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A Shock Tube Study of Nonequilibrium MHD Power Generation*

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Results are reported of the experiments with a shock tube on inert-gas MHD power generators utilizing nonequilibrium ionization. By preheating the whole low-pressure chamber of the shock tube, it was possible to seed sufficient amount of potassium to the working gas and to realize the conditions required for MHD power generation. The first type of generator made use of the induced electric field, resulting from the interaction of gas flow and magnetic field, to obtain nonequilibrium ionization. Whereas the steady-flow experiments reported so far have not yielded high electrical conductivities predicted by nonequilibrium theory, the results of detailed measurements in the present device were fairly close to those predictions. The reason is considered to be the absence of appreciable boundary effects and flow instability in experiments of such short durations. The unfavorable effect of small amount of impurities on the generator performance was also demonstrated. The second type of nonequilibrium MHD generator utilizing metastable nitrogen was similarly tested, and was found to be a promising alternative.

1. Introduction

Ever since the MHD (Magneto-Hydro-Dynamic) electric power generation was proposed as a method of direct energy conversion from heat to electricity at the end of last decade⁽¹⁾, research and development works have been active at various laboratories and several types of cycles have been devised. Working fluids for MHD electric power generation may be classified into the following categories;

- (1) combustion gas seeded with small amount of potassium (K),
- (2) inert gases [helium (He) or argon (Ar)] seeded with potassium (K) or cesium (Cs) and, finally,
- (3) liquid metals.

The first of these is to work as a topper stage of a steam power plant, and the second is to utilize an atomic reactor as its heat source⁽²⁾.

An MHD generation employing an inert gas seeded with K or Cs should be operated at temperatures below 2000°K on account of thermal problems associated mainly with atomic reactor materials. Additionally, an electrical conductivity of above 10⁷/m is required in the working plasma at pressures of about several atm in order for a meaningful

electrical output density to be generated⁽³⁾. The means thus far proposed for obtaining high electrical conductivities at such relatively low temperatures involve (1) photoionization, (2) ionization by incident particles like electrons, (3) electron emission by tiny particles⁽⁴⁾ and (4) chemi-ionization⁽⁵⁾. At present, however, much effort is concentrated on the method of nonequilibrium ionization by magnetically self-induced electric field⁽⁶⁾. The nonequilibrium ionization by means of an externally applied voltage is commonly observed in low-pressure discharge tubes. Thereby, energy is fed to electrons by an external electric field, elevating the electron temperature above the gas temperature. On the other hand, the above-mentioned method of nonequilibrium ionization by magnetically induced electric field has been experimented upon for the past few years in England, in U.S.A., etc. However, the experiments in steady-flow arrangements with straight-tube generator sections have almost entirely failed to yield evidences of theoretically-predicted nonequilibrium ionization phenomena. The major causes for this failure are considered to involve the effect of impurities, the electrical short-circuit phenomena in the boundary layer near the wall, and the instability phenomena due to the strong magnetic field. It is supposed that such influences were pronounced in the past steady-flow experiments, hindering nonequilibrium ionization from being clearly observed.

Consequently, it will be highly desirable, as

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the first step towards the application of the MHD principle to an atomic power generation, to perform power-generating experiments under conditions relatively free from those influences and to ascertain the possibility of the nonequilibrium ionization by means of induced electric field. Such near-ideal conditions can be achieved in the shock tube experiments. Namely, when one employs a shock tube, the elimination of impurities will be easy, the instability will not be fully amplified within the short duration time of the plasma and, additionally, the boundary effects will not come into play because of the thinness of the boundary layer in the shock tube. (The short duration of the plasma flow, on the other hand, introduces some difficulties in measurements.)

In addition to the above-mentioned nonequilibrium ionization, we have employed a different process whereby the electron density alone, which is directly related to the electrical conductivity, is efficiently raised. The method consists of generating nitrogen molecules in a metastable state by an electric discharge fired in an alkali-seeded inert gas with a small amount of nitrogen in it. The energy released in their transition to the ground state is utilized to cause the resonance ionization of the alkali metal atoms. In the following, the principles and the results are reported of the MHD electric power generation experiments for these two types of nonequilibrium ionization methods.

2. Nonequilibrium MHD power generation

2.1 Nonequilibrium ionization by magnetically induced electric field

The principle of this type of MHD power generation consists in the Joule heating of electrons (and the resulting enhancement of the electron temperature) by the electric field induced when a high-speed plasma flows across a strong magnetic field. If we denote the electrical conductivity of a gas by σ , and the electric current density by j , we have the following equation for the energy balance of the electrons.

$$\frac{j^2}{\sigma} = \left(\sum_i \delta_i \frac{m}{M_i} \nu_i \right) n_e \frac{3}{2} k (T_e - T) + L \quad (1)$$

In the right hand side of this equation δ_i , M_i and ν_i are the energy loss coefficient, the molecular mass and the collision frequency of the i th gas component, respectively, m the electron mass, n_e the electron number density, T_e and T the electron and gas temperatures, respectively, and k the Boltzmann constant. The left-hand side represents the energy acquired by the electrons by Joule heating, while the first term on the right-hand side denotes

the energy that the electrons lose when they collide with gas molecules. The second term L is the energy loss from the electrons by radiation, and consists principally of Cs or K resonance lines⁽⁷⁾. The left-hand side of Eq. (1) being positive, we have, when L is not too large, $T_e > T$, that is, the electron temperature is higher than the gas temperature. Consequently, the electron density is higher than the equilibrium value corresponding to the gas temperature, and the enhancement of the electrical conductivity is to be expected. The energy loss coefficient δ_i is 2 for inert monatomic molecules, but may take large values for polyatomic molecules. This fact and the larger value of ν_i , the collision frequency, keep the difference $(T_e - T)$ smaller for combustion gases so that nonequilibrium ionization is totally excluded there.

2.2 MHD power generation by metastable nitrogen

A nitrogen molecule has the electronically excited energy level $N_2^*(A^3\Sigma_u^+, T_{ex}=6.178 \text{ eV})$ as a metastable state⁽⁸⁾. The state of excited molecular vibration $N_2^{**}(X^1\Sigma_g^+, 0.289 \sim 5.456 \text{ eV})$ also is relatively long-lived, requiring a few microseconds for the relaxation with the translational temperature at 1500°K, 1 atm. As the energy drop from N_2^* to N_2^{**} is nearly equal to the ionization energy of K, a resonance ionization of a K atom may be expected on its collision with an N_2^* . (The use of a metastable state of Ar in an Ar-K plasma has also been proposed, which, however, would require a strong electric field⁽⁹⁾. Na might be preferable to K in some cases.)

The number density $n_{N_2^*}$ of metastable nitrogen is given by the following relations where T_e^* denotes the temperature of an electron excited by the applied electric field, and g and z the degeneracy and the partition function, respectively:

$$N_2 + e^- \rightleftharpoons N_2^* + e^- \quad (2)$$

$$n_{N_2^*} = \frac{g}{z} n_{N_2} \exp(-T_{ex}/T_e^*) \quad (3)$$

On the other hand, the time for the number density to attain the required value (which is of the order of $10^{15}/\text{cc}$ in typical MHD power generators) is determined from the following equation based on the kinetic scheme (2):

$$\frac{dn_{N_2^*}}{dt} = V_e C n_e n_{N_2} \quad (4)$$

Where V_e is the average thermal velocity of electrons, and C is the electronical excitation cross section of N_2 [i.e. for the reaction from left-hand side to right-hand side of (2)]. The value of C being of the order of 10^{-17} cm^2 ⁽¹⁰⁾, the time required in the above process is tens of microseconds.

We assume that, downstream of the N_2^* gene-

rator, energy transfer takes place from N_2^* to K (with ionization potential of 4.34 eV) according to the following scheme:

$$\frac{dN_2^*}{dt} = -V_g S n_K n_{N_2^*} \dots \dots \dots (6)$$

where V_g is the average thermal velocity of gas molecules, S the cross section of the reaction (5), and n_K the number density of K. S is equal to the product of collision cross section and the probability of reaction (ionization in this case) on collision, and is large under the condition of resonance ionization.

Electrons are considered to be generated by the scheme (5) and to recombine with K ions in three-body collisions (with another electron as the third body), so that we have the following relation:

$$\frac{dn_e}{dt} = -\gamma \frac{dn_{N_2^*}}{dt} - \alpha n_e^3 \dots \dots \dots (7)$$

$$(n_K^+ = n_e)$$

Here γ represents the probability of electron production. γ would be equal to unity if (5) were the sole mechanism of the decay of N_2^* . However, collisions with species other than K and also collisions with K leading to a mere excitation of the latter are considered to be present, so that the actual value of γ should be less than unity. Incidentally, α is the three-body recombination coefficient given in the following⁽¹¹⁾:

$$\alpha = (19.6 - 0.063T) \times 10^{-24} \text{ cm}^6/\text{sec} \dots \dots \dots (8)$$

We may neglect the time required to produce N_2^* by electric discharge, since this is short compared with the relaxation time for the ionization of K, calculated from Eqs. (6) and (7). If $n_{N_2^*}$ and n_K are given, Eqs. (6) and (7) may be used to obtain the temporal variation of the electron density, and hence the same of the electrical conductivity. Such an analysis, however, involves some uncertainties in connection with the values of S and γ . The electrical conductivity calculated by assuming S to be 10^{-17} cm^2 is 1 000 times larger than the equilibrium value even 1 msec after the auxiliary discharge, while the value for $\gamma = 0.2$ is 3 times larger than that in the absence of N_2^* (i.e. without the use of metastable nitrogen by auxiliary discharge, or $\gamma = 0$), as seen in Fig. 10. The momentum cross sections of an electron with Ar, N_2 and K have been assumed to be 0.4, 6 and $250 (\times 10^{-16} \text{ cm}^2)$ throughout.

3. Experimental apparatus

3.1 Shock tube

Shock tubes are widely used in experiments of ionization and chemical reaction phenomena (including combustion) as well as of aerodynamics, so that the associated instrumentation techniques are now well-established. In this study we employed a pres-

sure-driven shock tube with helium as the driver gas, which yielded a long enough duration of plasma (several milliseconds) with a reasonable uniformity of flow and a high purity of the test gas. The test gas was argon with potassium vapor in it. In order for the partial pressure of the potassium vapor to be high enough in the initial unshocked state the test section was heated to 500°K. This method enabled us to have a weak plasma on shock compression of the test gas at relatively low temperatures (around 2000°K), and was most suitable for an MHD power generation study.

Figs. 1 (a) and 2 (b) show the shock tube employed in this study. The main body is made of stainless steel pipes, and the test section is of hard glass for optical observations, with a dump tank (an upright circular cylinder) downstream of it. The main diaphragm initially separating the high- and low-pressure sections is an aluminium plate with press-cut grooves on it (and later annealed) and ruptures spontaneously at the pressure difference of 10 atm at 500°K. The low pressure section (including the test section) is separated from the dump tank by a 0.5 mm-thick aluminium foil (which ruptures when hit by the shock wave) so that the diffusion of K vapor into the latter is prevented. In order to ensure the required high purity of the test gas two pairs of the combination of an oil rotary pump, an oil diffusion pump and a liquid nitrogen trap are used to attain a vacuum of 10^{-5} mmHg . The test gas used is a research-grade sample with an impurity of about 10 ppm. Prior to each experiment the tube is baked for degassing.

3.2 MHD generator

The MHD generator (test section) is shown in Figs. 1 (b) and 2 (a). The hard glass pipe supports rows of stainless-steel electrodes, which are protruded 5 mm off the inner surface of the tube to avoid the influence of the wall boundary layers. Electrical floating probes are inserted between the electrode pairs to measure the spacewise electric potential variation. The dump tank is made electrically floating to eliminate the shorting by the Hall potential. Various types of electrode segmentation have been tested, and the typical geometry is as follows; the electrode pitch $b = 35 \text{ mm}$, the spacing between two neighboring electrodes (along wall) $c = 7 \text{ mm}$, and the spacing between the opposite electrodes $d = 54 \text{ mm}$. The electrodes in our shock-tube experiments are entirely the so-called cold electrodes, and the change of its material, e.g. to molybdenum or copper, made little difference in the operation characteristics obtained. The magnet is of an iron core, has an extent of 400 mm along the tube axis, and yields a magnetic field of 11 kG. It is known

that, if interaction between the magnetic field and the plasma is strong enough, a secondary wave will be generated when the incident shock wave enters the test section, complicating the power-generation measurements. In our range of conditions, however, the interaction parameter N_B defined below was always less than 0.05.

$$N_B = \sigma B^2 l / \rho U \dots\dots\dots (9)$$

In this expression σ , B , l , ρ and U are the electrical conductivity of plasma, magnetic field intensity, test section length, gas density and flow velocity, respectively. Various output voltages (developed across load resistors, etc.) are recorded on a pair of dual-beam single-sweep oscilloscopes. Under our experimental conditions, the Hall effect becomes pronounced due to the strong magnetic field. Thus the electromotive force, induced by the interaction of the flow with the magnetic field, has a nonvanishing component in the direction of the tube axis, necessitating the use of the segmented electrodes described above (for avoiding the shorting).

3.3 Plasma measurements

The number density of potassium in the working plasma was determined as the product of its initial number density and the volumetric compression ratio across the incident shock wave. The former was calculated, in turn, from the saturated vapor pressure of potassium at the initial temperature of the test section, which was kept at a prescribed value by automatic temperature regulators attached to it. The velocity of the shock wave was determined by measuring its transit time between two detector stations located in the tube-axial direction. Platinum thin film heat gauges, ionization gaps and barium titanate (BaTiO_3) piezoelectric transducers were used as detectors. The Rankine-Hugoniot relations were applied to calculate the plasma temperature, pressure, flow velocity behind the shock wave from the shock velocity.

The piezoelectric element is 5 mm each in diameter and thickness. The surface is covered with a thin layer of silicon grease to prevent the leakage of the generated electric charge to the plasma. In Fig. 3 (a) the signal starting from the upper spot and traversing the lower edge of the frame shows the output of this detector amplified by a high input-impedance circuit. The rise time is seen to be a few microseconds. The fast oscillation superposed on it is caused by the mechanical resonance vibration of the element.

The signal running upward from the lower spot in Fig. 3 (a) represents the electric current through the plasma between a pair of molybdenum foil electrodes (pasted on a glass rod end) at a potential difference of 300 V. From this the duration of the test plasma is

Fig. 1 Shock tube and MHD generator

(a) MHD generator

(b) Shock tube and measuring devices

Fig. 2 Photographs of experimental apparatus

shown to be of the order of 1 msec. The rise time corresponds to the ionizational relaxation time, and is related to the mechanism of thermal ionization.

The ionization gap consists of a pair of metal needles supported on a teflon rod at a potential difference of 300 V. Usually a capacitor is inserted in parallel with the needle-electrode pair to control the duration of discharge. If its capacity is large enough the duration of discharge corresponds to that of the test plasma.

The thin film heat gauge consists of a hard glass rod with a nickel electrode pair in it, a thin film of platinum coating bridging the electrode ends. The heat transfer from the plasma elevates the temperature of the film, the high temperature coefficient of whose resistance gives rise to a reasonable magnitude of the output voltage, indicating the relative value of the gas temperature. The output voltage increases at the shock front with a rise time of a few microseconds, and decreases as the

contact surface arrives in response to the temperature drop.

In Fig. 3 (b) are recorded the voltages developed between electrodes shown in Fig. 1 (b), V_{E5-E1} denoting the voltage between the fixed electrodes E_5 and E_1 , and V_{F2-F1} that between the floating probes F_2 and F_1 . Large negative bumps observed 20 cm ahead of the shock wave in both traces were caused, presumably, by precursor electrons. The electron density in this region is estimated to be about $10^7/\text{cc}$. Output voltages persist even after the contact surface.

Fig. 3 (c) shows the luminosity signals of the K resonance line. The upper and lower traces are the light from the standard source after passing the plasma and the light emitted from it. The relative magnitude of the two signals gives the variation of the electronic excitation temperature⁽¹²⁾.

(a) Pressure history and plasma duration

(b) Precursor electron effects

(c) K resonance line signals

(d) Faraday open voltage

(e) Faraday current (1Ω load) and Hall voltage

(f) Faraday current (10Ω load) for metastable nitrogen

Fig. 3 Typical oscillograms

4. Experimental results

4.1 Voltage-current characteristics and electric power output

The experimental study on MHD power generation by means of a shock tube, to be reported in the following, has been performed in a test duct shown in Fig. 1 (b) with Ar-K mixture as the working gas. The selected plasma conditions are;

temperature: $T=1970^\circ\text{K}$,
pressure: $P=1.2\text{ atm}$,
flow velocity: $U=900\text{ m/sec}$,
number density of K: $n_K=1.2\times 10^{15}/\text{cc}$.

An example of the open voltage of a Faraday generator for a magnetic field intensity of 11 kG is shown in Fig. 3 (d). The rise time is short, and the flow velocity determined from the open voltage (UBd) agrees with the value calculated from the shock velocity. The small irregularities on the signal are considered to come from the disturbance of the protruded electrodes. The fall of the voltage after 0.5 msec is probably due to the three-dimensional character of the contact surface and the influence of the boundary layers.

Fig. 3 (e) represents an oscillogram obtained when all electrodes ($E_1\sim E_9$) are loaded separately by resistors. I_E denotes the Faraday current (normal to the flow) on the electrode pair E_9 . The shock front reaches this electrode about $200\text{ }\mu\text{sec}$ after the oscilloscope is triggered, and a nearly uniform saturated current is attained about $350\text{ }\mu\text{sec}$ thereafter. $V_{E_9-E_8}$ is the open Hall voltage between the electrodes E_9 and E_8 . Superposed on the signal, an oscillation at a high frequency of about 100 kc is observed. From the Faraday current output the ionizational relaxation time behind the shock wave is estimated to be about 0.3 msec.

A conventional current-voltage characteristic curve is drawn in Fig. 4, whereby the mean value of the current after saturation is used. This has been obtained by successively varying the value of the load resistance, as indicated in the figure. In

Fig. 4 Current-voltage characteristics

the case of the negligible electrode drop and of a uniform electrical conductivity of the plasma, the V - J characteristics would be straight line connecting the open voltage (ordinate) and the short-circuit current (abscissa). The nonlinearity of the curve evidenced in Fig. 4 is considered to be caused by the electrode drop in small-current region, and by the nonequilibrium ionization in large-current region, respectively. The electric power P_W may be obtained from such V - J characteristics as

$$P_W = JV \dots \dots \dots (10)$$

Though in thermal equilibrium the curve P_W vs. J should be a parabola having a maximum, a monotonously increasing curve is obtained in the case of nonequilibrium MHD power generation.

4.2 Electrical conductivity and Hall coefficient

Even if the electrical conductivity of the plasma remains constant, the voltage drop near the electrodes caused by their low temperatures gives the voltage-current plot for an MHD generator a curved shape and makes it impossible for the conductivity to be derived directly from such data. Accordingly, probes $F_1\sim F_4$ were inserted between electrode pairs to measure the potential distribution and an example of the result is shown in Fig. 5. The voltage between an electrode pair is written⁽¹³⁾ as

$$V = V_0 - Ir - V_E \dots \dots \dots (11)$$

where V_0 , V_E , r and J denote, respectively, the open voltage (for a load resistance of infinity), the electrode drop, the plasma resistance and the electric current. Since V_0 , V_E and V are obtained from Fig. 5 and J is measured directly, r , and hence the mean electrical conductivity $\sigma_m = d/sr$, of the plasma may be calculated by way of Eq. (11), where d and s are the gap length and the effective area of the electrode pair, respectively. In order to de-

Fig. 5 Potential distribution between electrodes

termine the experimental value of the true (scalar) electrical conductivity σ_{exp} from σ_m , corrections have to be introduced for the Hall effect, represented by the Hall parameter $\beta = \omega_e \tau_e$ (ω_e being the cyclotron angular frequency and τ_e the mean collision period of electrons) and for the nonideal segmentation of the electrodes i.e. the finiteness of the electrode spacing b ⁽¹⁴⁾. Such a relation has in practice been given in numerical forms⁽¹⁵⁾, namely as

$$\sigma_{\text{exp}} = f(\sigma_m, \beta, b, c, d) \dots\dots\dots (12)$$

The value of the Hall coefficient β , required for the application of Eq.(12), was estimated here in the following way.

Denoting the electric current density by j , the electric field strength by E , the magnetic flux density by B and the flow velocity by U , each as vector quantity, the Ohm's law with the Hall effect (but in the absence of the ion slip) may be written as follows (the electrode segmentation being assumed to be ideal):

$$j = \sigma(E + U \times B) - \beta(j \times B)/|B| \dots\dots\dots (13)$$

The second term on the right-hand side represents the Hall effect. Let us now call the direction normal to the tube axis (and to the magnetic field) the Faraday direction and that parallel to the tube axis the Hall direction, and denote each by the subscripts N and H , respectively. Then the vector equation (13) is resolved into the following pair of scalar equations.

$$j_H = \sigma(E_H - U_N B) + \beta j_N \dots\dots\dots (14.a)$$

$$j_N = \sigma(E_N + U_H B) - \beta j_H \dots\dots\dots (14.b)$$

The interaction parameter defined by Eq. (9) being small, the velocity component U_N may be neglected. Let us further assume the axial velocity component U_H to be constant and write it simply as U . Then, by solving Eqs.(14.a) and (14.b), the Hall coefficient is expressed as

$$\beta = \frac{j_H(UB + E_N) - j_N E_H}{j_N(UB + E_N) + j_H E_H} \dots\dots\dots (15)$$

Correction should strictly be made to this value of the Hall coefficient for the finiteness of the electrode segmentation. For a smaller value of β , little difference exists between nonequilibrium and equilibrium situations⁽¹⁵⁾.

The electrical conductivity obtained by the above-mentioned procedures varied with the electric current density, as expected in nonequilibrium ionization.

Fig. 6 shows experimental results at $T=1970^\circ\text{K}$, $P=1.2$ atm $n_K=1.2 \times 10^{15}/\text{cc}$. The theoretical electrical conductivity in thermal equilibrium in the same thermodynamic state is represented by the horizontal broken line. This figure shows that the nonequilibrium effect prevails at current densities above 0.01 A/cm².

In any of the steady-flow induced electric field experiments reported so far, the characteristics has shown a slight increase of σ above the equilibrium level only at large j . On the other hand, the experiments with an externally applied electric field have always yielded σ - j characteristics fairly close to the nonequilibrium predictions⁽¹⁶⁾. Although the present result falls somewhat short of the theoretical curve, nonequilibrium behavior is clearly demonstrated in it. The agreement between the theoretical and experimental curves is improved in the neighborhood of the maximum current density, i.e. towards 1 A/cm². Incidentally, the discrepancy between them is considered to be partly due to the uncertainty in the value of argon-electron collision cross-section employed in the calculation. This point will be discussed later in this paper.

For smaller values of electric current density, the conductivity obtained was even lower than the equilibrium prediction. This came about probably because the electron temperature in the shock-produced plasma was hundreds of degrees lower than its translational temperature due to radiation loss from the electron gas⁽¹⁷⁾.

The electric potential distribution between the electrode pair shown in Fig. 5 demonstrates the presence of sizable electrode drops. The electrodes in the present work are considered to be completely cold electrodes. The typical thickness of boundary layers on them during the test time is estimated to be of the order of 0.1 mm, which is about $1/10$ of that in a practical generator duct. The Hall electric field intensity in the absence of Hall current may be written, from Eq.(14), as follows:

$$E_H = -\beta(E_N + UB) \dots\dots\dots (16)$$

Even when the current is short-circuited in the Faraday direction, the residual electric field E_N (due to the space charge effect on the electrodes) is still sizable, and, since it has an opposite sign

Fig. 6 Variation of conductivity with current density

to the term UB , the Hall electric field obtained is always smaller than the ideal value. This will provide an explanation to the fact reported in the past steady-flow works that the Hall open voltage is less than half of its theoretical value.

When the quantity δ in Eq. (1) is large, the difference between T_e and T will be small, and the nonequilibrium ionization will not take place. δ for a monatomic molecule is known to be close to 2, while that for a polyatomic component may exceed 10 due to the inelastic collisions⁽¹⁰⁾. Thus, in a nonequilibrium MHD power generation experiment, the presence of polyatomic impurities in the working gas would result in a reduction of the electrical conductivity.

Fig. 7 illustrates the results of experiments wherein a small amount of nitrogen or air was introduced in the test gas and the drop of electrical conductivity due to the impurity was measured. The effect of nitrogen consists exclusively in the increase of δ . Air had a much larger effect, an amount exceeding 100 ppm resulting in a considerable decrease of σ . In this case, an additional effect is probably brought about by oxygen in air combining with free K atoms and reducing the number of the latter. The chemical equilibrium conditions for the reactions between K and O are expressed (for KO and K_2O formations, respectively)⁽¹⁸⁾ as

$$\log \frac{(K)\sqrt{(O_2)}}{(KO)} P^{1/2} = -5740/T + 2.35 \quad (17)$$

$$\log \frac{(K)^2\sqrt{(O_2)}}{(K_2O)} P^{3/2} = -16600/T + 6.20 \quad (18)$$

where () denotes the mole fraction of the component concerned. In the presence of water vapor and carbon dioxide, Eqs. (17) and (18) are to be supplemented by the following:

$$\log \frac{(K)(OH)}{(KOH)} P = -20000/T + 6.23 \quad (19)$$

$$\log \frac{(K_2O)(CO_2)}{(K_2CO_3)} P = -19200/T + 4.95 \quad (20)$$

Throughout the above equations P denotes the total

Fig. 7 Variation of conductivity with impurity level

pressure, i.e. the sum of the pressures of K and the impurities.

Under the present shock tube conditions, 4000 ppm of air is roughly estimated to cause a reduction of the K number density which results in a 90% drop in the electrical conductivity. The attainment of impurity level below 100 ppm will not be impracticable in view of the development of the purification technology for the He gas-cooled atomic reactor⁽¹⁹⁾. One of the reasons of the past failure in the steady-flow nonequilibrium ionization experiments is considered to be the presence of impurities issuing from heaters or duct walls simulating the atomic reactor arrangements.

4.3 Electron energy balance

The energy balance condition for the electron gas is given by Eq. (1), wherein the collision frequency ν_i may be rewritten, in terms of the number density of the i th species n_i and its cross section with the electron Q_i , as

$$\nu_i = n_i Q_i \sqrt{\frac{8kT_e}{\pi m}} \quad (21)$$

On the other hand, the electron density is expressed, by virtue of the identity $\sigma = (e^2/m)n_e\tau$ (e is the unit charge), as

$$n_e = \sigma B / e\beta \quad (22)$$

The equilibrium condition for the electron gas gives the Saha equation, by which the electron temperature T_e is determined from n_e , n_K and P . Thus, if we put $\delta = 2$, the elastic collision term in Eq. (1) becomes known. The radiation loss L at

Fig. 8 Electron energy balance

various electron temperatures is obtained by subtracting this quantity from the measured Joule heating energy (see Fig. 8). For the value of the load resistance below $10\ \Omega$, the elastic collision term exceeds the radiation loss term. Theoretically, the latter depends also on the duct shape.

At lower current densities the Joule heating energy is negligible and the electron temperature can be lower than the gas (translational) temperature by hundreds of degrees. Under such circumstances, the temperature of the bound electrons and that of the electron gas are essentially in equilibrium, and, since the bound electrons keep losing energy by radiation, the electron temperature has to be lower than the gas temperature.

The energy balance equation in this case is reduced⁽¹⁷⁾ to

$$L = \left(\sum_i \delta_i \frac{m}{M_i} \nu_i \right) n_e \frac{3}{2} k (T - T_e)$$

This is why the elastic collision loss becomes negative for T_e below the equilibrium gas temperature (1970°K) in Fig. 8. Also the heat conduction by electron gas would no longer be negligible if the diameter of the duct is below about 1 cm. Anyway, the nonequilibrium electrical conductivity is observed only when the electron density exceeds $10^{12}/\text{cc}$. The conductivity may amount to about 20 times the equilibrium value.

A comparison is made in Fig. 8 between the radiation loss calculated as above by Eq. (1) (using experimental data for Joule heating energy and elastic loss) and an available theoretical curve⁽⁷⁾. The agreement is considered to be satisfactory.

4.4 Momentum cross sections

The value of the momentum cross section of a neutral component in its collision with an electron is not quite well-established except for hydrogen. Here we have devised a method to determine it

experimentally by way of the measured Hall coefficient. Namely, while we obtain the Hall coefficient β from Eq. (15) with appropriate corrections made for the finite segmentation of electrodes, the theory of collisions yields

$$\beta = \frac{eB}{mc} \frac{1}{V_e \sum_i n_i Q_i} \quad (23)$$

$$V_e = \sqrt{\frac{8kT_e}{\pi m}} \quad (24)$$

where m , c , n_i , k and Q_i denote the electron mass, the light speed, the number density of gas molecules, the Boltzmann constant and the cross section between the i th component and the electron, respectively. If we have n_i and T_e in addition to β , then Q_i may be calculated by means of Eq. (23).

Fig. 9 shows the relation between the cross sections for Ar, N_2 and K and the temperature. The results for nitrogen are seen to be in agreement with the curve obtained in the past, whereas those for argon turned out to be twice as large as the data from the D.C. discharge experiments. It is likely that the cross section of Ar obtained in the latter type of experiments is not applicable in the presence of a magnetic field⁽¹⁰⁾. The values for K showed a considerable scatter, and an indication of the Ramsauer effect for this species (as well as for Ar) was seen⁽¹³⁾.

4.5 Nonequilibrium MHD power generation experiments with nitrogen in a metastable state

In order to produce nitrogen molecules in an electronically metastable state, experiments were performed in the shock tube with an auxiliary discharge system (600V, 500 μF , 5 cm-gap) installed upstream of the generator section⁽²²⁾. Fig. 3 (f) shows a typical sample of the output current and the auxiliary discharge current in an Ar- N_2 -K plasma (1530°K , 1.8 atm, 850 m/sec, $n_K = 10^{14}/\text{cc}$). The electrical conductivity was calculated by the procedures described in 4.2, and is shown in Fig. 10. The electrical output was very small in the absence of the auxiliary discharge, or in the presence of impurities like carbon dioxide and air intentionally introduced in the test gas. The discontinuities in the output signal in Fig. 3 (f) have been caused by the influence of the auxiliary discharge. However, the absence of the effect on the output current of the polarity of the discharge seems to indicate that the latter caused no appreciable electrical disturbances. Incidentally, the input power for the auxiliary discharge was about 10 kW, and was small compared with the thermal input for the shock-produced plasma (about 100 kW). Since the seeding ratio in this method is smaller than in other methods, being below 10^{-4} , a reduction in the technical difficulties associated

Fig. 9 Momentum cross section

with the life of structural materials and the restoration of seeding materials is to be expected. Further studies are still needed on the nonuniformities in the electrical conductivity and the flow instability observed in experiments utilizing magnetically induced electric field. Also desirable is a quantitative measurement of the electrical conductivity, electron density, and metastable molecule density over 10 msec (flow time in an actual generator). A shock tube provides too short a duration for such a work, and a steady flow apparatus will be more useful.

5. Discussion

Nowadays, there at least are five conditions yet to be fulfilled before the MHD power generation utilizing the nonequilibrium ionization by magnetically induced electric field is put to practical use. Those are (1) the increase of the magnetic field and the flow speed (to produce a stronger induced voltage), (2) the minimization of impurities, (3) the design criteria for optimum duct and electrode shapes, (4) the elimination of plasma instabilities and the resulting conductivity deficit and (5) the clarification of the ionizational relaxation processes.

In connection with the item (1), the increase of the magnetic field could not be done so easily in this case as in combustion gas plasmas because of the possibility of the instability promotion, whereas the unlimited increase of the flow speed, though desirable, would lead to a drastic drop of the gas (static) temperature (the total temperature being

Fig. 10 Nonequilibrium ionization by metastable nitrogen

kept constant in the adiabatic processes). Thus there would be an optimum value for the latter. Further studies in this respect are needed. The influence of impurities has been shown in Fig. 7, whence its maximum allowable level is seen to be about 100 ppm.

As regards the duct and electrode shapes, Kerrebrock⁽²³⁾ performed a theoretical analysis of the boundary layers on the electrodes and the insulator wall sections, and inferred theoretically that a sizable deficit of electron temperature as compared with the ideal value would occur from the nonuniformity in the electrical conductivity inherent in nonequilibrium ionization. This indeed is an important aspect of nonequilibrium MHD power generation. The use of some duct shapes other than simple straight ducts which might eliminate this difficulty (for example, the disk-type generator yielding high output density wherein the Faraday current forms a circumferentially closed loop) should perhaps be considered. A shock tube is not quite suitable for the study of such boundary effects because of its thin boundary layers. However, since it gives the data of generator performance in ideal conditions as reported here, it will be profitable to test various types of generators by the shock tube measurements in the first place, and then to perform the corresponding steady-flow experiments. In this sense, the MHD power generation experiments by shock tubes will in future become more popular in all countries.

Fig. 11 Effective conductivity and Hall coefficient

The plasma instability consists of the thermal and the magneto-acoustic wave instabilities. The former occurs in the electron gas and originates from the spatial variations of electron temperature and density and the phase difference between the two. In the latter, the energy for ionization is consumed in the excitation of sound waves. In either case, the effective conductivity drops with the increase of Hall parameter. Those instabilities are not readily observed in shock tube experiments because they require finite times for their growth to finite amplitudes. Thus such phenomena have to be investigated in a steady-flow apparatus or a discharge tube. Fig. 11 shows the ratio of the conductivity σ at finite β (Hall coefficient) to the conductivity σ_0 at $\beta=0$ with β as the abscissa. The curve 1 is from Kerrebrock's experiments⁽²³⁾, and the curve 2 from Belousov's discharge-tube measurements⁽²⁴⁾. The curve 3 shows the results of the Brederlow's theoretical analysis,⁽²⁵⁾ while the curves 4 are the same as by Louis. If we denote the ratio of the root-mean-square A.C. component of the electron density due to instability to its D.C. level by $A^{1/2}$, σ/σ_0 is expressed in terms of β as follows:

$$\frac{\sigma}{\sigma_0} = \frac{1 + \left(\frac{\beta^2 A I}{1 + \beta^2} \right)^2}{1 + \left(\frac{\beta^3 A I}{1 + \beta^2} \right)} \quad (25)$$

where

$$I = \frac{(\beta^2 - 1) \tan^{-1} \beta}{2\beta^2} - \frac{1}{2\beta} \quad (26)$$

The curves 4 correspond to $A=0.1$ and 0.5 . The experimental results of this work are shown by the curve 5. The decrease of effective conductivity is small compared with other curves, clearly due to the short duration and incomplete growth of the instability waves. In calculating this curve, the ideal conductivity was taken from Fig. 6, and its effective value and Hall coefficient determined experimentally were used. Incidentally, a comparison of Fig. 3(e) and (f) shows a prominence of high frequency oscillation (about 100 kc) in the nonequilibrium output current by the magnetically induced electric field as compared with the same by the metastable nitrogen.

The method of nonequilibrium MHD power generation with metastable nitrogen molecules as energy carriers seems promising. An alternative method using a metastable state of argon (11.6 eV) to ionize potassium requires a higher voltage, but has as large a cross section as $2.08 \times 10^{-15} \text{ cm}^2$, so that it might be worth considering also.

6. Conclusions

The performances of the nonequilibrium MHD

generators so far obtained in steady flow experiments have all fallen far short of theoretical predictions. The present study was started with an aim to investigate the cause of such discrepancies between theory and experiment and further to establish the potentiality of the inert-gas MHD power generation, clarifying the phenomenon of nonequilibrium ionization and finding the required conditions in the development of MHD power generation at the same time. The main results obtained in this paper may be summarized as follows:

(1) A method of heating the shock tube itself was tested in order to seed the inert gas with an alkali metal at suitable partial pressures. Conditions appropriate for MHD power generation were successfully obtained in the shock tube.

(2) It was verified that, unlike in steady-flow experiments, nonequilibrium ionization under near-ideal conditions, free from instability phenomena and boundary effect, was realized in the shock tube. The values of the nonequilibrium electrical conductivity close to the theoretical predictions were obtained.

(3) It was shown that the nonequilibrium ionization was strongly influenced by the presence of diatomic molecules (especially the oxygen molecules in air) and that the impurity level above 100 ppm caused an appreciable drop in the electrical conductivity. It was demonstrated accordingly that the high purity level of the working gas would be an essential condition for future nonequilibrium MHD power generation.

(4) In view of practical difficulties in the nonequilibrium ionization by induced electric field, an alternative method utilizing metastable nitrogen molecules was proposed, and some preliminary performance data were presented.

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Errata (Vol. 10, No. 37, February, 1967)

Author	Page	Column	Line	For	Read
K. MIZOGUCHI	61	Eq. (15)	3	$\Theta = \sqrt{\frac{\rho a^3 h^2}{D}} \omega$	$\Theta = \sqrt{\frac{\rho a^2 h^3}{D}} \omega$
	64	left	27	$c = 5 \text{ m/sec}$	$c = 5 \times 10^{3/2} \text{ m/sec}$
	65	Fig. 4		$(c = 0.5 \text{ m/sec})$	$(c = 0.5 \times 10^{3/2} \text{ m/sec})$
	"	Fig. 5		$(c = 1 \text{ m/sec})$	$(c = 1 \times 10^{3/2} \text{ m/sec})$
	"	Fig. 6		$(c = 3 \text{ m/sec})$	$(c = 3 \times 10^{3/2} \text{ m/sec})$
	"	Fig. 7		$(c = 5 \text{ m/sec})$	$(c = 5 \times 10^{3/2} \text{ m/sec})$

Errata (Vol. 11, No. 45, June, 1968)

Author	Page	Column	Line	For	Read
K. MIZOGUCHI et al.	401	Fig. 9	caption	$m_\theta / 6M_\theta / h / Pl / 4\pi a^2$	$m_\theta = 6M_\theta / h / Pl / 4\pi a^2$
T. HATA et al.	406		14	dy	by
	407		2	$= \frac{-\omega^2 \frac{E_z^*(\bar{\theta})}{E_r^*(\bar{\theta})} \nu_{r\theta} - \nu_{zr}^2}{\omega^2 \frac{E_z^*(\bar{\theta})}{E_r^*(\bar{\theta})} - \nu_{zr}^2}$	$= \frac{-\omega^2 \frac{E_z^*(\bar{\theta})}{E_r^*(\bar{\theta})} \nu_{r\theta} - \nu_{zr}^2}{\omega^2 \frac{E_z^*(\bar{\theta})}{E_r^*(\bar{\theta})} - \nu_{zr}^2}$
S. KUMAKURA	436	left	10 from bottom	macrographic	macroscopic
	"	"	8 from bottom	micrographic	microscopic
Y. SATO et al.	447	Fig. 2		Exchange photo. (a) for (c).	
Y. YAMADA et al.	459	Eq. (36)	18	$L_0^* = 12\mu r_i r_0 Q \dots$	$L_0^* = -12\mu r_i r_0 Q \dots$
	"	"	20	$= \frac{12\mu\pi r_i r_0 e}{2\delta^2 + e^2 \sqrt{\delta^2 + e^2}}$	$= \frac{12\mu\pi r_i r_0 e}{(2\delta^2 + e^2) \sqrt{\delta^2 + e^2}}$
K. FUJITA	516	left	foot-	Okayama University	Okayama University
	518	right	notes	axis	axes