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Non-equilibrium MHD Power Generation using

Non-seeded Argon Plasma*

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Experiments have been made in a shock tunnel non-equilibrium MHD power generator using non-seeded argon plasma. A linear generator with constant cross section and a diverging generator with diverging cross section have been used for the experiments. The main purpose of the experiments is to observe the effects of $J \times B$ force on the plasma flow when large powers are extracted from the generator. As the result, the MHD power generator performance is shown to be well described by the two temperature theory with considerations of Coulomb collision, the segmentation of the electrodes, the electrode voltage drops and $J \times B$ force effects. In the linear generator, the reflected shock wave was observed at the interaction parameter 5 and the distribution of the steady current was affected by the shock wave. The enthalpy extraction efficiency reached 4 % in the linear duct. When this efficiency is above 1 %, $J \times B$ force effects become appreciable.

1. Introduction

The necessity of research of the non-equilibrium MHD power generation has been recognized recently because the nuclear fuel power generation has become important relating to the dwindling fossile fuel resources.

On the other hand, because temperature of the outlet gas from UHTR (ultra high temperature gas reactor) which will be a heat source of the non-equilibrium power generation systems is still 1000 K at the maximum, it has been shown that construction and operation of the practical power plants containing an MHD generator would depend on the future technical developments of the reactor. Then, the recent trends of research put emphasis on the physical aspects of the non-equilibrium partially ionized gas in the MHD generator.

It has been shown that research on the fluid dynamic aspects of partially ionized gases in the generator has not yet been done satisfactorily. Practical MHD generator would have an output up to several tens of hundred megawatts and this value may be attained using high flow velocity of working gases and high magnetic field strength. But, this would result in strong interaction between the working fluid and the magnetic field and, then, the

fluid would be turbulent or be choked. This is called the $J \times B$ force effects. The $J \times B$ force would cause the boundary layer separation, the formation of a secondary shock wave when the flow is supersonic and the two dimensional effects in the flow. These effects would result in reduction of the generator performance.

The studies on $J \times B$ force effects have been performed in recent years theoretically and experimentally.

Rosciszewski⁽⁴⁾ showed that in the equilibrium plasma a pressure rise was observed after the incident shock wave when the interaction parameter S became large. Here the interaction parameter is a non-dimensional ratio between the $J \times B$ force and the inertial force and is defined as $S = J \times BL / \rho U^2$.

This result was confirmed by Zauderer⁽²⁾ in the shock tube experiments and he also observed reduction of speed of the incident shock waves.

Sardei⁽³⁾ has shown theoretically by the method of characteristics that the reflected shock wave grew in the region of interaction. In his calculations, the variation of electrical conductivity along the flow was taken account and he has shown that the incident shock wave was accelerated by Joule heating of the plasma. He also made experiments in the shock tube and confirmed the theoretical results.

Jhonson⁽⁴⁾ made categorization of the interactions and theoretically showed that a reflected shock wave was produced when the local sound velocity was attained behind that shock wave. The developments of this work have been made by Hashiguchi et al.⁽⁵⁾ They considered the variation of the electrical conductivity.

Zauderer⁽⁶⁾ also has observed the

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development of a secondary shock wave in the generator when the amount of power extraction becomes large and after the shock wave the value of the output current is abruptly reduced. This research was made in nearly the same conditions of our works, but, the range of interaction parameter was different.

Recently, Loubisky et al.⁽⁷⁾ have observed the interaction processes by the schlieren technique and have shown a two dimensional structure in the shock front and the ionization front.

In our works, we have observed the JXB force effects on the performance of the non-equilibrium MHD power generator when the value of the interaction parameter becomes high and the effects of the generator duct shape on the performance and on the JXB force. Because we used non-seeded argon gas as the working gas, the stagnation temperature of the gas was very high. We also considered this effect on the performance of the generator.

The following conclusions are reached.

- (1) The performance of the generator is revealed to agree well with the two temperature plasma theory with considerations of Coulomb collisions, electrode voltage drops and JXB force effects.
- (2) The reflected shock wave is observed when the interaction parameter exceeds 5 or the enthalpy extraction efficiency is over 1 %.
- (3) The cooled layer of the plasma near the electrode surface is effective to determine the performance of the generator in the diverging power generator.

Nomenclature

- A: surface area of electrode
 B: magnetic field intensity
 C: segmentation ratio of electrode
 $= p / D$
 D: width of the duct
 E: electric field strength
 e: charge
 $f = C / 2$
 h: Planck's constant
 I: current
 J: current density
 k: Boltzmann's constant
 L: length of the duct
 M: Mach number
 Ms: Mach number of the flow
 n: number density
 P: pressure
 Ps: static pressure
 Po: output power
 Pe: electrode loss of power
 Pj: Joule loss of power
 p: pitch of the electrode
 S: interaction parameter $= J \times BL / \rho U^2$
 T: temperature
 U: fluid velocity
 V: voltage
 δ_{eff} : effective collision loss coefficient
 ν : collision frequency
 ρ : density

σ : conductivity
 ω_c : Hall parameter
 Suffixes

e: electron
 g: gas
 i: ion
 eff: effective value
 ideal: ideal value
 x: Hall direction
 y: Faraday direction

2. Experimental apparatus

The experimental apparatus consists of a shock tunnel, a vacuum pump system, a gas supply system and an electromagnet as shown in Fig.1.

Fig.1 Schematic of the shock tunnel

2.1. The shock tunnel

The shock tunnel is 11.81 m in length and consists of a high pressure chamber, a low pressure chamber, a power generator and a dump tank. The high pressure chamber is 1.2 m in length with inner cross section of 70 x 100 mm² and is connected to the low pressure chamber by a sleeve. As a driver gas, we used hydrogen. An aluminum diaphragm of 2 mm thickness and of 198 mm diameter was placed between the driver chamber and the driven chamber. This diaphragm is broken naturally at pressure of 30 atm. The low pressure chamber has a length of 4.75 m. Inner cross section of this chamber has the same dimension as the high pressure chamber. The low pressure chamber is filled with argon. Following the low pressure chamber, two types of the generator ducts were prepared according to the experimental conditions.

The evacuation of the shock tunnel was made by the oil rotary vacuum pumps with total outgas rate of 2000 liter/min. and the oil diffusion pumps with total outgas rate of 1000 liter/min. The shock tunnel can be evacuated up to 0.001 Torr.

2.2. The power generator

Two types of the generator ducts have been prepared. The first is a constant cross section duct and the other is a diverging cross section duct.

The schematic of a constant cross section duct (linear duct) is shown in Fig.2. This duct is made of epoxi-glass resin and consists of a Laval

nozzle with length 160 mm, inlet cross section $19 \times 19 \text{ mm}^2$ and outlet cross section $19 \times 54 \text{ mm}^2$, and a power generator with length 760 mm and cross section $19 \times 54 \text{ mm}^2$. Because the Laval nozzle is located out of the applied magnetic field, the pre-ionization electrodes are set in the Laval nozzle. In the power generator duct, 18 pairs of copper electrodes with surface area $19 \times 10 \text{ mm}^2$ are imbedded flush with the inner surface of the duct wall. The electrode dividing ratio is 0.463. Thirty-six probes made of molybdenum are set along the inner surface of the generator.

Fig.2 Constant cross section duct

A schematic of the diverging cross section duct is shown in Fig.3. It has 920 mm length, $17 \times 17 \text{ mm}^2$ inlet cross section and $17 \times 70 \text{ mm}^2$ outlet cross section. Forty pairs of copper electrodes of surface area $17 \times 10 \text{ mm}^2$ have been set at 2 mm pitch. This electrode can be protruded into the flow to measure the effects of cooled boundary layer along the inner surface of the generator. Sixty copper probes of 2 mm diameter have been set to measure voltage distribution along the generator.

Fig.3 Diverging duct

2.3 The electromagnet

The electromagnet has an iron core with $80 \times 400 \text{ mm}^2$ cross section and gap width 90 mm. The magnetic field intensity was varied from 0.68 to 0.97 Teslas according to the current density of 120 A to 500 A.

3. The shock tunnel performance

The gas dynamic performance of the shock tunnel was predicted by the measurements of the incident shock wave speed in the low pressure chamber, the stagnation pressure behind the reflected shock wave, the static pressure at the inlet of the generator duct and the flow velocity in the generator.

The experimental data are shown in Table 1.

	linear duct		diverging duct	
argon init. pressure	10 Torr	5	5	
incid.shock velocity	1870 m/s	2400	2700	
incid.shock pressure	1.02 atm	0.44	0.58	
stagnation pressure	3.12 atm	2.5	3.2	
#1 stag. Temperature	5600 K	12600	12300	
inlet press. of duct	1.02 atm	0.56	0.68	
#2 inlet temp. of duct	3460 K	6900	6700	
flow Mach number	1.41	1.15	1.24	
flow velocity	1550 m/s	1800	2300	
#4 stag. electron dens.	$2 \times 10^{13} / \text{cm}^3$	2×10^{13}	3×10^{13}	
### inlet electron dens.	$1 \times 10^{12} / \text{cm}^3$	1×10^{14}	----	

Table 1. Gasdynamic performance of the shock tunnel

The stagnation temperature (*1 in Table) is calculated by Rankine-Hugoniot theory (8) using the measured stagnation pressure. The inlet temperature (*2) is predicted using measured inlet pressure and the measured flow velocity by the adiabatic expansion theory.

Using these values of the stagnation pressure and temperature, we can calculate the stagnation electron density (***) by Rankine-Hugoniot theory with the real gas effects (9) and also we can calculate the electron density at the outlet of the generator (***) as shown in the table.

The electron density is over $10^{13} / \text{cm}^3$ and it fulfils the condition for the validity of the two temperature theory (10).

4. MHD generator performance

The MHD generator performance is predicted by the measurements of Faraday voltage-current characteristics, the conductivity in the plasma, the electron density in the plasma, Hall voltage-current characteristics and the effective Hall parameter. They are also compared with the simple theory.

4.1 Faraday voltage-current characteristics

Faraday voltage-current characteristics was predicted from the voltage measured by a pair of probes across the generator duct and the current measured by a pair of the electrodes which are set against the probes. The curves of the characteristics are shown in Fig.4 and Fig.5, which correspond to the data of the linear generator and the diverging generator respectively. In these figures, the measured voltages are given by that are sustained in the plasma, so that the voltage drops near the electrodes are subtracted from the measured values.

The theoretical values of Faraday voltage-current relation calculated by the two temperature theory are shown in the same figures. The two temperature theory demonstrates that, in the high electron density plasma ($n_e \geq 10^{13} / \text{cm}^3$), the steady state plasma are predicted from the balance between the energy losses in the electron by collision with the heavy particles and the Joule heat input to the plasma from

the applied magnetic fields.

The electron energy equation is given as follows,

$$\tilde{r}^2/\sigma_{eff} = \delta_{eff} n_e \frac{2m_e}{m_p} \nu_e \frac{3}{2} k(T_e - T_s) \dots (1)$$

The electron continuity equation agrees in this case to Saha's equation,

$$\frac{n_e^2}{n_p} = \left(\frac{2\pi m_e k T_e}{h^2} \right)^{3/2} \exp(-E_{ion}/kT_e) \dots (2)$$

where E_{ion} is the ionization energy of argon.

The effective conductivity is described by Hurwitz-Kilb-Sutton theory⁽⁴⁾ which accounts for the effects of finite segmentation of the electrodes,

$$\sigma_{eff} = \sigma_0 / [1 + 2f(\omega\tau - 0.4)] \dots (3)$$

Faraday voltage-current relation is given by the following equation which is valid in the case of an opened Hall mode of operation,

$$j_y = \frac{\sigma_0(UB - E_s - E_s')}{1 + 2f(\omega\tau - 0.4)} \dots (4)$$

where E_s is the voltage drop near the electrode.

Because the ideal conductivity is given by equation,

$$\sigma_0 = n_e e^2 / m_e \nu_e \dots (5)$$

the theoretical voltage-current characteristics are given by the equation (4).

Fig. 4 Faraday V-I relation in the linear generator

Fig. 5 Faraday V-I relation in the diverging generator

The curve A in Fig. 4 and Fig. 5 shows the value of the voltage reduction due to the Joule losses and curve B shows the values of the voltage reduction due to the electrode drops and $J \times B$ force effects. The data in small current density range are scattered due to the complex mechanism of voltage drops. From another measurement, we can show that the effects of $J \times B$ force become appreciable above the current density of 10 A/cm² and the flow is disturbed above 100 A/cm². The mean electrode voltage drops become about 8 V/cm as shown in Fig. 5.

4.2 Conductivity

The relation of conductivity vs. current density is shown in Fig. 6. The conductivity is the effective conductivity and is calculated from the measured Faraday voltage-current characteristics.

Fig. 6 Conductivity vs. current density

The theoretical values are shown in the same figure by two curves. The value σ_{ideal} shows the ideal conductivity without electrode segmentation effects and σ_{eff} shows the effective conductivity calculated from the equation (3). At the current density above 10 A/cm², increase of the conductivity becomes small because Coulomb collision is effective. The experimental values well agree to the values of σ_{eff} .

We can conclude that the electrical characteristics of the working plasma can be well described by the two temperature theory with consideration of Coulomb collision, $J \times B$ force effects and the electrical voltage drops.

4.3 Electron density

The relation between the electron density and the Joule heating in the

plasma is shown in Fig.7.

When we compare the experimental values with those of the two temperature theory, we can show that the effective collision frequency is nearly 2.0 which equals to the value of the rare gas plasma. Value of the electron density of plasma becomes about $2 \times 10^{15} \text{ 1/cm}^3$. This fact shows that the Joule heating in the plasma is sufficient to recover the stagnation electron density.

Fig.7 Electron density vs. Joule heating

4.4 Hall voltage

Hall voltage vs. Faraday current density is shown in Fig.8.

At the current density above 20 A/cm², Hall voltage saturates to 50 V/cm in the diverging duct and 20 V/cm in the linear duct. The discrepancies in the values of Hall voltage would be due to the difference of the static pressure between two types of the ducts.

The phenomena of Hall voltage saturation are caused by Coulomb collision and are not due to the ionization instability. In the conditions of our experiments, high stagnation temperature and high electron density make the critical Hall parameter of the instability above 10. This result coincides with the experimental data in which we could not observe any fluctuations of Faraday voltage, Faraday current and Hall voltage.

Fig.8 Hall voltage vs. Faraday current

4.5 Effective Hall coefficient

The effective Hall coefficient vs.

Faraday current density is shown in Fig.9.

Fig.9 Effective Hall coefficient

The effective Hall coefficient is given by the ratio between Hall field E_x and Faraday field E_y^* as follows,

$$\omega\tau_{\text{eff}} = E_x/E_y^* \quad (6)$$

here

$$E_y^* = UB - E_y \quad (7)$$

In Fig.9, values of $\omega\tau_{\text{eff}}$ calculated by the two temperature theory are shown as a solid line. When current density becomes lower than 10 A/cm², theoretical $\omega\tau_{\text{eff}}$ linearly grows against J_y and it attains a value of 12. This fact shows that in this current range $\omega\tau_{\text{eff}}$ is not affected by Coulomb collision. If current density becomes higher than 10 A/cm², $\omega\tau_{\text{eff}}$ is affected by Coulomb collision and saturated. The experimental values, however, are nearly constant over a wide range of current densities. These values are especially lower than the theoretical values in the current range from $J_y = 10 \text{ A/cm}^2$ to 50 A/cm^2 . This fact is due to $J \times B$ force effects as shown later.

5. Electrode voltage drops

Electrode drops are shown to have important effects on the generator performance especially in the diverging duct. The amount of the electrode drops depends on the nozzle shape and the effective length of the generator. In the diverging generator, because it has a long nozzle, the plasma is strongly cooled at the duct wall and the electrode drops become large.

In Fig.10, the distribution of Faraday potentials in the diverging generator is shown. The potential distribution is measured by probes set across the generator. In this figure, the point of zero potential is described to accord with the duct center. The number with E indicates the position of the electrode. E11 electrode is in the location of the inlet of the generator. We show that the potential distribution has a very complex shape. Another group of probes exists before E14, E18, E23 and E28 electrodes respectively. This group of probes would build up a weak stationary shock wave before the probes which are situ-

ated behind them and reduce the thermal boundary layer thickness. Then, we have relatively small potential drops at these probes. The anode side is relatively insensitive to the fluid flows.

Fig. 10 Potential distribution in the diverging generator

The values of the electrode voltage drops vs. Faraday current density is shown in Fig. 11.

The voltage drop of cathode is, on the average, about 20 V/cm higher than that of anode. When the current density is larger than 5 A/cm², the values of the voltage drops are saturated and reduced.

Fig. 11 Electrode drops vs. Faraday current

6. J × B force effects

J × B force exerts different influence on the linear generator and the diverging generator respectively. This fact is caused by a difference of the interaction parameter between these two generators.

In the linear generator, Faraday current can be made large and the interaction parameter reaches 5.0. The measured static pressure distribution in the case of the interaction parameter 5.0 is shown in Fig. 12.

The electrode E1 is in the position of the beginning of interaction between the current and the magnetic field. Behind the electrode E6, a secondary pressure growth indicated by an arrow is observed and this grows to be a reflected shock wave. This reflected shock wave has no steady state structure because there are interactions with expansion waves from the

Fig. 12 Pressure distribution in the linear duct at $S = 5.0$

Distribution of Faraday current densities in the generator is shown in Fig. 13. Circles indicate mean values of the experimental data by the interaction parameter 5.0. At the position E1, the plasma enters the interaction region and a current is induced. In the downstream, the current value rapidly grows by accumulation of the Joule heating. At the position of the electrode E6, a reflected shock wave is produced by J × B force and the current is reduced. In the downstream position after the electrode E6, the current seems to be recovered due to the Joule heating in the plasma. This fact indicates that, even in the presence of a strong J × B force, a decrease of the output power due to this force can be compensated when the reflected shock wave is located at adequate position.

When the interaction parameter is 0.5, the current distribution is smooth after the ionization relaxation and we do not observe a reflected shock wave.

Fig. 13 Current distribution in the linear generator at $S = 5.0$

$J \times B$ force affects the value of Hall field in the diverging duct as shown in Fig.14. In this figure, the ratio between the measured and the theoretical Hall field vs. the interaction parameter S is shown. The theoretical values are calculated by the two temperature theory as shown in Fig.9. Because the variation of S corresponds to the variation of J_y , we can indicate in Fig.14 the corresponding temperature ratio of the electron and the gas T_e/T_g , here at $S=0$, $T_e/T_g=1.0$. It is shown in Fig.14 that, when the value of T_e/T_g is smaller than 1.4, the ratio between the measured Hall voltage and the theoretical Hall voltage becomes smaller as the interaction parameter grows, but, when this value is larger than 1.4, the ratio becomes smaller.

This fact is interpreted as follows: When $T_e = T_g$, because the state of the plasma is sensitive to T_g , T_g and n_e increase with an increasing $J \times B$ force. But, if J_y is small and constant, $n_e \times E_x$ is also constant and the effect of an increasing $J \times B$ force would result in reduction of E_x . On the other hand, the ratio between the measured and the theoretical Hall voltages decreases due to the effect of Coulomb collision which becomes effective as the plasma is sensitive to T_e when T_e is larger than T_g .

Fig.14 Hall voltage vs. interaction parameter

In Fig.15, we show the current distribution in the diverging channel. Some electrodes were made to protrude into the flow in order to reduce the electrode voltage drops. Crossed data show the current distribution with the protruding electrodes and full circles show that with the pre-ionization at the entrance of the generator. The pre-ionization was made across the flow. The values of current become larger than in the case of the flush electrodes.

7. Power generator output performance

The performance of the power ge-

Fig.15 Current distribution in the diverging generator

neration is shown in Fig.16 (for the linear generator) and in Fig.17 (for the diverging generator). In the linear channel, the value of the output power is maximum at 0.1Ω load and decreases with an increasing load. On the other hand, in the diverging channel, the maximum output power is obtained at 1Ω load. This shows the mean resistivity of the plasma in the diverging channel is larger than that in the linear channel. This fact is due to the large electrode drops in the diverging channel.

Fig.16 Power output of the linear channel

Fig.17 Power output of the diverging generator

The power losses due to the electrode drops equal to $P_t - P_o$. This value is 3 kW / one electrode and 80% of the power output in the linear generator, and 300 W / one electrode in the diverging generator. The performance of the generator depends on the electrode voltage drops strongly.

The effective total power output is 200 kW in the linear channel and 9 kW in the diverging channel. The enthalpy extraction efficiency is 4% and 0.2% respectively. When the enthalpy extraction efficiency exceeds 1%, the $J \times B$ force effect appears appreciably in the flow.

8. Conclusions

Experiments have been made in a shock tunnel non-equilibrium MHD power generator using non-seeded argon plasma. A linear generator with a constant cross section and a diverging generator with a diverging cross section have been used for the experiments. The main purpose of the experiments is to observe the effects of $J \times B$ force on the performance of the generator.

It can be concluded mainly that

- (1) the MHD generator performance is well described by the two temperature theory with considerations of Coulomb collision, the segmentation of the electrodes, the electrode voltage drops and $J \times B$ force effects;
- (2) the maximum electron density exceeds the value calculated by the stagnation temperature;
- (3) a reflected shock wave is observed in the linear generator at the interaction parameter 5.0 and the distribution of steady currents is affected by the shock wave;
- (4) the generator performance depends strongly on the electrode voltage drops especially in the shock tube experiments;

and

(5) the overall power output is 200 kW in the linear generator and 9 kW in the diverging generator. These values correspond to 4% and 0.2% of the enthalpy extraction efficiency respectively. When the enthalpy extraction efficiency reaches 1%, $J \times B$ force effects become appreciable.

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