High-Enthalpy Extraction Experiments with Disk MHD Generators*

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Power generation experiments have been performed for disk MHD generators with different channel shapes. The increase in the enthalpy extraction ratio by enlargement of the area ratio has been shown experimentally, and the highest enthalpy extraction ratio of 18.0% was achieved. The experimental results have shown that for the generator with the large area ratio, the wall static pressure in the MHD channel is kept lower than that for the small-area-ratio generator. These phenomena suggest that a high Hall parameter is obtained by enlargement of the area ratio. Furthermore, the swirl ratio at the channel exit was measured and was characterized by the ratio between Hall current and mass flow rate of the working gas.

Key Words: MHD Power Generation, Supersonic Flow, Magnetohydrodynamics, Disk MHD Generator, Area Ratio, Swirl

1. Introduction

An energy conversion device that utilizes the continuous motion of an electrically conducting fluid in a magnetic field is referred to as a magnetohydrodynamic (MHD) electrical power generator. For the disk-shaped Hall-type MHD generator, in particular, the Hall effect plays a dominant role in the

extraction of electrical current⁽¹⁾. Therefore, the Hall parameter and the working gas velocity are important physical quantities that determine a generator's performance, and it is necessary to achieve high values for these quantities by accelerating the working gas flow to supersonic flow. However, a large surface-to-volume ratio of the disk-shaped channel and a strong Lorentz force, which acts so as to cause break-up of the fluid flow, give rise to an unfavorable reduction of the working gas velocity^{(2),(3)}. The authors have thus so far experimentally determined that an increase in the channel area ratio suppresses the pressure rise in the MHD channel and leads to high energy conversion efficiency⁽⁴⁾.

In the present paper, in order to demonstrate the high performance of the MHD generator, the effects of the fluid-dynamical properties on power generation performance are experimentally investigated using disk-shaped generators with larger channel cross-sectional area ratio than the previous one, installed in a blow-down facility.

Nomenclature

A^* : Channel cross-sectional area at throat

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Fig. 1 Schematic cross sectional view along the radial direction of the disk MHD generator

Fig. 2 Variation of the channel cross-sectional area ratio along the radial direction

- A : Channel cross-sectional area
 B : Magnetic flux density
 E : Electric field
 e : Elementary electric charge
 I : Current
 J : Current density
 k : Boltzmann constant
 M : Mach number
 $\dot{m}$: Mass flow rate
 m_e : Mass of electron
 m_j : Mass of j -th particle (j represents the seed atoms and noble gas atoms)
 n_e : Electron number density
 p : Static gas pressure
 p_0 : Stagnation gas pressure
 r : Radius
 S. F. : Seed fraction
 T_e : Electron temperature
 T_g : Static gas temperature
 T_0 : Stagnation gas temperature
 u : Gas velocity

- V : Voltage
 β : Electron Hall parameter
 γ : Ratio of the specific heat
 $\bar{\nu}_{e-j}$: Average collision frequency for electrons with j -th particles
 ρ : Mass density of the working gas
 σ : Electrical conductivity
 Subscripts
 in : Inlet of the MHD channel
 out : Outlet of the MHD channel
 r : r -component
 θ : θ -component
 H : Hall-component

2. Experimental Apparatus and Procedure

The experiments were conducted using the blow-down facility described in Refs. 2 and 4. In the present experiments, to obtain nonequilibrium plasma, we used cesium-seeded argon as a working gas. The argon gas is heated up to about 2 000 K by the regenerative heat exchanger and is mixed with small concentrations of cesium (this process is called "seeding"), and then heated working gas flows through the disk MHD generator when the energy is extracted directly in the form of electric energy.

Two types of disk generators, called DISK-F3a and DISK-F3r, were used. Their cross-sectional configurations are shown in Fig. 1 with the principal dimensions. Figure 2 gives the channel cross-sectional area ratio A/A^* as a function of radial direction. The locations of the nozzle throat ($r=90$ mm) and four pairs of electrodes are kept constant between the two generators. However, they have a different height at the channel inlet ($r=160$ mm) and exit ($r=380$ mm); thus the area ratio of the channel exit to the inlet increases from 4.1 for DISK-F3a to 6.9 for

DISK-F3r. A single external load resistance is connected between the second anode (A 2) and the second cathode (C 2); therefore the region between these two electrodes ($160\text{mm} \leq r \leq 380\text{mm}$) is defined as the MHD channel.

The experimental conditions are summarized in Table 1. It must be noted that the input enthalpy (thermal input) to the DISK-F3r generator was smaller than that to the DISK-F3a generator due to the smaller cross-sectional area at the throat and operation under a slightly lower stagnation pressure for the DISK-F3r generator.

3. Experimental Results and Discussion

3.1 Flow behavior without magnetic field

To confirm the basis for supersonic flow in a disk-shaped channel, we first considered the experimental results in the absence of a magnetic field under the same stagnation conditions as power generation experiments. Figure 3 shows a comparison of the wall static pressure distribution along the radial direction for DISK-F3a and that for DISK-F3r. In this figure,

Table 1 Experimental conditions

MHD channel	DISK-F3a	DISK-F3r
Working gas	Ar + Cs	Ar + Cs
Stagnation gas temperature (K)	1850	1950
Stagnation gas pressure (MPa)	0.46	0.41
Thermal input (MW)	2.60	1.65
Seed fraction	$2.0 \sim 3.0 \times 10^{-4}$	$1.0 \sim 5.0 \times 10^{-4}$
Load resistance (Ω)	0.051 ~ 2.5	0.31, 0.51, 0.82
Magnetic flux density (T)	4.4 (inlet) ~ 2.7 (exit)

Fig. 3 Wall static pressure distributions without MHD interaction

the pressure distributions, which are calculated by the quasi-one-dimensional model taking into account the back pressure condition⁽⁵⁾, are also described. For both generators, the static pressure decreases along the radial direction to the midstream of the channel, and it increases in the region from the midstream to the downstream of the channel. Since this increase in static pressure is much smaller than the pressure increase through the normal shock calculated by the quasi-one-dimensional model, it is suggested that the pressure recovery mechanism is different from the pressure rise through the normal shock wave.

Yamane et al.⁽⁶⁾ investigated the shock wave behavior in radial supersonic flow, and clarified that the static pressure increases gradually by pseudo-shock waves in the disk-shaped channel. They also reported that, when the Mach number just ahead of the pressure rise becomes more than 1.85, the structure of the pseudo-shock waves shifts from λ -type to X -type, and then the length of the pseudo-shock waves reaches about 4 or 5 times the channel height. In the present experiments, the Mach number at the beginning of the pressure rise is calculated to be in the range of 3.8 to 4.1, which is obtained from the static pressure and upstream stagnation pressure, using the isentropic relationship, and the length of the pseudo-shock waves can be estimated to be about 10 times the channel height. Here, we defined the end of the pseudo-shock waves in the experiment as the end of the pressure rise obtained by the quasi-one-dimensional calculations. Although we cannot find any information for the case of higher Mach number in Ref. (6), from the shape of the static pressure distributions and the length of the pressure rise region, it is suggested that the pseudo-shock waves and the boundary layer separation are formed in the present experiments.

Moreover, we can see from Fig. 3 that the increase in static pressure for DISK-F3r begins at $r = 295$ mm, which is an upstream point compared with $r = 325$ mm for DISK-F3a. This tendency is obtained through the calculation, and it is found that it becomes easy to accelerate the working gas in the channel with enlargement of the channel area ratio.

3.2 Electrical output power and voltage-current characteristics

When a magnetic field is applied to the generator, i. e., in the case of power generation experiments, we also expect that an increase in the channel area ratio will improve the power generation performance. To elucidate this point, we investigated the relationship between fluid-dynamical properties and electrical ones, and discuss the influences of channel area ratio on power generation performance.

As summarized in Table 1, in the experiment with

the DISK-F3a generator, two seed fraction values of about 2.0×10^{-4} (in the first half-period) and 3.0×10^{-4} (in the latter half-period) were examined, and the external load resistance was changed stepwise in the range from 0.051Ω to 2.5Ω every 2 seconds in each period. On the other hand, in the experiment with the DISK-F3r generator, the seed fraction was changed continuously in the range from 1.0×10^{-4} to 5.0×10^{-4} for three values of load resistances of 0.031Ω , 0.51Ω and 0.82Ω . Thus, the experimental results obtained from both generators are compared here for two kinds of seed fractions ($S.F. = 2.0 \times 10^{-4}$, 3.0×10^{-4}).

As a typical example of the power generation characteristics, the enthalpy extraction ratio against the external load resistance and the Hall voltage - Hall current characteristics are shown in Figs. 4 and 5, respectively. The enthalpy extraction ratio is an important efficiency to estimate the performance of the MHD generator, and is defined as the ratio of the change in total enthalpy due to electric power generation to the thermal input.

It can be seen from Fig. 4 that the maximum enthalpy extraction ratio of 18.0 % for the DISK-F3r generator was achieved under the higher seed fraction of 3.0×10^{-4} . This value of 18.0 % is the highest enthalpy extraction ratio in the experiments on non-equilibrium disk MHD generators using a blow-down facility. In contrast to the case of DISK-F3r generator, the maximum enthalpy extraction ratio for the DISK-F3a generator was obtained under the lower seed fraction of 2.0×10^{-4} . We should note that the enthalpy extraction curves for DISK-F3a are less sharp than those for DISK-F3r.

Figure 5 also shows clearly the difference in the power generation performance between the two generators. We can see the linear voltage-current characteristics for DISK-F3a at both seed fractions. It is obvious from the electrical matching between an

Fig. 4 Enthalpy extraction ratio against external load resistances for the two types of disk MHD generators

external load resistance and an MHD generator that the gradient of a voltage-current characteristic corresponds to the internal resistance of plasma. Therefore, the linear voltage-current characteristics in Fig. 5 show that the internal resistance of plasma in the DISK-F3a generator is kept almost constant for all values of the external load resistance. In the case of the DISK-F3r generator, gradients of the voltage-current characteristics differ between higher and lower load resistances. The above-mentioned characteristics show that enlargement of the channel cross-sectional area ratio provides the possibility of elevating the generator performance under the strong MHD interaction which occurs under the condition of a high seed fraction.

3.3 Wall static pressure distribution under MHD interaction

Figure 6 shows the wall static pressure distributions in the DISK-F3a generator. Measurement data in the region from the throat to A2 are in good agreement with isentropic values, but at the downstream

Fig. 5 Hall voltage-Hall current characteristics for the two types of disk MHD generators

Fig. 6 Wall static pressure distributions with MHD interaction for DISK-F3a generator

part of A2, static pressure increases sharply at a short distance from the channel inlet ($140\text{ mm} < r < 200\text{ mm}$), and the absolute values of the static pressure for S. F. $= 3.0 \times 10^{-4}$ are higher than those for S. F. $= 2.0 \times 10^{-4}$. The explanation for these results is that the increase in electron number density with the seed fraction produces a stronger Lorentz force $J_e B$, which acts upon the working gas as a retarding force.

Figure 7 shows the wall static pressure distributions in the DISK-F3r generator. It can also be seen that working gas expands along the isentropic pressure curve in the region from the throat to A2, the pressure rises near the inlet of the MHD channel, and the absolute values of the static pressure for S. F. $= 3.0 \times 10^{-4}$ are higher than those for S. F. $= 2.0 \times 10^{-4}$. From a comparison between Fig. 6 and Fig. 7, however, it can be seen that the magnitude of the pressure gradients at the channel inlet for the DISK-F3r generator becomes smaller than that for the DISK-F3a generator. When we denote the static pressure gradient in the region of $145\text{ mm} \leq r \leq 180\text{ mm}$ by dp/dr , it is found that, in the case of S. F. $= 3.0 \times 10^{-4}$, the inlet pressure gradient for DISK-F3r ($dp/dr = -0.022\text{ MPa/m}$) takes a lower value than that for DISK-F3a ($dp/dr = -0.52\text{ MPa/m}$), and in the case of S. F. $= 2.0 \times 10^{-4}$, that for DISK-F3r ($dp/dr = -0.28\text{ MPa/m}$) also takes a lower value than that for DISK-F3a ($dp/dr = 0.14\text{ MPa/m}$).

3.4 Hall potential distributions

We have shown in the previous section that a variation of the channel area ratio affects the wall static pressure distributions for both $B=0$ and $B \neq 0$. In this section, we shall discuss the influences of enlargement of the channel area ratio on electrical property.

Hall potential distributions along the radial direc-

Fig. 7 Wall static pressure distributions with MHD interaction for DISK-F3r generator

tion of DISK-F3a are shown in Fig. 8 for the two kinds of seed fractions. As shown in this figure, in the upstream region of C1, almost the same distributions are measured for both seed fractions, but in the downstream region of C1, the Hall potential for S. F. $= 2.0 \times 10^{-4}$ is higher than that for S. F. $= 3.0 \times 10^{-4}$. Using a "generalized Ohm's law", which describes the dependence of the current density on the electric field and fluid properties, the Hall electric field E_r can be written in the form

$$\frac{dV_H}{dr} = -E_r = \beta u_r B - \frac{1 + \beta^2}{\sigma} J_r. \quad (1)$$

This equation states that, in order to realize a sufficiently high Hall electric field, the Hall electromotive force $\beta u_r B$ must be large compared with the voltage drop due to the internal resistance of plasma which is given by the second term on the right-hand side of Eq. (1). The increase in electrical conductivity σ with the seed fraction gives rise to a strong Lorentz force, and consequently, static pressure increases and the Hall parameter β , which is inversely proportional to the number density of the working gas, decreases. Thus, a decrease in the Hall parameter and gas velocity with an increase in the seed fraction, which is suggested from the pressure behavior in Fig. 6, lowers the Hall potential in the region from C1 to C2 of the DISK-F3a generator, as shown in Fig. 8. It is found from the above consideration that the DISK-F3a generator can generate non-equilibrium plasma with high electrical conductivity at the channel inlet, but it does not have a large enough channel area ratio to reduce deceleration of the working gas flow with an increase in the seed fraction.

Fig. 8 Hall potential distributions along the radial direction for DISK-F3a generator

Figure 9 shows the measurement results of Hall potential distributions along the radial direction of the DISK-F3r generator. Comparing it with Fig. 8, we can see that the Hall electric field E_r near the channel inlet of the DISK-F3r generator is reduced compared with that of the DISK-F3a generator. In the DISK-F3a generator, the difference between the two Hall potential distributions for S.F. = 2.0×10^{-4} and S.F. = 3.0×10^{-4} appears only in the downstream part of C1, as seen in Fig. 8, while in the DISK-F3r generator, the Hall electric field for the case of S.F. = 2.0×10^{-4} reduces just behind A2 (160 mm $\leq r \leq 200$ mm), and downstream from that region ($r \geq 200$ mm) it reaches almost the same electric field strength for the case of S.F. = 3.0×10^{-4} . Therefore, the seed fraction must be increased to obtain high electrical conductivity in the DISK-F3r generator, and then we should note that an unfavorable pressure rise can be suppressed due to the larger channel area ratio of DISK-F3r as compared to DISK-F3a.

3.5 Consideration of channel shape

The function of a supersonic nozzle of a Hall-type MHD generator is not only to accelerate a stream to some desired final Mach number but also to generate a nonequilibrium plasma that has sufficiently high electrical conductivity. This nonequilibrium ionization occurs because the joule dissipation feeds energy into electrons during expansion of the working gas through the supersonic nozzle. In this ionization process, the rate at which electrons gain energy per unit volume from the electric field through the nozzle is balanced by a loss of energy to heavy particles in elastic collisions, and this relationship is given by the following expression:

Fig. 9 Hall potential distributions along the radial direction for DISK-F3r generator

$$\frac{|J|^2}{\sigma} = 3n_e k (T_e - T_g) \sum_j \frac{m_e}{m_j} \bar{v}_{e-j} \quad (2)$$

Employing the loading parameter $K_H = -E_r/(\beta u_r B)$, and substituting it into Eq. (2), we obtain, after rearrangement⁽⁷⁾,

$$\frac{T_e}{T_g} = 1 + \frac{\gamma(1 + \beta^2 K_H^2)}{3} \frac{\beta^2}{1 + \beta^2} M^2. \quad (3)$$

This equation, based on the energy balance, makes it clear that high Mach numbers and high Hall parameters are desirable for nonequilibrium MHD generators that require high electron temperature, and to realize such situations it is necessary to lower the working gas pressure throughout the supersonic nozzle.

The present experiments were performed under the inlet Mach number conditions of $M = 2.5$ for DISK-F3a and $M = 2.3$ for DISK-F3r. Accordingly, as listed in Table 1, the experiment with the DISK-F3r generator was carried out under a lower stagnation pressure, to promote joule heating. As seen in Fig. 9, however, the seed fraction of 3.0×10^{-4} , which is higher than the optimum seed fraction of 2.0×10^{-4} for the case of the DISK-F3a generator, was required to obtain enough electrical conductivity in the DISK-F3r generator. Moreover, as is apparent from Fig. 7, the pressure rise due to the Lorentz force is suppressed near the channel inlet and static pressure is kept lower in the region from the anode to the diffuser, by increasing the area ratio of DISK-F3r. It is well known that the situation of low pressure causing a high Hall parameter is suitable for a Hall-type disk MHD generator.

On the other hand, at the channel inlet of the DISK-F3a generator, nonequilibrium plasma can be obtained, and it is estimated to have a high electrical conductivity compared with that at the channel inlet of DISK-F3r. In the downstream region of the MHD channel, however, the electrical motive force does not become large enough to maintain the same strength of the Hall electric field as that in the upstream region of the channel, because of the smaller area ratio of the DISK-F3a generator. We can conclude that it is important to design a Mach number in the supersonic nozzle that is high enough to produce sufficient electrical conductivity, and to design a channel cross-sectional area ratio that is large enough to maintain low pressure in the MHD channel.

3.6 Swirl at exit of MHD channel

As mentioned elsewhere in this paper, the Lorentz force along the radial direction which is caused by the interaction of J_θ with B decelerates a working gas flow to low velocity in the MHD channel. On the other hand, the azimuthal Lorentz force of $J_r B$ acting on the radial current induces the swirl in the MHD channel.

Since the gas velocity is an important physical quantity which is directly relative to the

Fig. 10 Swirl ratio at the MHD channel exit against Hall current

Fig. 11 Swirl ratio at the MHD channel exit against characteristic property of $I_H/\dot{m}$

electromotive force of the MHD generator⁽⁸⁾, it is necessary to obtain information on each component of the gas velocity under the MHD interaction. Taking into account this situation, in the present experiments, we estimated the swirl ratio of $-u_r/u_\theta$ at the channel exit from the data of the pressure distribution measured with a vane-shaped pressure probe. This probe has a cylindrical surface that faces the gas flow, and several pressure holes with uniform spacing are arranged on the cylindrical surface, to determine stagnation pressure and flow direction⁽²⁾.

The measurements of the swirl ratio are plotted against the Hall current in Fig. 10. It is clear from this figure that the swirl ratio increases with Hall current for both generators. We can consider that the increase in the swirl ratio is caused by the decrease in u_r or the increase in u_θ . The latter effect of u_θ can be judged by solving the angular momentum equation:

$$\rho u_r \frac{du_\theta}{dr} + \frac{\rho u_r u_\theta}{r} = -J_r B. \quad (4)$$

Integration of Eq. (4) yields the following expression:

$$u_\theta = -\frac{I_H B}{2\dot{m}} \cdot r + \frac{C_0}{r}, \quad (5)$$

where C_0 is the constant determined by the boundary condition of u_θ . In obtaining Eq. (5), we assumed that the magnetic field takes a constant value along the radial direction for simplicity, which will not limit the following discussion. Equation (5) indicates that, when Hall current I_H is large, which means increase in the azimuthal component of Lorentz force, or mass flow rate $\dot{m}$, i.e., momentum of the working gas is small, u_θ becomes large. Therefore, the investigation of the relationship between the characteristic property of $I_H/\dot{m}$ and swirl ratio would explain the effect of changes in u_θ on variation in swirl ratio.

Figure 11 is constructed by plotting the swirl ratio for different kinds of mass flow rate against the characteristic property of $I_H/\dot{m}$. In the range of $0 < I_H/\dot{m} < 400$, the swirl ratio shows linear dependence on $I_H/\dot{m}$. Thus, it is suggested that, concerning variations of swirl ratio, change in u_θ becomes quite significant relative to change in u_r under operating conditions represented by the above range of $I_H/\dot{m}$.

4. Conclusions

Power generation experiments with disk-shaped MHD generators were carried out to investigate the effects of channel cross-sectional area ratio on power generation performance. The experimental results lead to the following notable conclusions:

- (1) Increase in the enthalpy extraction ratio and suppression of the pressure rise in the MHD channel due to enlargement of the channel cross-sectional area ratio were shown experimentally.
- (2) The experimental results suggested that it is necessary to design a Mach number that is high enough to produce high electrical conductivity in the supersonic nozzle, and to design a channel cross-sectional area ratio that is large enough to maintain low pressure in the MHD channel.
- (3) It was clarified that the effect of changes in the azimuthal component of velocity on variations of swirl ratio is characterized by the ratio of the Hall current to the mass flow rate of the working gas.

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