Flow Behavior in a Disk MHD Generator with Helium

Hiroshi Imai, Tomoyuki Murakami, Hiroshi Takanashi, Yoshihiro Okuno, and Hiroyuki Yamasaki
Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology
4259, Nagatuta, Midori-ku, Yokohama, Japan

Abstract

Power generation experiments have been conducted by a shock-tube driven MHD generator with He/Cs. The effects of fluid-dynamical behavior and plasma behavior on the generator performance were discussed paying attentions to the power output from the supersonic nozzle region, the radial distribution of pressure, and the fluctuation in the supersonic nozzle region. It was found that the difference of condition in the supersonic nozzle region affects the generator performance. The present study suggested that the fluid behavior having no static pressure increase and plasma behavior with small fluctuations in the nozzle region contributes to the high performance. Then, the enthalpy extraction ratio of 14.0% and high isentropic efficiency of 40.5% are achieved when the nozzle load resistance is 0.85×10^5 and seed fraction is 10×10^3.

Keywords Disk MHD generator, fluctuation, flow behavior, Plasma behavior, nozzle loading condition

1 Introduction

In Tokyo Institute of Technology, we had been interested in the performance of a disk MHD generator with a large area ratio (exit / inlet cross section) because a high enthalpy extraction ratio could be achieved. But a high isentropic efficiency could not be attained. Subsequently it has been suggested that the relationship between enthalpy extraction and isentropic efficiency depends on the cross sectional area ratio of the generator. We have experimented with a generator that has a small area ratio. The result obtained by using cesium-seeded argon (Ar/Cs) has indicated that a high isentropic efficiency could be achieved [1][2]. Although, power generation using He/Cs has conducted with large area ratio generator [3], there is a little work on power generation with small area ratio channel [4].

Fig.1 Front and cross sectional views of the disk generator. Windows and ports plotted by - - - are employed in the present experiments.

2 Experimental Procedure

Fig. 1 shows front and cross sectional views of the disk MHD generator. The disk generator made of acrylic consists of the supersonic nozzle (between a 1st anode and a 2nd anode) and the generation channel (between the 2nd anode and a cathode) from which electrical power is extracted. Static pressure ports and electrical probes to obtain radial distributions of static pressure and Hall potential are illustrated. When magnetic flux density is not applied,
Mach number at \( r = 0.1 \text{m} \) and at \( r = 0.26 \text{m} \) are 1.7 and 3.5, respectively. An external magnet applies magnetic flux density in the normal direction to the fluid flow in the disk. The density is 3.0 T at the radius of 0.1 m and approaches 0.3 T with increasing radius. Operating conditions are summarized in Table 1. The working gas, the inlet stagnation pressure, inlet stagnation temperature and magnetic flux density were kept constant.

Table 1: Operating conditions of the power generation experiments. The values of seed fraction and Channel load resistance are variable.

<table>
<thead>
<tr>
<th>Working gas</th>
<th>He+Cs</th>
</tr>
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<tbody>
<tr>
<td>Thermal input [MW]</td>
<td>5.5</td>
</tr>
<tr>
<td>Stagnation Pressure [MPa]</td>
<td>0.15</td>
</tr>
<tr>
<td>Stagnation Temperature [K]</td>
<td>2500±50</td>
</tr>
<tr>
<td>Seed Fraction</td>
<td>( 2 \times 30 \times 10^{-4} )</td>
</tr>
<tr>
<td>Nozzle Load Resistance [Ω]</td>
<td>0.2~9</td>
</tr>
<tr>
<td>Channel Load Resistance [Ω]</td>
<td>0.55</td>
</tr>
<tr>
<td>Maximum Flux Density [T]</td>
<td>3.0</td>
</tr>
</tbody>
</table>

3 Results and Discussions

3.1・・Performances

Fig. 2 shows enthalpy extraction ratio, E.E. and isentropic efficiency, I.E. achieved under various conditions.

In the Fig. 2, theoretical curves showing the relation between the E.E. and I.E. are also drawn. The theoretical calculation is based on the following simple equation.

\[
\frac{E.E.}{I.E} = 1 - 1 - \left( \frac{p_{\text{inlet}}}{p_{\text{exit}}} \right)^{\frac{2}{\gamma}} \left( \frac{A_{\text{exit}}}{M_{\text{exit}}} \right)^{\frac{2}{\gamma}} \left( \frac{2 \gamma - (\gamma - 1)M_{\text{exit}}^2}{\lambda + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}
\]

(2)

where \( p_{\text{inlet}}, p_{\text{exit}}, A_{\text{inlet}}, A_{\text{exit}}, M_{\text{exit}}, \) and \( \gamma \) denote total pressure at an exit, total pressure at an inlet, a cross sectional area of a throat, a cross sectional area of an exit, exit Mach number, and specific heat ratio. The theoretical curves are obtained from eq. (2), where \( A_{\text{exit}}/A_{\text{throat}} = 4.25 \), and \( M_{\text{exit}} = 1.0 \) or 2.1. It is found from Figs. 2 that the calculated gradient of I.E./E.E. well agrees with the measured one.

For the seed fraction of \( 10^4 \cdot 10^{-4} \) and channel load resistance of 0.55, the highest isentropic efficiency of 40.5% and the highest enthalpy extraction ratio of 14.0% for He/Cs were achieved, where the exit Mach number was 2.08. Since the exit Mach number is relatively high, it is expected that fluid velocity is kept high in MHD generator.

Fig. 2: Isentropic efficiency, I.E. as a function of enthalpy extraction ratio, E.E. A seed fraction S.F., is varied. Theoretical curve is calculated using Mach number, \( M_{\text{exit}} \).

Figs 3 ••(a) Relation Between enthalpy extraction ratio and seed fraction, (b) relation between isentropic efficiency and seed fraction. Nozzle load resistances, \( R_e \) are 0.2~9.85~9 and 10.0~9. Channel load resistance is constant (\( R_n = 0.55 \) •).

3.2 ••Effect of nozzle road resistance

Figs. 3 show (a) the enthalpy extraction ratio and (b) the isentropic efficiency as a function of seed fraction. The nozzle road resistances are 0.2~9.85~9 and 9. The channel load resistance is constant (\( R_n = 0.55 \) •).

At first, this result indicates that enthalpy extraction ratio tends to increase with increasing seed fraction when seed fraction is low. But enthalpy extrac-
tion ratio decreases with increasing seed fraction when seed fraction is high. Optimum value for seed fraction exists. For example, when the nozzle road resistance is 0.85\(\cdot\)10\(-4\), the enthalpy extraction ratio rises from 0% to 14% with increasing for relatively low seed fraction (\(\leq 10\cdot 10^{-4}\)). But the enthalpy extraction ratio slightly decreases from 14% to 8% when the seed fraction increases from 10\(-4\) to 23\(-4\). When the nozzle road resistances are 0.2\(\cdot\)10\(-4\) and 0.85\(\cdot\)10\(-4\), the same tendency are indicated. That reveals that the performance of MHD generator with He/Cs depend on seed fraction specifically under the condition of low seed fraction.

In addition, it is found from Figs. 3, that the nozzle resistance affects the optimum seed fraction. In the previous research [4], the excessive nozzle load resistance has been one of the performance-limiting parameters in the He/Cs experiments. The employment of the high seed fraction under the high nozzle loading condition resulted in the large pressure loss and the deterioration of the performance. The present experiments indicate that the performances under the condition of relatively low seed fraction (Rn=0.2\(\cdot\)10\(-4\) and Rn=0.85\(\cdot\)10\(-4\)) are better than that of high nozzle load resistance (Rn=9\(\cdot\)10\(-4\)).

![Fig. 4 Nozzle load resistance, Rn, dependence of nozzle output and enthalpy extraction ratio, as a function of a seed fraction. Channel load resistance, Rc is constant (Rc=0.55\(\cdot\)10\(-4\)).](image)

Fig. 4 shows enthalpy extraction ratio and power output from the supersonic nozzle region, as a function of seed fraction. Where the nozzle load resistances, Rn are 0.2\(\cdot\)10\(-4\) and 0.85\(\cdot\)10\(-4\). Channel load resistance, Rc is constant (Rc=0.55\(\cdot\)10\(-4\)).

Fig. 4 indicates the dependence of power output from supersonic nozzle region on various seed fraction is different from nozzle load resistances. The power output from supersonic nozzle region depends on the MHD interaction. Because the behavior of fluid and plasma depends on Lorenz force and Joule heating due to MHD interaction, it is expected that power output from the supersonic nozzle region suggest the effects of the behavior of fluid and plasma.

At first, When the nozzle load resistance is 0.2\(\cdot\)10\(-4\) power output from the supersonic nozzle region, Pn is low (\(\leq 8\)kW) under the condition of low seed fraction (\(\leq 8\cdot 10^{-4}\)). MHD interaction is low in the supersonic nozzle region and enthalpy extraction ratio is relatively low.

When seed fraction is optimum value\(\approx 11\cdot 10^{-4}\), for enthalpy extraction ratio, the plasma on the supersonic nozzle region start to be ionized slightly the plasma isn't enough to be ionized because Pn increase slightly. Then, enthalpy extraction ratio increases gently with increasing seed fraction.

![Fig. 5 Radial profiles of (a) normalized static pressure, and (b) hall potential and (c) strength of electric field measured under the different seed fraction conditions. A line referred to as isentropic flow is obtained in an experiment with no MHD interaction.](image)

Table 2 the performances of the experimental results in the Fig. 5 under two cases of seed fraction

<table>
<thead>
<tr>
<th>S.F.</th>
<th>E.E. (%)</th>
<th>I.E. (%)</th>
<th>M_eol</th>
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<tbody>
<tr>
<td>10(-4)</td>
<td>14.0</td>
<td>40.5</td>
<td>2.1</td>
</tr>
<tr>
<td>12(-4)</td>
<td>14.0</td>
<td>33.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

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When seed fraction is high (≥15·10⁻⁴), $P_n$ is high (≥48kW). But enthalpy extraction ratio decreases. The reason is that it is expected that Lorentz force reduce the fluid velocity on the supersonic nozzle region due to strong MHD interaction.

Secondly, When the nozzle load resistance is 0.85·$R_n$, $P_n$ is different from $P_n$ under the condition of $R_n=0.2$·$R_n$. The $P_n$ increases when seed fraction is low (≤8·10⁻⁴). It is expected that ionization in the supersonic nozzle region is relatively high and enthalpy extraction ratio increases.

When seed fraction is optimum value $\approx 10·10^{-4}$ for enthalpy extraction ratio, $P_n$ is appropriate for the plasma on the supersonic nozzle region. It is expected that ionization due to MHD interaction is enough. Enthalpy extraction ratio becomes the highest value.

When seed fraction is high (≥12.0·10⁻⁴), $P_n$ decreases because strong Lorentz force reduce the fluid velocity on the supersonic nozzle region. After all, the fluid velocity in the whole generator decreases. Despite of high electric conductivity due to high seed fraction, the enthalpy extraction ratio decreases.

Figs. 5 presents the radial profiles of (a) normalized static pressure, (b) Hall Potential, and (c) strength of electric field on the boundary between optimum value for seed fraction and high seed fraction. Channel load resistance, $R_n$ and nozzle load resistance, $R_n$ are constant ($R_n=0.55$·$R_n=0.85$·$R_n$). Static pressure is normalized by an inlet stagnation pressure. Isentropic flow in the Fig. 5 shows under the condition of no MHD interaction. Table 2 shows enthalpy extraction ratio, E.E. isentropic efficiency, I.E. exit Mach number, $M_{exit}$ under the condition of optimum seed fraction (10·10⁻⁴) and high seed fraction (12·10⁻⁴)

The radial distribution of the normalized pressure indicates that the static pressure steeply increases on the supersonic nozzle region under the condition of high seed fraction (12·10⁻⁴). However the static pressure don't increases at the supersonic nozzle region under the condition of optimum seed fraction (10·10⁻⁴). The difference of static pressure increase implies that Lorentz force due to MHD interaction exerts the flow on the supersonic nozzle region under the condition of high seed fraction more strongly than under the condition of optimum seed fraction. The radial distribution of strength of electric field indicates that MHD interaction on the supersonic nozzle region under the condition of high seed fraction is stronger than under the condition of optimum seed fraction. Then, table 2 indicates isentropic efficiency of optimum seed fraction is better than one of high seed fraction despite of the same enthalpy extraction ratio under the both seed fraction conditions. The result of high seed fraction indicates makes dissipation of enthalpy because the static pressure increase is generated by large pressure loss due to strong Lorentz force on the supersonic nozzle region. It is considered that the flow behind the static pressure increase might decelerate rapidly. Enthalpy extraction of high seed fraction is the same as enthalpy extraction ratio of optimum seed fraction because electric conductivity under the condition of high seed fraction is higher than optimum seed fraction. But isentropic efficiency of high seed fraction decreases due to large pressure loss.

3-3. Fluctuations

In the previous chapter, we described that MHD interaction on the supersonic nozzle region influenced the performance of MHD generator.

Figs 6  Time series data of Intensity of recombination continuum measured at the supersonic nozzle region (r=0.1m), under the condition of (a) optimum seed fraction (S.F.= 10·10⁻⁴) and (b) high seed fraction (S.F.= 12·10⁻⁴). The nozzle load resistance is 0.85·$R_n$.

Figs 7  The result is that power spectrum by FFT analysis for intensity of recombination continuum at the supersonic nozzle region (r=0.1m)
We attend to time series behavior in order to go into details any further about the condition of flow and plasma in MHD generator.

Figs. 6 shows time series date of Intensity of recombination continuum measured at the supersonic nozzle region (r=0.1m), under the condition of (a) optimum seed fraction (S.F.= 10\cdot 10^{-4}) and (b) high seed fraction (S.F.= 12\cdot 10^{-4}), where the experimental condition is the same as Fig. 5. The nozzle load resistance is 0.8\cdot \Omega. Channel load resistance is 0.55\cdot \Omega.

The Fig. 6 indicates that intensity of recombination continuum fluctuates quickly under the both conditions of seed fraction. The mean value of the intensity is 1.1 under the condition of the optimum seed fraction, and the mean value of the intensity is 1.3 under the condition of high seed fraction.

Figs. 7 shows the result of FFT (Fast Fourier Transform) analysis for intensity of recombination continuum at the supersonic nozzle region (Ref. Figs. 6).

Fig. 8 shows the relationship between fluctuations of the intensity of recombination continuum and seed fraction. The nozzle load resistance is 0.2\cdot \Omega and 0.8\cdot \Omega. The channel load resistance is constant (R_c=0.55\cdot \Omega). Seed fraction is varied. The fluctuation defined, as is the following simple equation.

\[ \text{fluctuation} = \frac{\text{standard deviation}}{\text{mean value}} \]  

Figs. 9 show photographs of the discharge structure of MHD generation plasma using He/Cs, under the condition of R_c=0.55\cdot \Omega. The photograph is taken though the acrylic desk from the direction being against to the shock-tube. The region of 0.095m\leq r \leq 0.175m is given in the picture. An exposure time of the high-speed camera is about 8.3\cdot s. The photographs of (A)–(E) are placed in increasing order of seed fraction. the seed fraction are 4\cdot 10^{-4}, 8\cdot 10^{-4}, 10\cdot 10^{-4}, 12\cdot 10^{-4}, and 15\cdot 10^{-4}. These photographs of (A)–(E) also are taken in the experiments (A)–(E) in Fig. 8.

Figs. 7(b) indicates the characteristic frequencies exist. The characteristic frequencies are about 60kHz and 250kHz. It is expected that these frequencies depend on the MHD interaction because Figs. 7(b) is high seed fraction (12\cdot 10^{-4}). For example, Fig. 9(D) is photograph of the discharge structure under the condition of high seed fraction (12\cdot 10^{-4}). It is found that bright circular band in Fig. 9(D) exist. The bright circular band might be related to be the intensity of the characteristic frequency, 250kHz.

When the nozzle load resistance is 0.8\cdot \Omega fluctuation is 34% under the condition of S.F.=4\cdot 10^{-4} in Fig. 8. The Fig. 9(A) show the whole disk is dark and the discharge structure is distorted. It is expected that fluctuation is large from the Fig. 9(A).

The fluctuation decreases with increasing seed fraction in the Fig. 8. In the Fig. 9(B), though the structure in the channel region become uniform, that in the supersonic nozzle region isn’t bright and don’t become uniform radially.

Then, the minimum fluctuation, 23% is achieved under the condition of S.F.=10\cdot 10^{-4} in the Fig. 8. The Fig. 9(C) show the structure is uniform radially in the both supersonic nozzle region and

\[ (A) \quad S.F.=4\cdot 10^{-4} \quad (B) \quad S.F.=8\cdot 10^{-4} \quad (C) \quad S.F.=10\cdot 10^{-4} \quad (D) \quad S.F.=12\cdot 10^{-4} \quad (E) \quad S.F.=15\cdot 10^{-4} \]

Figs. 9 Photographs are placed in increasing order of seed fraction, (A)–(D). The operating condition are same as those in Fig. 9.
channel region. It is expected that the Fig. 9 (C) confirm the fact that the fluctuation is small on the supersonic nozzle region. The Fig. 7 (a) indicates the intensity of recombination continuum has the various frequencies. However, it is difficult to show characteristic frequency exists in these frequencies, when the seed fraction is $10^{-4}$.

When seed fraction increases more, the fluctuation increases slightly in the Fig. 8. Bright structure exists in the Fig. 9 (D). The structure starts to be distorted again. The fluctuation is $27\%$ under the condition of $S.F. = 15 \times 10^{-4}$ in the Fig. 8. The Fig. 9 (E) shows the structure is brighter and more distorted.

When the nozzle load resistance is $0.2 \times$ the fluctuation is the same tendency as the fluctuation under the condition of $R_e = 0.8 \times$.

The fluctuation is $24\%$ under the condition of $S.F. = 4 \times 10^{-4}$, the minimum fluctuation is $21\%$ when the seed fraction is $11 \times 10^{-4}$. The fluctuation of $S.F. = 15 \times 10^{-4}$ is $23\%$, with increasing seed fraction.

Fig. 3 and Fig. 8 indicate the optimum seed fraction is the same as the optimum seed fraction for enthalpy extraction ratio ($10^{-4}$). The fact indicates, although the reason is that the performance of MHD generator depends not only fluctuation but also various factors (fluid velocity, dielectric flux density, electric conductivity, and matching load resistance), higher enthalpy extraction ratio can be obtained under the condition of small fluctuation for a given nozzle.

4 Conclusions

Power generation experiments have been conducted with the shock-tube driven MHD generator using He/Cs. The results are compared with fluid-dynamical behavior and plasma behavior on the supersonic nozzle region by seed fraction and nozzle load resistance. The concluding remarks can be summarized as follows

1. When the nozzle load resistance change $9 \times 0.85 \times$ and $0.2 \times$ not only the optimum seed fraction but also the performance of MHD generator change. when the seed fraction is $10^{-4}$ and the load conditions are $R_e = 0.8$ and $R_e = 0.55 \times$ the highest isentropic efficiency of $40.5\%$ and the highest enthalpy extraction ratio of $14.0\%$ for He/Cs were achieved.

2. It is expected that power output from the supersonic nozzle region suggest the effects of the behavior of fluid and plasma. When the seed fraction is $10^{-4}$, the power output from the supersonic nozzle region is relatively higher enthalpy extraction ratio is achieved $14\%$ under the condition of $R_e = 0.8 \times$.

3. The highest isentropic efficiency of $40.5\%$ and the highest enthalpy extraction ratio of $14.0\%$ for He/Cs were achieved under the flow behavior condition of static pressure doesn't increase on the supersonic nozzle region but increases on the channel region. This result implies that the high velocity plasma-fluid flows into the channel without large pressure loss in the nozzle.

4. The fluctuation in the supersonic nozzle has minimum value $23\%$ under the condition of $S.F. = 10^{-4}$ for $R_e = 0.85 \times$. It is expected that enthalpy extraction ratio under the condition of small fluctuation is higher than that of large fluctuation.

References


