18. EXPERIMENTS OF AN MHD POWER GENERATION COUPLED WITH A RADIO-FREQUENCY ELECTROMAGNETIC FIELD

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Abstract. Feasibility on a coupling of a radio-frequency (rf) electromagnetic field to non-equilibrium ionization and enthalpy extraction in a disk-shaped Hall-type MHD power generator has been examined. A shock-tube facility is used as a plasma source. A working medium is a cesium seeded helium gas. The rf electromagnetic field (CW 13.56 MHz, up to 10 kW) is inductively coupled to the generator. Since the electromagnetic led induced by the inductive coupling antennas is azimuthally symmetric, the structure of the plasma excited is desirable for the disk MHD generator. The rf power externally applied to the highly-pressurized gas assists the non-equilibrium ionization. The effect of the rf power is considerable for a wide variety of the seed fraction; from insufficient to excessive via optimum seed fractions.

Keywords—non-equilibrium MHD generator, radiofrequency electromagnetic field, plasma behavior

I. Introduction

Plasma generation is essential issue for on-board MHD power generating or flow controlling MHD systems. The efficiency of enthalpy extraction or enthalpy addition by the MHD depends on the situation of the in-site plasma. Pre-ionization and control of off-designed plasma conditions should be effectively coupled with the main MHD systems.

In the present study, feasibility on a coupling of a radiofrequency (rf) electromagnetic field to a non-equilibrium ionization and an enthalpy extraction in a disk-shaped Hall-type MHD power generator has been examined.

Our previous two-dimensional numerical simulations have been shown that the deterioration of the generator performance attributed to the inflow of the plasma with the low electron temperature and low electrical conductivity to the MHD channel was suppressed by applying the rf inductive coupling electromagnetic field [1-2].

Then, the possibility of improvement in the generator performance of a disk MHD generator by the rf preionization was examined experimentally using a shock-tube facility [3]. The increase in the output power by the rf pre-ionization has been verified and the fact that the rf power triggers the plasma production by the Joule heating attributed to a self-excited electromotive force has been confirmed.

However, in the previous experiment, most attentions were paid to the improvement in the plasma condition suffered by a lack of the electrical conductivity. Therefore, the power generating experiments were operated only under the insufficient seed fraction. In contrast, in the present experiment, the effect of the rf power on the plasma behavior and the generator performance is examined for a wide variety of the seed fraction; from insufficient to excessive via optimum seed fractions.

Generally, an ionization of cesium atoms in an argon gas is easily evolved due to a small collision frequency between electrons and neutral argon atoms. It is proper for the MHD power generation plasma which needs the high electrical conductivity, so that a cesium seeded argon (Ar/Cs) gas was used in the previous experiment. On the other hand, it is well known that an alternative working gas, a cesium seeded helium (He/Cs), is also attractive to realize a high power generating performance. Despite of its larger electron-collision frequency, the helium with a small mass has an advantage to achieve high fluid velocity, which yields high electromotive force. In addition, it is expected for the He/Cs gas to be more stable against electron temperature fluctuations in the plasma because of helium’s high ionizing energy level. Thus, for the present experiments, the He/Cs is used as a working medium for the first time.

II. Experimental Setup

A shock-tube facility is used as a plasma source. The shock-tube driven disk MHD generator consists of a shock tube, a seed supply device, a disk MHD generator, a magnet, and a working gas supply and exhaust system as shown in Fig.1. A Helmholtz type normal conducting pulsed magnet supplies a stable magnetic flux density in the normal direction to the fluid flow in the disk. The density is about 3.0T in the supersonic nozzle region \( r = 85-110 \text{mm} \), and decreases from 3.0T to 0.3T with the radius in the MHD channel region \( r = 110-270 \text{mm} \). The magnet offers the strength for 6 ms which is longer than the generation period of 0.6 ms.
Fig. 1. Schematic view of a shock-tube driven disk MHD generator.

Figure 2 shows (a) the schematic diagram and (b) the channel geometry of the disk generator with the rf inductive coupling coils. The two disk walls of the disk are made of acrylic. The channel consists of the supersonic nozzle region \( (r=85-110\text{mm}) \), the MHD channel region \( (r=110-270\text{mm}) \), and the diffuser region \( (r>270\text{mm}) \). Three rf induction coils (made of copper) to which rf power is supplied are embedded in one side of the walls. Middle radii of the three induction coils are \( r=95.5\text{mm} \) (1st coil), \( r=119.5\text{mm} \) (2nd coil) and \( r=132.5\text{mm} \) (3rd coil), respectively. The 1st coil is located in the supersonic nozzle region, and 2nd and 3rd coils are in the MHD channel region. The rf power supply system consists of a rf power supply (up to 10kW, excitation frequency of 13.56MHz) and a matching network. The aim of the rf pre-ionization is not only the plasma production near the inlet of the MHD channel, but also the stabilization of plasma in the region of MHD channel. Therefore, the rf power is supplied to the most outer 3rd induction coil so as to apply a rf electromagnetic field to the wide region of the MHD channel. The supplied rf power is estimated from the difference between the forward and reflected powers monitored.

There is no anode on the this side of the disk walls. The cathodes are put on each of the two disk walls. These electrodes made of copper are divided in two parts in the azimuthal (\( \theta \)) direction, so as to avoid currents induced there. It is possible to take the photograph of plasma structure by means of a high-speed camera.

Table 1. Experimental conditions of power generation experiments.

<table>
<thead>
<tr>
<th>Working gas</th>
<th>He + Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal input [MW]</td>
<td>3.5</td>
</tr>
<tr>
<td>Stagnation temperature [K]</td>
<td>2250 ± 50</td>
</tr>
<tr>
<td>Inlet stagnation pressure, ( p_{in} ) [MPa]</td>
<td>0.09</td>
</tr>
<tr>
<td>Seed fraction, S.F.</td>
<td>( 1 \times 10^{-4} )</td>
</tr>
<tr>
<td>Magnetic flux density ( r=110-270\text{mm} ) [T]</td>
<td>3.0 - 0.3</td>
</tr>
<tr>
<td>Inlet Mach number</td>
<td>1.7</td>
</tr>
<tr>
<td>Load resistance [( \Omega )]</td>
<td>0.2</td>
</tr>
<tr>
<td>RF power (net) [kW]</td>
<td>6.0</td>
</tr>
<tr>
<td>RF power (net) / Thermal input [%]</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 1 presents the experimental conditions. 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 \( 1 \times 10^{-4} \) by adjusting the temperature in the seed tank. An inlet total pressure (stagnation pressure) is measured at the end wall of the shock-tube. The inlet stagnation pressure is set to 0.09 (±0.005) MPa. The inlet stagnation temperatures are set to 2250 (±50) K. The 1st anode and the 2nd anode are electrically shorted, and the external load resistance of 0.2 to extract the electrical output power is connected between the 2nd anode and the cathode.

III. Results and Discussions

A. Improvement in the generator performance

Figure 3 shows electrical power output as a function of seed fraction of the experiments.
coupled with the rf-power and those without the rf-power. The seed fraction varies in the range of 1-30×10⁻⁷. The net rf input-power is 6 kW.

![Graph showing power output vs seed fraction with and without rf-power.](image)

**Fig.3.** Electrical power output as a function of seed fraction of the experiments coupled with the rf-power and those without the rf-power.

It is seen from Fig.3 that the power output is improved by applying the rf electromagnetic field for the entire seed fraction region. The improvement is considerable under the insufficient seed fraction. Without the rf assist, the power output is almost zero, while power output of 67 kW is obtained by applying the rf power of 6kW for the seed fraction of 6×10⁻⁴.

Maximum power output of 219 kW is achieved for the optimum seed fraction of 9.8×10⁻⁴ in the rf assist-case, which is significantly higher than that of 157 kW obtained in the experiments without rf power. This increase of the peak power output (62 kW) is one orders of magnitude larger than the supplied rf power (6 kW). It can be also seen that this peak performance is shifted to lower seed fraction; the seed fraction of 15×10⁻⁴ which is required for the conventional experiment is reduced to 9.8×10⁻⁴ by using the rf power. It implies that the additional Joule heating due to the rf power effectively evolved the nonequilibrium ionization to obtain suitable electrical conductivity even for the lower seed fraction.

Although the seed fraction of 14-15×10⁻⁴ is not suitable for the power generation coupled with the rf power but optimum for that without the rf power, the improvement in the performance can be seen under the excessive seed fraction.

### B. Plasma behavior

Figures 4(a) and (b) show the photographs taken though the acrylic disk from the direction being against to the shock-tube. The region of less than r=175 mm is given in the picture. A center and a part of right-hand side are hidden by the 1st anode and a beam, respectively. The bright appearance in the photograph is caused by higher cesium ion density of these region with respect to the rest of the structure except a brightly reflecting 2nd-anode ring which can be recognized between 1st and 2nd coils. An expose time of the camera is about 8.3 μs. Assuming a radial flow velocity of 2000-3000 m/s, the fluid is supposed to flow in a distance of about 16.6-27.6 mm during the expose time, which limits a spatial resolution (around 1/3-1/5 in the radial direction of the photographs).

**Insufficient fraction (∼6×10⁻⁴)**

(a) w/o RF power (b) with RF power

![Photographs of discharge structure under the condition of insufficient seed fraction of around 6×10⁻⁴.](image)

**Fig.4.** Photographs of discharge structure under the condition of insufficient seed fraction of around 6×10⁻⁴.

(a) experiment without the rf power. (b) experiment coupled with the rf power.

Without the rf assist, the discharge structure is not uniform in the azimuthal direction as shown in Fig. 4(a), under the insufficient seed fraction of around 6×10⁻⁴. The non-uniform plasma structure results in poor generator performance as indicated in Fig.3. In contrast, when the rf power applied to the generator, the structure of the plasma becomes more symmetric as shown in Fig. 4(b). It is confirmed that since the electromagnetic field induced by the inductive coupling antennas is azimuthally symmetric, the structure of the plasma excited is desirable for the disk MHD generator. But even if the rf power is applied, the plasma is not so bright because the self exciting joule heating is insufficient due to a lack of enough cesium atoms.

Figure 5 is taken when the highest power output of 219 kW is obtained by coupling the rf power to the power generation. Since the seed fraction is optimum one, the plasma becomes quite uniform. Although the rf antenna is located in the MHD channel region (3rd coils), the nonequilibrium ionization is evolved in the upstream supersonic nozzle, then high ionization degree of cesium is kept in the channel.
Figure 5. Photograph of discharge structure coupled with the rf power under the optimum seed fraction of $9.8 \times 10^{-4}$

(a) optimum SF $15 \times 10^{-4}$ for w/o RF power

(b) excessive SF $14 \times 10^{-4}$ for RF –assist case

Figure 6. Photographs of discharge structure. (a) optimum seed fraction of $15 \times 10^{-4}$ for the experiment without the rf power. (b) excessive seed fraction of $14 \times 10^{-4}$ for the experiment coupled with the rf power.

Figure 6(a) shows the discharge structure under the optimum seed fraction of $15 \times 10^{-4}$ for the experiment without the rf power in detail. It is seen that the plasma is perturbed by bright layers results from a growth of an ionization instability caused by the excessive seed injection. This result suggests that the generator performance can not be recovered only by the increase in the seed fraction as long as the seed material is effectively ionized by the suitable Joule heating. Contrary, as implied from Fig. 6(b), the plasma behavior strongly suffered by the ionization instability is stabilized by the rf power. Although the improvement in the power output under the high seed fraction (more than $14 \times 10^{-4}$) is not significant even by applying the rf power because of a miss-matching between electrical conductivity and load resistance, the effect of plasma stabilization is verified.

IV. Conclusions

Power generation experiments of the nonequilibrium disk MHD generator have been conducted to investigate effects of the coupling of the rf electromagnetic field to non-equilibrium ionization and enthalpy extraction. The power generating performance is successfully improved by the rf power over the wide range of seed fraction; from insufficient to excessive via optimum seed fractions.

1. By coupling the rf power of 6 kW to the MHD power generation, the peak power output significantly increased from 157 kW to 219 kW. In other word, a peak enthalpy extraction ratio (= [power output]/[thermal input]) is improved from 4.5 % to 6.3 % by employing a tiny rf energy addition ratio of 0.16 % (= [supplied rf power]/[thermal input]).

2. The rf power externally applied assists the nonequilibrium ionization. The effect of the pre-ionization is considerable under the condition of from insufficient to optimum seed fraction. As a result, the peak generator performance is shifted to the lower seed fraction.

3. The rf power effects even for the excessive seed injection. The ionization instability caused by the insufficient Joule heating is suppressed by the rf electromagnetic field, so as to maintain the symmetric plasma structure.

References

