAL STUDY ON DISK MHD GENERATOR WITH SEGMENTED LOADING

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Abstract

Power generation experiments of a disk MHD generator under segmented loading conditions have been performed. We have newly equipped an electrode at the midstream part of the disk MHD channel. Each individual power generating part affects each other electrically and fluid-dynamically. High loading condition is required to get appropriate Joule heating in the upstream part. The downstream fluid-dynamical condition has an influence on pressure at the exit of the upstream part. Relatively low loading condition is preferable in the downstream part to avoid large increase in static pressure at the exit of the upstream part.

Keywords disk MHD generator, segmented loading condition, non-equilibrium plasma

1. Introduction

One of the advantages of a disk MHD generator is a simple configuration and small number of electrodes. A single external load resistance connects between the anode and cathode of the MHD channel in general. In order to obtain sufficient electrical power output from the MHD generator, it is preferable that the plasma having suitable electrical conductivity and velocity flows though the MHD channel.

The inlet plasma condition with low electrical conductivity limits the output power. Therefore, load resistances have been set not only on the MHD channel but also on the supersonic nozzle equipped in the upstream of the generator. Those works have indicated that the loading condition in the nozzle is an important factor affecting Mach number, static pressure, Hall potential and discharge structure at the inlet of the MHD channel. But it is difficult for the single loading way to control the Joule heating only in the region of low electrical conductivity.

A segmented loading disk MHD generator in which four electrodes are provided between anode and cathode has been proposed by Sens et al. It is found from the experimental study that a large voltage drop caused by low electrical conductivity at the inlet of the channel could be avoided under the segmented loading condition.

In the present work, the power generation experiments are carried out with a shock-tube driven disk MHD generator, where a middle electrode is installed between the anode and cathode. Features of the segmented loading generator are investigated focusing on the influences of the upstream and downstream loading conditions on the generator performance.

2. Experimental Setup

A shock-tube driven disk MHD generator, which is used in the present experiments, is shown in Fig.1. The shock-tube made of stainless steel has the inner diameter of 130 mm. An aluminum diaphragm separates the driver-section and driven-section. The working gas is cesium vapor seeded helium. Cesium is vaporized in a seed tank heated by an electric heater.

Fig.1 Schematic outline of the present shock-tube driven disk MHD generator.

An iron core magnet supplies a stable magnetic field to the disk generator. The magnetic flux density is 2.6 T that is almost uniform in the entire region of the MHD channel.

A stagnation temperature and a seed fraction are measured by a line reversal method through optical
windows located at the end of the shock-tube. The seed fraction is defined as the ratio of the number density of seed (cesium) atoms to noble gas (helium) atoms. It is controlled in the range of $10^4 \cdots 4 \times 10^4$ by changing the temperature in the seed tank. An inlet stagnation pressure is measured at the end wall of the shock-tube.

Figure 2 shows a front view of a segmented loading MHD generator installed in the present shock-tube facility. The disk made by acrylic consists of a supersonic nozzle with swirl vanes and an MHD channel from where electrical power is extracted.

![Diagram of MHD generator](image)

**Fig.2 Front view of a segmented loading disk generator.**

Three electrode rings of copper (5 mm in width) are arranged in a concentric configuration. Those radii are 80 mm (1st electrode, E1), 170 mm (2nd electrode, E2) and 250 mm (3rd electrode, E3), respectively. The MHD channel is divided into two parts by the 2nd electrode, that is upstream and downstream parts. Two load resistances, $R_u$ and $R_d$, are individually connected between E1 and E2 (upstream part) and between E2 and E3 (downstream part), respectively.

The height of the MHD channel is kept constant to 17 mm from inlet to exit. An area ratio of the channel defined as the ratio of the exit cross-section to the inlet cross-section is 11.7.

Piezo-resistive pressure sensors and electrical probes are equipped to measure radial distributions of static pressure and Hall electrical potential. The static pressure is measured through pressure ports of S1 - S10. The radial profile of the electrical potential is obtained with four electrical probes indicated by P1 - P4 and three electrodes, E1 - E3. An exit total pressure is measured by an outer-most pressure sensor through a Pitot tube at the position of T5.

Operating conditions of the present experiments are summarized in Table 1. A load resistance under a single loading condition is set between E1 and E3.

<table>
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<th>Table 1 Operating conditions of power generation experiments</th>
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<tr>
<td>Working gas</td>
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<td>Thermal input [MW]</td>
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<td>Stagnation temperature [K]</td>
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<td>Inlet stagnation pressure, $p_{\text{in}}$ [MPa]</td>
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<td>Downstream load resistance, $R_d$ [Ω]</td>
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<td>Single loading resistance [Ω]</td>
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3. Segmented Loading and Single Loading

The radial distributions of (a) static pressure normalized by inlet stagnation pressure, $P_s/p_{\text{in}}$, and (b) Hall potential measured under the segmented and single loading conditions are shown in Fig.3. The seed fraction is $10^4 \cdots 4 \times 10^4$. A broken line in Fig.3(a) is a result of non-MHD case. The exit Mach number obtained under the non-MHD condition is 3.0.

In the case of the segmented loading, the upstream resistance, $R_u$, of $1.0 \cdot 2.0$ and the downstream resistance, $R_d$, of $1.0 \cdot 2.0$ are connected. In the single loading case, the load resistance of $2.0 \cdot 2.0$ is connected.

![Graphs of radial profiles](image)

**Fig.3 Radial profiles of (a) static pressure normalized by the inlet stagnation pressure, $P_s/p_{\text{in}}$, and (b) Hall potential measured under the segmented and single loading conditions. Segmented load resistances are $R_u=1.0 \cdot 2.0$ and $R_d=1.0 \cdot 2.0$. A broken line is obtained for non-MHD case.**
The static pressure under the single loading condition gradually decreases as the plasma flows in the MHD channel. The Hall potential increases from 0 V at E1 to 445 V at E3 monotonically, whereas the electric field decreases from 4.7 kV/m at r=90 mm to 0.3 kV/m at r=235 mm. It suggests that a sufficient MHD interaction in the downstream part is not achieved in comparison with the inlet part of the MHD channel.

The result obtained under the segmented loading condition shows that $p_s/p_{\text{in}}$ is relatively low in the upstream part, and steeply increases at the inlet region of downstream part. This steep increase of the pressure indicates that a larger Lorentz force acts in this region.

We can confirm that the plasma-fluid properties in each power generating part can be changed in the way to operate the generator under the segmented loading in spite of the total load resistance is the same as that of the single loading.

4. Effect of Seed Fraction on Segmented Loading Generator Performance

The generator performance under various seed fraction conditions is shown in Fig.4. This figure shows typical radial distributions of (a) normalized static pressure and (b) Hall potential. The seed fraction is changed 0.4*10$^{-3}$, 0.9*10$^{-3}$, and 1.0*10$^{-3}$. The segmented load resistances are fixed to $R_u=0.5 \Omega$ and $R_d=0.5 \Omega$.

The static pressure and Hall potential are kept relatively low in the entire channel under the low seed fraction (0.4*10$^{-3}$). These radial profiles are attributed to insufficient electrical conductivity. A steep drop of static pressure appears at the adjacent to the middle electrode. This fact suggests that the Faraday current does not flow over the middle electrode leading insufficient Joule heating and little Lorentz force. The influence of the middle electrode is significant especially under the low seed fraction condition.

The static pressure and Hall filed increase with increasing seed fraction in the entire channel in this experiment. In particular, larger seed fraction leads higher Hall field at the inlet of the MHD channel. The Hall field in the downstream part has a small dependence on the seed fraction.

5. Variation in Segmented Loading Condition

The load resistances of $R_u$ and $R_d$ are individually varied. Figures 5 and 6 present the radial distributions of (a) normalized static pressure and (b) Hall potential. The seed fractions are about 0.8*10$^{-3}$ and 1.0*10$^{-3}$, respectively.

Figure 5 shows an influence of upstream load resistance on the generator performance. The upstream resistance is varied from 1.0 to 2.0 $\Omega$, keeping the downstream load resistance to 1.0 $\Omega$.

Fig.5 Radial profiles of (a) normalized static pressure, $p_s/p_{\text{in}}$, and (b) Hall potential measured under the different upstream loading conditions. Upstream load resistance is varied from 1.0 to 2.0 $\Omega$, while downstream resistance is constant of 1.0 $\Omega$. The seed fraction is about 0.8*10$^{-3}$.
A negative Hall potential region appears in the upstream part when the upstream resistance is 1.0 \times 10^{-5} \text{ } \Omega. At the same time, the static pressure decreases along with the non-MHD profiles around the 1st electrode. It seems that the electrical conductivity at the inlet of the MHD channel is low because of insufficient non-equilibrium ionization in the supersonic nozzle. The appearance of the negative potential suppresses the entire generator performance, although the Hall potential increases in the downstream part.

The Hall potential increases when the upstream part is loaded with higher resistance. In particular, the potential at the channel inlet is remarkably increased by varying $R_u$ from 1.5 to 2.0 \text{ } \Omega.

Influence of the downstream load resistance on the plasma properties is shown in Fig.6. The downstream load is varied from 0.5 to 2.0 \text{ } \Omega keeping the upstream load resistance to 1.0 \text{ } \Omega. When the downstream is loaded with higher resistance, the Hall potential at the 3rd electrode increases. On the contrary, the Hall potential at the middle electrode, $E_2$, decreases with increasing $R_u$. It is considered that the static pressure at the exit of the upstream channel is influenced by the downstream loading condition. Relatively low loading condition is preferable in the downstream channel in order to avoid a large increase in static pressure at the exit of upstream channel.

Voltage-current curves of the respective generating part are shown in Fig.7. Hall current, $I_{Hall}$, and Hall voltage, $V_{Hall}$, are measured in both the upstream and downstream part. The open marks represent the V-I characteristics of the upstream part. The upstream resistance is changed keeping the downstream resistance to 0.5 \text{ } \Omega or 1.0 \text{ } \Omega. The solid marks represent the downstream V-I characteristics measured by changing the downstream resistance under the constant upstream resistance of 0.5 \text{ } \Omega or 1.0 \text{ } \Omega.

We can see from Fig.7 that the gradient of the upstream channel V-I curves is larger than that of the downstream ones. This fact means that high loading condition is required to cause appropriate Joule heating in the upstream part since the electrical conductivity at the inlet of the upstream channel is not always high enough. On the other hand, the electrical conductivity is relatively high in the downstream part but the Hall electromotive force is small due to small flow velocity. The enthalpy extraction ratio obtained from upstream part is about 8 \times 14 \%, while that obtained from downstream part is 2 \times 4 \% in the present experiments.

![Fig.6 Radial profiles of (a) normalized static pressure, $p/p_{max}$, and (b) Hall potential measured under the different downstream loading conditions. Downstream load resistance is varied from 0.5 to 2.0 \text{ } \Omega while upstream resistance is constant of 1.0 \text{ } \Omega. The seed fractions are about 1.0 \times 10^{-5}.

![Fig.7 Voltage-current curves of the segmented loading generator. Open marks (\textbullet \textcircled{r} \textdagger) represent V-I characteristics of upstream part and solid marks (\textsuperscript{•} \texttt{•} \textdagger) represent downstream part one.](image)

Influence of the output power derived from the upstream and downstream parts on the total generator performance is presented in Fig.8; (a) relation between the generator performance (enthalpy extraction ratio, E.E., and isentropic efficiency, I.E.) and output power from upstream part, $P_{up}$, and (b) relation between output power from downstream part, $P_{down}$, and that from upstream part. The $R_u$ and $R_d$ vary from 0.5 to 2.0, respectively. The seed fraction is in the range of 0.4 \times 10^{-3}.
Both $P_{up}$ and $P_{down}$ increase simultaneously up to $P_{up}=100$ kW as shown in Fig.8(b). Both the enthalpy extraction ratio and isentropic efficiency also increase in this condition as shown in Fig.8(a).

When the power higher than 100 kW is extracted from the upstream part, $P_{down}$ declines. This fact leads a saturation of the enthalpy extraction ratio. The isentropic efficiency in this condition decreases with increasing $P_{up}$. This result confirms that high energy-conversion efficiency cannot be expected in the downstream part when the enthalpy of the fluid is extracted too much from the upstream part.

![Graph showing enthalpy extraction ratio, isentropic efficiency, and power output vs $P_{up}$](image)

Fig.8 (a) Relation between enthalpy extraction ratio, E.E., isentropic efficiency, I.E., and electrical output power obtained from the upstream part, $P_{up}$. (b) $P_{up}$ dependence of the power derived from the downstream channel, $P_{down}$. $R_a$ and $R_d$ are changed in the range from 0.5 to 2.0, respectively.

6. Conclusions

Power generation experiments of non-equilibrium disk MHD generator have been carried out under the segmented loading condition. Conclusions are summarized as follows:

1. High loading condition is required to get appropriate Joule heating in the upstream part in the present generator. On the other hand, relatively low loading condition is preferable in the downstream part to avoid large increase in static pressure at the exit of the upstream part.

2. The middle electrode has a bad influence upon the generator performance especially under a low seed fraction condition.

3. It is confirmed that high energy-conversion efficiency cannot be expected in the downstream part when the enthalpy is extracted too much from the upstream part.

References

