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HIGH ENTHALPY EXTRACTION DEMONSTRATION WITH CLOSED CYCLE DISK MHD GENERATORS

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ABSTRACT

Recent results of high enthalpy extraction experiments with closed cycle MHD disk generators at Tokyo Institute of Technology were described. Power generation experiments were carried out with two types of facilities; the shock tube facility with the Disk-IV generator and the FUJI-1 blow-down facility.

In the shock tube experiments, the effects of channel shape on generator performances were studied using helium seeded with cesium as working fluid. More divergent channel shape was effective to sustain high Hall field throughout the channel. The high enthalpy extraction of 27.3% was achieved. Furthermore, these experimental results agreed well with the results of one-dimensional calculations.

In the FUJI-1 blow-down experiments, the effects of stagnation gas pressure on the performances were studied with a working gas of seeded argon. The highest enthalpy extraction ratio of 15.7% was achieved with the lower stagnation pressure of 0.46MPa, whereas the largest output power of 516.7MW and power density of $70 MW/m^3$ were extracted with the nominal stagnation pressure of 0.6MPa. This suggested the possibility of a part load operation without significant degradation of generator performance by reducing stagnation pressure.

INTRODUCTION

Performances of a closed cycle disk MHD generator have been studied using both the shock tube facility [1,2] and the FUJI-1 blow-down facility [3,4] at Tokyo Institute of Technology. The main purpose of these experimental studies is to achieve sufficient enthalpy extraction with a disk generator under the conditions of fully ionized seed.

In the shock tube experiments, high enthalpy extraction ratio of over 20% was achieved for the stagnation temperature of around 2000K using helium seeded with cesium as a working gas.[1] The experimental results showed good agreement with the results of one-dimensional calculation. It is indicated that the strong deceleration by Lorentz force resulted in the decrease of Hall field in the downstream part of channel.[2] Furthermore, it is suggested by the numerical prediction that the use of more divergent channel geometry was effective to reduce the bad effects of flow deceleration.

In this paper, the effects of channel geometry on generator performances are studied experimentally using the new disk generator with more divergent channel shape than the previous Disk-III generator.

So far, a series of power generation experiments have been conducted with the disk generators, DISK-F2 and DISK-F3, in the FUJI-1 blow-down experiments. In RUN619 (June 1988), the output power of the DISK-F2 generator was increased up to 240kW and the enthalpy extraction ratio reached 7.3% using cesium seeded argon as a working gas.[3] However the results suggested that the performance of the DISK-F2 generator was limited by insufficient channel geometry. In order to improve generator performances, the new DISK-F3 generator with large area ratio of the exit cross section to the inlet was installed in July 1988, and then a series of power extraction experiments were carried out (RUN6202-6207). Remarkable increase in both output power and power density was obtained and the enthalpy extraction ratio was improved up to 15% with the reduced stagnation pressure.[4,5]

The new generator DISK-F3a, which has more larger area ratio than the DISK-F3, has been installed in the FUJI-1 facility and power generation experiments (RUN6208-6210) are performed to study the effect of stagnation gas pressure on the performances in October 1989. Results are described in the present paper.

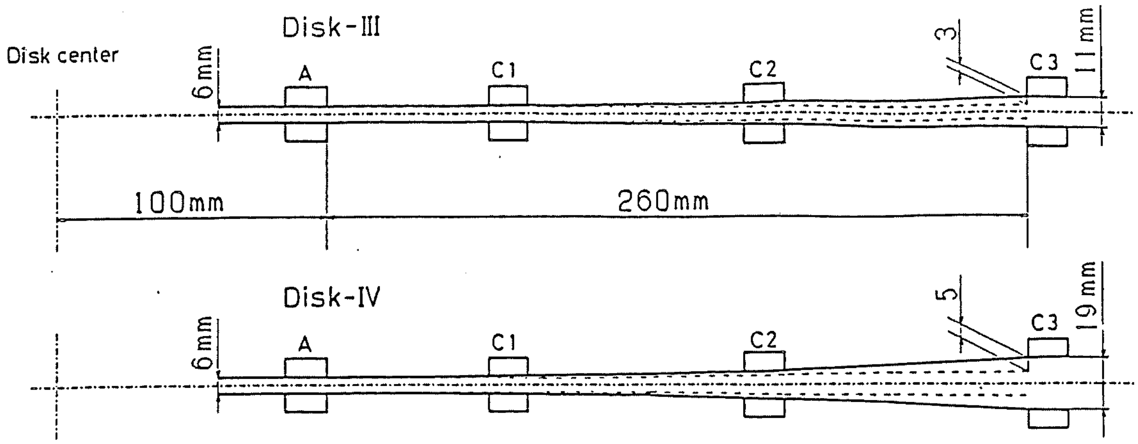

Fig.1 Schematic cross sectional view of the Disk-III and Disk-IV generator.

SHOCK TUBE EXPERIMENTS

Experimental set up and conditions

In a series of shock tube experiments, the effects of channel geometry on generator performances have been studied in detail. The new disk generator channel "Disk-IV" was installed in the T.I.T. shock tube facility. The cross sectional view of the Disk-III and the Disk-IV channel are shown in Fig.1, where the actual channel shape is shown by solid line and the effective one, which is used in the numerical calculations, is shown by dashed line. The effective channel height is calculated by subtracting the displacement thickness of boundary layer from the actual channel height. This displacement thickness is assumed to be 0.5mm at the inlet of both channel, 3mm at the exit of the Disk-III and 5mm at the exit of the Disk-IV channel according to the measured static pressure distribution and to the results of r-z plane 2-dimensional calculation.[6] The shape of the new Disk-IV channel shows to be more divergent than the previous Disk-III channel especially in the downstream part so that the effects of gas flow deceleration due to an MHD interaction is expected to be reduced.

Figure 2 shows the output power and the enthalpy extraction ratio predicted by the one-dimensional calculation using the effective channel shape. The procedures and the basic equations are presented in Ref.[2,7]. It can be seen clearly from this figure that, for the case of Disk-IV channel with the more divergent channel shape, the output power and the enthalpy extraction ratio become significantly increased, and the latter reaches over 30%. The value of a load resistance, which gives the peak output power, shifts to a larger value. These results are ascribed to the increase of Hall electromotive force owing to the reduction of flow deceleration effect and the increase of a Hall parameter.

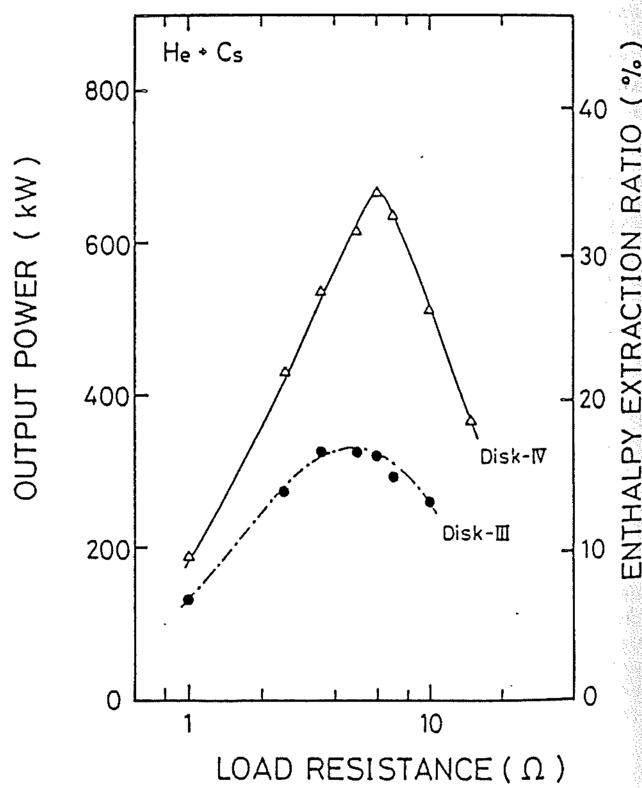

Fig.2 Calculated output power and enthalpy extraction ratio vs. load resistance for the Disk-III and Disk-IV generator.

Experimental conditions are shown in Table 1. Helium seeded with cesium is used as working medium. The stagnation temperature is in the neighborhood of 2000K, which is expected to be in a closed cycle MHD commercial plant. Seed fraction is kept in the order of 10^{-4}.

Table 1 Experimental conditions for the shock tube experiments.

Channel	Disk-IV
Working gas	He + Cs
Stagnation gas temperature(K)	1950 ~ 2100
Stagnation gas pressure (MPa)	0.25 ~ 0.28
Thermal input(MW)	1.9 ~ 2.1
Seed fraction	1×10^{-4}
Magnetic field strebgth (T)	2.6 ~ 1.8
Load resistance(Ω)	1.0 ~ 15.0

Experimental results

Power generation experiments have been carried out by changing the external load resistance in the range of 1 Ω ∿ 15 Ω, and results were compared with the results obtained by the Disk-III generator. The HAll voltage-Hall current characteristics are shown in Fig.3. Obtained electrical output power and enthalpy extraction ratio are plotted in Fig.4 against the external load resistance. In these figures, open circles show the results with the Disk-IV channel.

We can see the substantial increase in output power and enthalpy extraction ratio in the range of load resistance 2.5 Ω ∿ 7.0 Ω for the case of the Disk-IV channel. Especially for the load resistance of 3.5 Ω, the highest output power of 510kW and the corresponding enthalpy extraction ratio of 27.3% are achieved. The more divergent channel shape of Disk-IV results in these substantially higher values than the case of Disk-III channel. It can also be seen that the value of load resistance which yields the peak output power sifts to larger value 3.5 Ω ∿ 5 Ω compared to 2.5 Ω in the case of Disk-III. These results agree qualitatively well with the calculated ones shown in Fig.2. Quantitative discrepancy, however, still exists between them. The main cause for this discrepancy is considered to be insufficient prediction of a boundary layer thickness.

Hall Potential Distribution

Typical Hall potential distribution along the radial direction for the load resistances of 1.0 Ω, 2.5 Ω and 7.0 Ω are shown in Fig.5, where the results with the Disk-III channel are also shown by dashed lines. It is evident on comparing those two cases that high Hall field can be sustained even in the downstream part of a channel for the case of Disk-IV generator. For the case of smaller load resistance of 1.0 Ω, the negative Hall

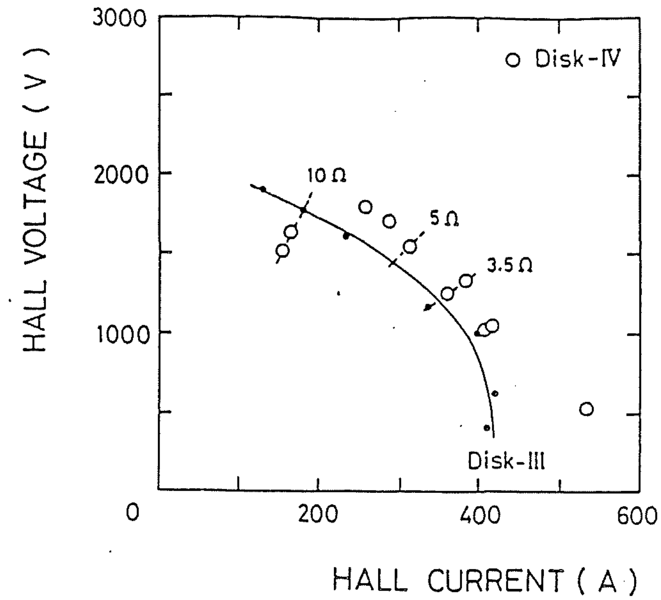

Fig.3 Hall voltage-Hall current characteristic of the Disk-IV generator.

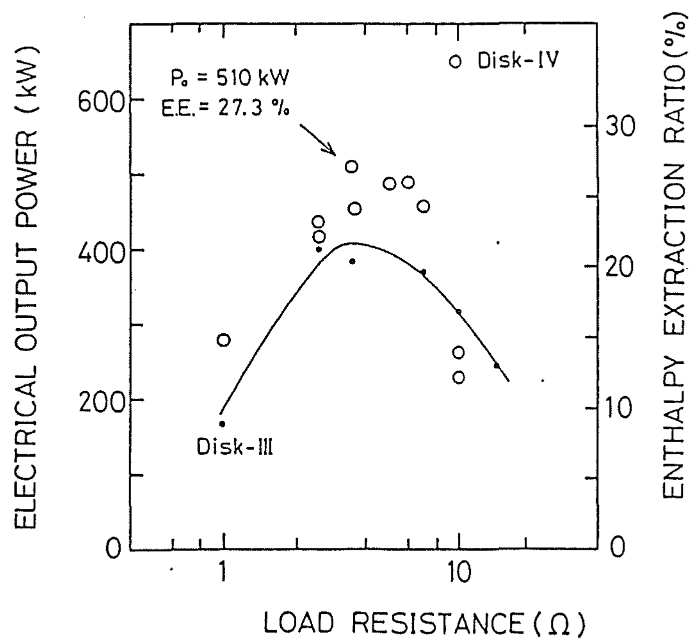

Fig.4 Output power and enthalpy extraction ratio vs. load resistance.

potential region appears near the anode because of the lower electrical conductivity owing to the small Joule heating of electrons.

Comparison of the experimental results with calculated results of a Hall potential distribution are shown in Fig.6. Experimental results agree quite well with the calculated ones for all load resistances.

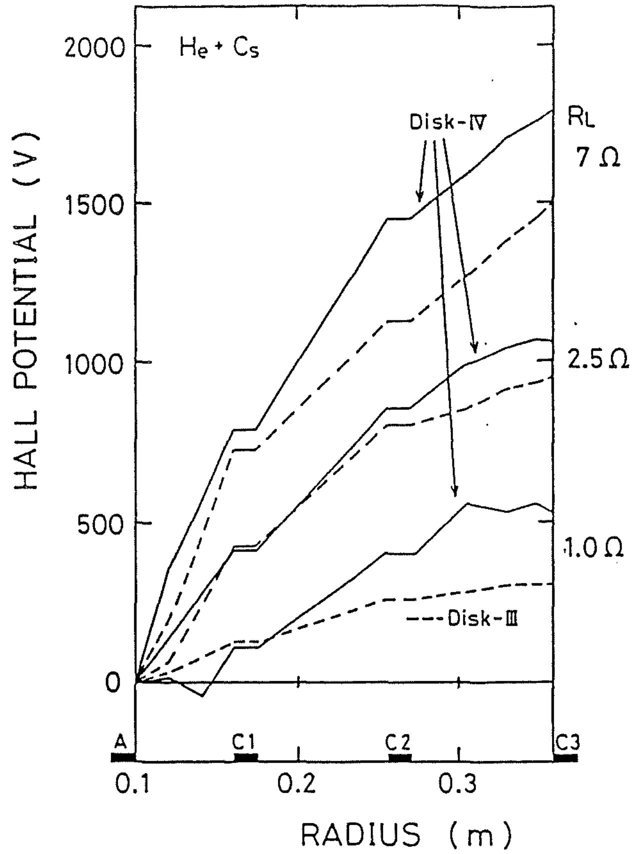

Fig.5 Hall potential distributions for the load resistances of 1.0, 2.5 and 7Ω.

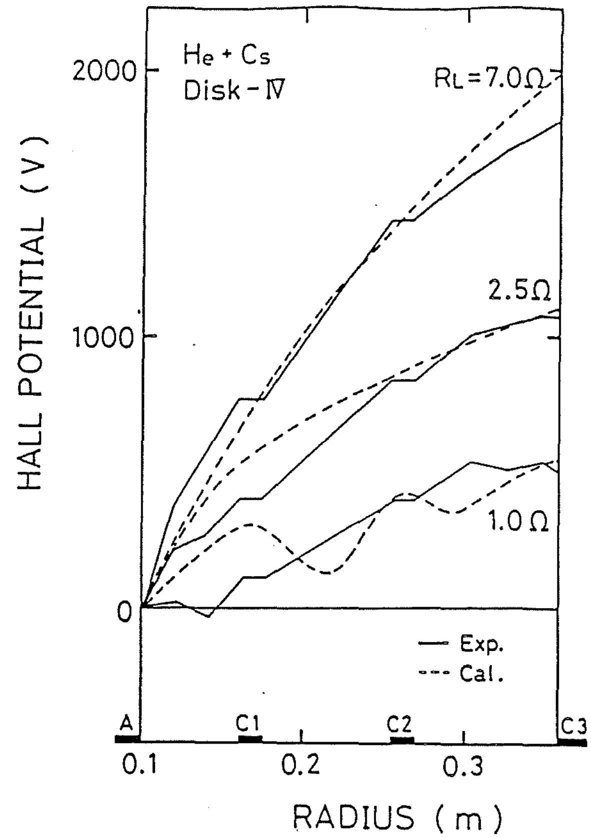

Fig.6 Comparison of measured Hall potential distributions with calculated ones.

When the load resistance is 1.0Ω, the calculated result looks wave-like distribution. We can consider that the ionization instability prevails in the channel, and the plasma becomes separated into two phases; a power generating plasma with a positive gradient of Hall potential and a power consuming plasma with a negative gradient. In the experiment, such negative gradient part can be seen near anode where the electrical conductivity is still low due to small Joule heating. If the two-dimensional effect can be taken into account, the agreement is expected to be improved.

<u>Gas Velocity</u>

Figure 7 shows the variation of gas velocity in the radial direction for external loads of 2.5 Ω and 10 Ω together with the calculated ones which is shown by dashed lines. The radial component of gas velocity is estimated so-called correlation method; the distance between certain two different positions of measurement divided by the delay time which gives the maximum value of correlation function between these two signals. The larger load resistance results in the stronger effect of flow deceleration because of the stronger interaction between the flow field and the electromagnetic field. The present results are well explained by one-dimensional calculations.

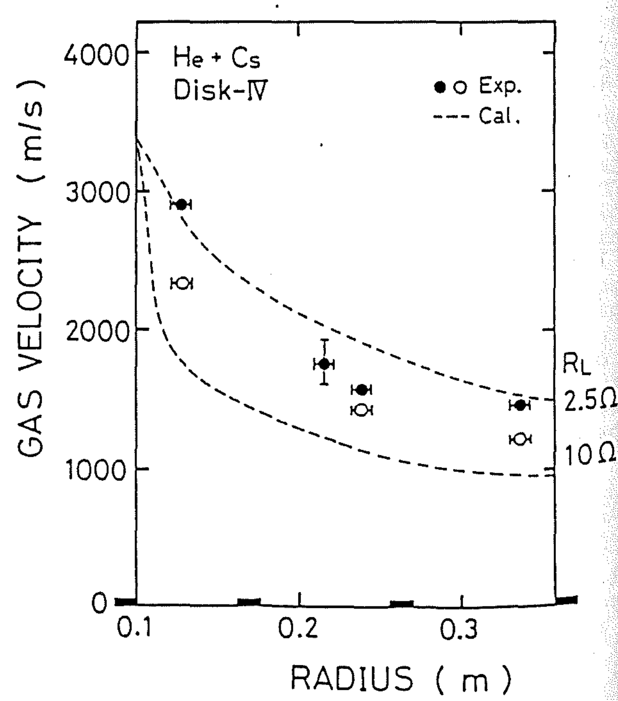

Fig.7 Variation of gas velocity along the radial direction.

FUJI-1 BLOW-DOWN EXPERIMENTS

Experimental set up and conditions

Experimental studies on the performance of a closed cycle MHD disk generator have been conducted not only with the shock tube facility but also with the FUJI-1 blow-down facility. The last series of power generation experiments, RUN6208, 6209 and 6210 were carried out with the new generator, DISK-F3a. Total system of the FUJI-1 facility are explained in the earlier papers.[8,9] Figure 8 shows a schematic diagram of the DISK-F3a generator. It has four pairs of water-cooled ring electrodes, A1, A2, C1 and C2. The first (A1) and the second (A2) anodes are externally short circuited, and the external load resistance is connected between the second anode(A2) and the second cathode(C2). The insulating walls are made of silicon nitride. The channel also has optical windows, static pressure ports and electrical probes along the radical direction.

The dimensions and the designed inlet Mach number of the DISK-F3 and DISK-F3a channels are summarized in Table 2. The previous experimental results with the DISK-F3 channel showed the strong increase in static pressure, which suggested the remarkable decrease of gas velocity owing to the strong MHD interaction.[3,5] We have to reduce the effect of flow deceleration in order to achieve higher performances. For the new DISK-F3a channel, the ratio of an exit cross sectional area to an inlet one is increased from 3.5 of the DISK-F3 to 4.2. It is noted that the designed inlet Mach number is also increased from 2.3 to 2.6.

The experimental conditions are shown in Table 3. Argon seeded with cesium is used as working medium. In this series of experiments, the stagnation pressure is changed as 0.46, 0.60 and 0.69 MPa in order to study the effects of stagnation pressure on generator performances for a given channel geometry. It must be noted that the thermal input is also changed from 2.57MW to 3.84MW corresponding to the change in stagnation pressure. Seed fractions are kept low in the order of 10^{-4} for all runs.

Table 2 Dimensions and designed inlet Mach number of DISK-F3 and DISK-F3a generator.

Channel	DISK-F3	DISK-F3a
Anode		
radius(mm)	160	160
height(mm)	14.7	16.0
2nd Cathode		
radius(mm)	380	380
height(mm)	22.0	28.0
Inlet Mach Number	2.3	2.6
Area ratio (exit/inlet)	3.5	4.2

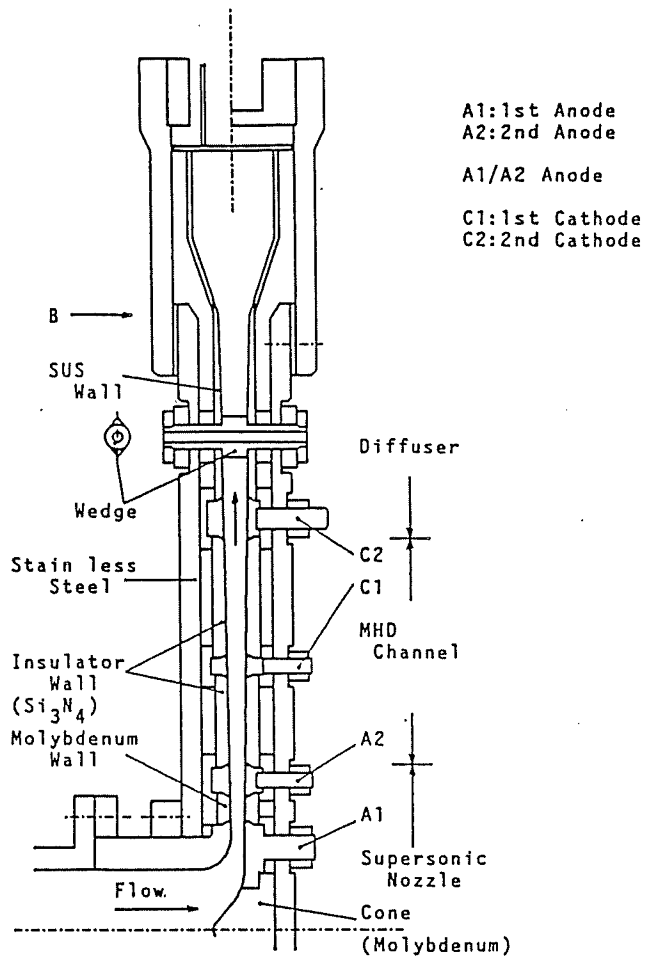

Fig.8 Schematic cross sectional view of the DISK-F3a generator.

Table 3 Experimental conditions for FUJI-1 blow-down experiments.

RUN No.	6208	6209	6210
Date	5,10,1989	6,10,1989	6,10,1989
Working gas	Ar + Cs	Ar + Cs	Ar + Cs
Stagnation gas temperature(K)	1850	1850	1890
Stagnation gas pressure (MPa)	0.46	0.60	0.69
Thermal input(MW)	2.57	3.40	3.84
Seed fraction ($x10^{-4}$)	2.0~3.0	1.7~1.8	1.6~1.7
Magnetic field strebgth (T)	4.4 (inlet) ~ 2.7 (exit)		

Typical time history of the upstream stagnation pressure, the seed fraction, the load resistance and the output Hall voltage in RUN6208 are shown in Fig.9. In this run, two values of seed fraction about 2×10^{-4} (50∿65sec) and 3×10^{-4} (70∿95sec) are examined. We can see noticeable fluctuation in measured seed fraction. It is reported that this fluctuation is the main cause of the fluctuation of output power.[4] In each period, the load resistance is changed stepwise in the range of 0.07Ω∿2.5Ω. We can see that the output Hall voltage shows also step-like change with the change of load resistance. This output voltage reaches up to 700V, which corresponds to the averaged Hall field of 3.5kV/m for the case of 2.5Ω.

Hall Voltage-Hall Current Characteristic

Hall voltage - Hall current characteristics for various stagnation pressures are shown in Fig 10. It can be seen that Hall current increases in the near short circuit regime and Hall voltage decrease in the near open circuit regime when stagnation pressure is increased. This decrease in Hall voltage is ascribed to the decrease of Hall parameter as the pressure increases. It is known that the gradient of a voltage-current characteristic corresponds to an internal resistance of a plasma. We can see from Fig.10 that the internal resistance becomes large with the increase of gas pressure.

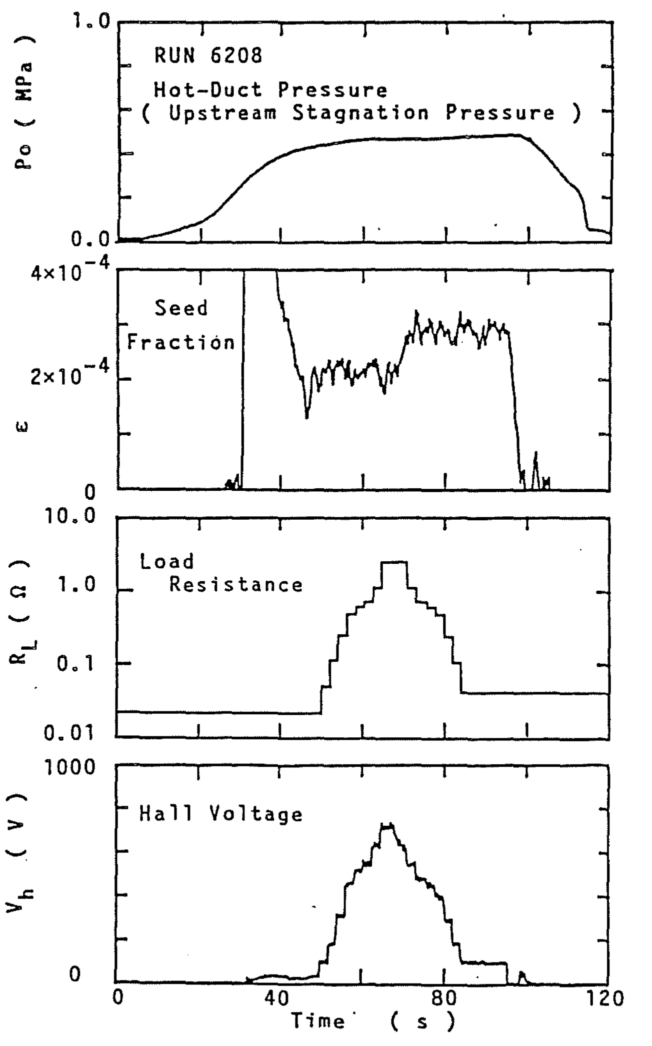

Fig.9 Typical time traces of stagnation pressure, seed fraction, load resistance and output Hall voltage.

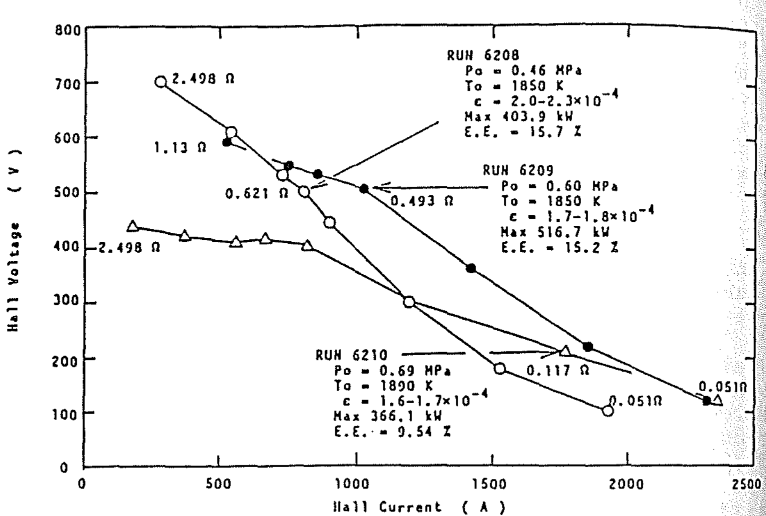

Fig.10 Hall voltage-Hall current characteristics for various stagnation pressures.(RUN6208, 6209 and 6210)

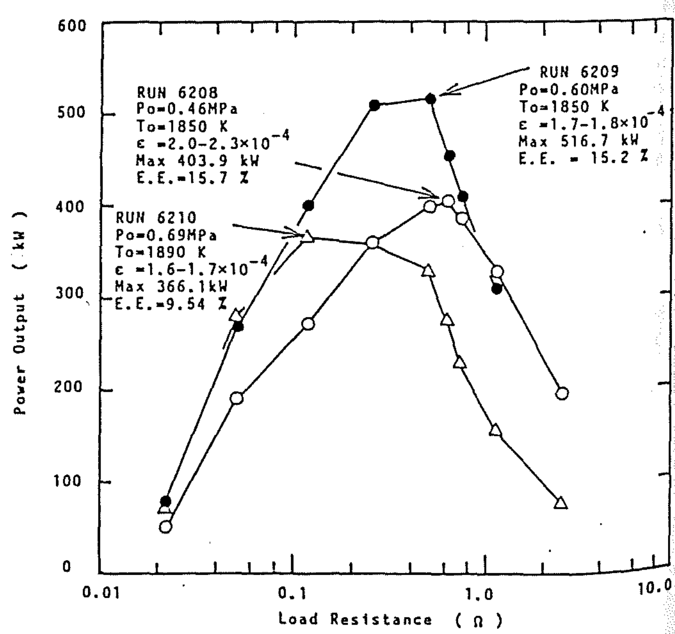

Fig.11 Output power vs. load resistance for various stagnation pressures.

Figures 11 and 12 show the obtained output power and enthalpy extraction ratio against the load resistance for various stagnation pressures. The highest enthalpy extraction ratio of 15.7% is achieved with the stagnation pressure of 0.46MPa, whereas the largest output power of 516.7KW and the corresponding high output power density of 70 MW/m^3 are extracted with the stagnation pressure of 0.6MPa. It is important that for the case of 0.46MPa, which corresponds to a part load condition by about 25% reduction of thermal input from the nominal condition of 0.6MPa, the obtained enthalpy extraction ratio keeps the same level of over 15% as the nominal value. This result suggests the possibility of a part load operation without significant degradation in enthalpic efficiency by means of reducing stagnation pressure.

The value of load resistance which provides the peak output power shifts to higher values as the pressure decreases. This can be ascribed to the increase of an internal impedance of a plasma due to the decrease of gas pressure.

Hall Potential Distribution and Swirl

Measured Hall potential distributions along the radial direction are shown in Fig.13, when the output power reaches its maximum for each stagnation pressure. We can see that high Hall field can be measured even at the entrance of a channel for the lower stagnation pressure of 0.46MPa, whereas the negative Hall potential region appears near the anode in RUN6209 with the stagnation pressure of 0.6MPa. Low gas pressure and corresponding high Hall parameter results in the enhancement of Joule heating even in the supersonic nozzle, and therefore, the negative Hall potential disappears in RUN6208. On the other hand, for the case of the higher stagnation pressure of 0.69MPa, the negative Hall potential at the entrance of the channel becomes much significant. This voltage drop reduces the output voltage very much and results in the reduction of output power.

The swirl is defined as the ratio of an azimuthal component of gas velocity U_θ to a radial component U_r. In the FUJI-1 experiments, this swirl is measured at the wedge which is located just downstream of channel exit as shown in Fig.8. Results are plotted in Fig.14 against the Hall current for various stagnation pressures. It can be seen that the negative swirl becomes large with the increase of Hall current. This is quite reasonable because this is induced by the Lorentz force $J_r \times B$. The swirl is enhanced with the decrease of stagnation pressure. For lower gas pressures, the effect of this Lorentz force becomes relatively significant due to the decrease of the inertial force.

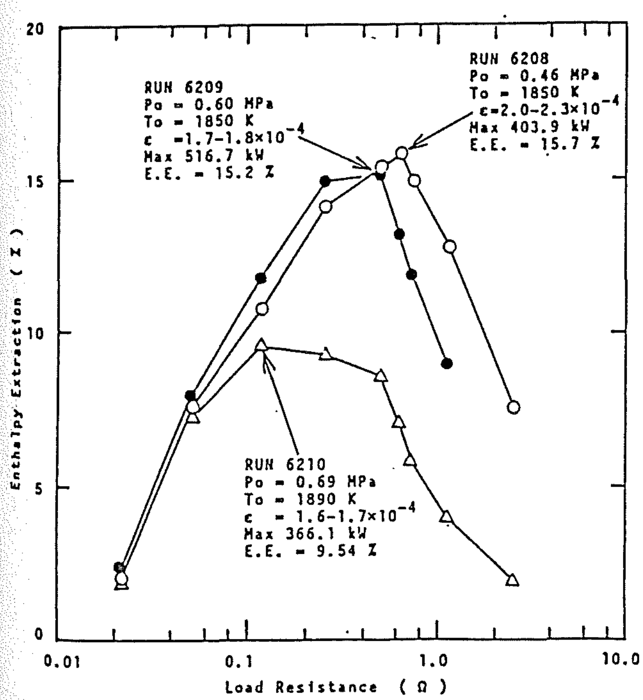

Fig.12 Enthalpy extraction ratio vs. load resistance for various pressures.

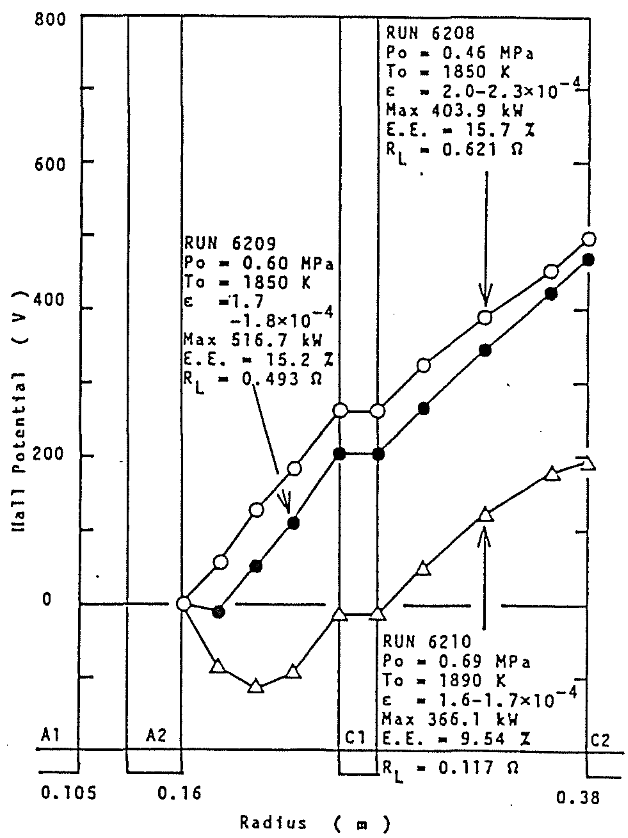

Fig.13 Hall potential distributions along the radial direction for the stagnation pressures of 0.46, 0.6 and 0.69MPa.

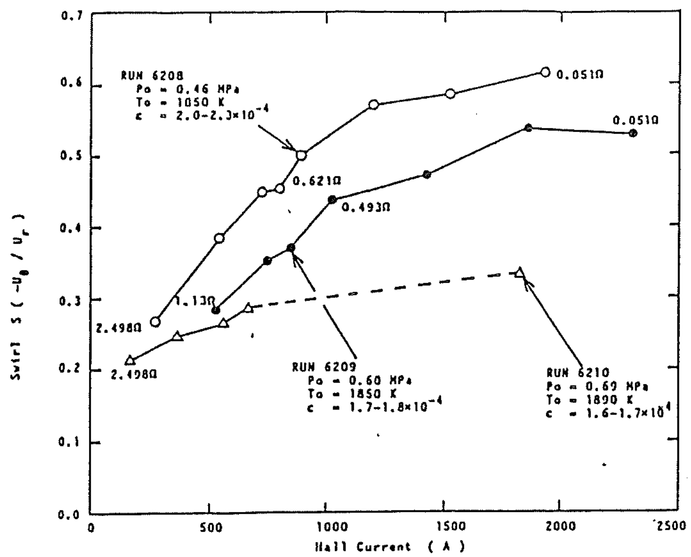

Fig.14 Swirl at the exit of disk channel against the Hall current.

Experiments with He/Cs Working Gas

The shock tube experiments showed the advantage of using helium such as high induced voltage, high output power density and also high enthalpy extraction ratio. [1,10] In the FUJI-1 facility, the experiments with a helium working gas are left to be studied. After the last power generation runs with an argon working gas, modification of the facility and preparation for helium experiments have been carried out. The special attentions were paid to the electrical isolation because the output voltage is predicted to be above 3kV owing to high velocity of helium. Hot helium blow was successfully completed in this March. The stagnation gas temperature of 1900K was measured and the thermal input was 5MW with the helium flow rate of 10000 Nm^3/h. The first power generating experiments using He/Cs working gas will be conducted with the Disk-F3a channel in this May. Results will be presented at the conference.

CONCLUSIONS

Power generation experiments with closed cycle MHD disk generators were carried out at T.I.T. to demonstrate a high enthalpy extraction. Concluding remarks were as follows.

In the shock tube disk experiments, the effects of channel shape on generator performances were studied using helium seeded with cesium as working medium. More divergent channel geometry was effective to sustain high Hall field throughout the channel, and resulted in a remarkable increase in both the output power and enthalpy extraction ratio. The highest enthalpy extraction ratio of 27.3% was achieved with the new Disk-IV generator. Present experimental results of the effect of channel shape on the generator performance, the Hall potential and the gas velocity distributions agreed well with the results of one-dimensional calculations.

In the FUJI-1 blow-down experiments, The new disk generator Disk-F3a with a large area ratio of the exit cross section to the inlet were installed, and performances were studied for various stagnation pressures. High output power of 516.7kW and corresponding power density of over 70MW/m^3 were obtained with the nominal condition of stagnation pressure 0.6MPa. On the other hand, the highest enthalpy extraction ratio of 15.7% were achieved with the lower pressure of 0.46 MPa, which corresponded to the 25% reduction of thermal input from the nominal case. This result suggested the possibility of a part load operation without significant degradation in enthalpic efficiency by means of reducing stagnation pressure. For the case of higher stagnation pressure, the inlet negative Hall potential became much pronounced owing to small Joule heating, and reduced the output power. The swirl at the exit of the channel was measured and was enhanced with the increase of Hall current and with the decrease of stagnation pressure.

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