The use of double water-lubricated seal causes the cold trap system to separate the drained water.

(4) The heat transfer tests of the polyzonal spiral fins with splitters are made by the use of the HTPG loop.

(5) The efficiency of the trapezoidal fins which can be obtained by the solution of the conduction equation is represented. As the result, it has been found that over the range of operation, the friction factor and Nusselt number produce linear plots against Reynolds number.

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Experimental Study of MHD Power Generation*

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An MHD generator, with constant flow sectional area of 50×120 mm and active length of 1000 mm, was constructed and experiments were conducted using combustion gas as working fluid. Generator channel was composed of MgO insulating walls and 20 segmented graphite electrode pairs and magnetic field of 14 kG was applied. Voltage, current, and output power characteristics were investigated under various conditions and maximum output of 17 kW was obtained at 7 MW input.

The analysis of the generator was done assuming one-dimensional flow and the results were compared with experiment. As to induced voltage, theoretical and experimental results showed good agreement, but there was substantial discrepancy as to current and output power. By estimating, however, the electrical conductivity of gas lower than the theoretical value, agreement was improved. From this it may be concluded that, apart from the problem of electric conductivity of gas, the one-dimensional hydraulic flow analysis of channel represents the reality fairly well even on this scale of generator.

1. Introduction

MHD power generation is of interest for its high thermal efficiency and low generating cost. To understand the nature of MHD power generation and technical difficulty of its practical development, we have conducted various experiments on MHD power generation including a tentative manufacture of a 7 MW thermal input experimental

MHD generator. Technology of MHD power generation involves a wide field ranging from a high temperature technique of over 2000°C which is not common except in rocketry, etc. to the development of a superconducting magnet which still belongs to the domain of science. Thus, it is not easy at the present stage to make any definite forecast for the future possibilities of MHD power generation. In this respect, our achievement may be regarded as a mere milestone on the long way to perfection of MHD power generation; yet fully aware of its own merit, we are going to introduce the results of our researches centering around the 7 MW experimental MHD

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generator.

Notations employed in this paper are as follows:

- A : sectional area of generator channel
- B : magnetic flux density
- C_f : index to friction drag on wall surface
- C_h : index to heat loss from wall surface
- D : hydraulic diameter of channel
- e : electron charge
- ΔH : difference between total enthalpy of working gas and enthalpy of it at wall temperature
- h : Planck's constant
- i : enthalpy
- j_e : current density due to thermionic emission
- k : Boltzmann's constant
- K : ratio of sum of terminal voltage and electrode drop to induced voltage
- K_{el} : ratio of electrode drop to induced voltage
- m_e : electron mass
- M : Mach number, average molecular weight of gas
- n : isentropic exponent
- P : pressure
- R : gas constant
- T : temperature
- ϕ : work function
- σ : electric conductivity
- τ_e : mean free time of electron
- ω_e : cyclotron frequency of electron

2. 7 mW thermal input MHD experimental generator

A 7 mW thermal input was taken as minimum scale that can simulate the real scale to a certain extent. The induced voltage was expected to exceed 100V, which is sufficiently higher than the electrode drop. Thus, the experimental generator is believed to permit investigation from the standpoints of

Fig. 1 7 mW thermal input MHD experimental generator

both thermodynamics and power generation characteristics. Its details are as follows (its appearance as shown in Fig. 1):

(a) thermal input—7 mW, (b) fuel—light oil (if necessary, kerosene or heavy oil), (c) seeding—potassium soap dissolved in fuel, (d) flow rate of combustion gas—800 g/sec (max), (e) generator channel— $50 \times 120 \times 1000$ mm, (f) electrode—segmented graphite, 20 pairs, (g) magnetic field strength—14 kG, (h) running time—5 minutes, (i) electric output—17 kW

2.1 Combustion system

The combustor was tentatively designed as a reaction motor, with a considerably large ratio between combustion chamber section and nozzle throat section for the sake of higher combustion efficiency and greater flame stability, accordingly resulting in 50 msec residence time which was larger by a factor of almost ten than about 10 msec of a common reaction motor.

A block diagram of the combustion system is shown in Fig. 2, and Fig. 3 shows a cross section of the combustor. The combustion chamber is composed of an oxygen chamber, a swirler, the inner tube and nozzle of the combustion chamber which are fabricated of heat resisting stainless steel, and the outer tube fabricated of mild steel plate. A mixture of light oil with pure oxygen is employed for combustion and the combustor is so designed as to permit continuous operation to a certain extent. As illustrated in Fig. 2 showing the control system, oxygen at first goes into the surge tank and after being adjusted to the pressure corresponding to the necessary flow rate by the pressure regulating valve it is fed through a solenoid valve to the oxygen chamber.

Potassium in the form of soap is blended into the fuel, which is well agitated by the mixer, properly compressed and then through a solenoid valve supplied to the main fuel nozzle. Ignition is done by an electric spark acting on propane gas added with an appropriate amount of oxygen. If the main fuel is supplied immediately after ignition, combustion will take place so suddenly that there will be a sharp rise in the temperature and in consequence the parts of apparatus will be exposed to an excessively heavy thermal shock; to prevent this, the generator channel is preheated by the propane gas for ignition. Following the preheating, oxygen and main fuel are sent to the combustion chamber in approximate proportions of 3 : 1. Thereby, the inner tube, which is exposed to much radiation heat, is cooled with water which is circulated in the space between inner and outer tubes.

The internal pressure of combustion chamber at rated condition exceeds the gauge pressure of 2 kg/cm^2 and the expanded gas becomes a jet stream of almost sonic speed at the nozzle throat. Under such high speed the proportion of convective heat transfer reaches an enormous value near the nozzle and the wall temperature rise becomes remarkable. Therefore, the nozzle portion is attached with fins on the cooling water side to increase the heat transfer area and thereby improve the cooling effect.

Through these design considerations, the temperatures at inner tube and nozzle throat were held to about 300°C .

2.2 Generator channel

The generator channel is constructed of MgO side wall bricks, graphite electrodes and MgO pieces inserted among electrodes to insulate them. The sectional area of the path of gas flow is constant

along the channel length and its dimension is $50 \times 120 \times 2000 \text{ mm}$, of which the central 1000 mm serves for power generation. The electrodes are composed of independently loaded 20 pairs to prevent Hall current.

The generator channel is set in the magnetic field of 14 kG created by an electromagnet and it is cooled with water circulated between the stainless steel frame and the magnetic pole piece contacting therewith.

To know the behavior near the electrode, an external DC voltage was impressed to investigate the voltage-current characteristic. The results showed that the voltage drop near the electrode increased in proportion to the current at a current density of less than 0.8 A/cm^2 , but beyond this density it would be saturated to about 20 V . The current density due to thermionic emission, j_s , is expressed by

$$j_s = AT^2 \exp(-e\phi/kT) \text{ A/cm}^2$$

where

$$A = 4\pi me k^2 / h^3$$

Substituting $j_s = 0.8 \text{ A/cm}^2$, $T = 2500^\circ\text{K}$ into the above gives the work function $\phi = 4.53 \text{ eV}$, which corresponds to $\phi = 4.4 \text{ eV}$ for graphite. Thus, up to 0.8 A/cm^2 it is a thermionic emission and beyond that it is supposed to change into an arc condition, making the electrode drop constant.

For the purpose of obtaining highly heat-resisting bricks, it is necessary to assure high purity of materials and to adopt high baking temperature; commercially available MgO bricks are of 95% purity and baked at 1500 to 1600°C . As the temperature of over 70% of the melting temperature is necessary for baking, this is obviously insufficient and it will readily be eroded and go out of service under severe conditions of temperature and speed in MHD generator channel.

We prepared 99% pure brick baked at 1700 to 2000°C and compared it with the common one in the generator channel. Fig. 4 illustrates the test results after about 10 repetitions of 2 to 3 minutes operation. The common brick was eroded to half its

Fig. 2 Control system diagram

Fig. 3 Combustor section

original thickness, while the tentative one was only a little eroded, which showed that it could be sufficient for the experimental purpose.

2.3 High temperature gas for experiment

For practical development of MHD power generation, the working gas should possess an electric conductivity of at least 10 mho/m or so. To secure such high electric conductivity, the gas temperature ought to be higher than 2000°K; then the gas will be subject to dissociation and no simple expression of its properties will be possible. We employed for our experiment a mixed solution of light oil with potassium compound and burned it with oxygen. A stoichiometric reaction equation for our experiment is illustrated by

Fig. 4 Erosion of MgO brick

C : H : O : K = 1 : 1.994 : 2.998 : 0.017

CO₂ gas, H₂O crystal, H₂ crystal, O₂ crystal, their enthalpies at 0°K being assumed zero

Fig. 5 *i-s* chart of combustion gas employed for experiment

The *i-s* chart of this gas is given in Fig. 5, which shows that dissociation is promoted at a higher temperature and lower pressure and there is a sharp increase in enthalpy.

Average molecular weight and electric conductivity were also calculated and shown on the *i-s* chart of Fig. 5.

In the power generating experiment using this fuel the values of σ were measured to be 20 to 30 mho/m which gives a rough agreement with theoretical value. The Hall coefficient $\omega_e \tau_e$ was calculated to be about 1.5 at the representative condition of experiment.

3. Experiments and considerations

3.1 Characteristic tests of combustor

The combustor as the source of working fluid should desirably be fully stable at a high temperature of 3000°K or so, less subject to heat loss through cooling and possess high combustion efficiency. In this connection, the characteristics of combustor were investigated prior to power generating experiment.

This combustor burned on pure oxygen, so that it was relatively easy to obtain a high heat release rate and the combustion was stable under the condition of no generator channel being connected up to the rated fuel flow of 200 g/sec. Next, a cooling loss test was performed.

The cooling heat loss was found from the amount of cooling water and its temperature rise. If for example the heat loss in the case of fuel flow 100 g/sec is taken on the abscissa, against the theoretical heat of combustion with the time lapse after ignition, we get Fig. 6, which shows that the loss in the combustor accounts for about

Fig. 6 Heat loss in combustor

17% of the thermal input from fuel at steady state. The temperature drop from the adiabatic flame temperature as the result of this loss will amount to about 200°K, while the decline in electric conductivity is still more remarkable, amounting to half the original value.

Thus in an experimental device like this, the proportion of heat loss will be great and particular attention should be paid to minimizing the heat loss.

Next, the contents of this heat loss are to be analyzed. Heat flux into the cylindrical part of combustor due to this 17% heat loss is calculated to be about 5×10^5 kcal/m²hr. Such radiative heat transfer of seeded gas accompanied by considerable thermal dissociation at high temperature has very much left to be investigated by further researches. But if thermal dissociation is neglected and the gas is assumed to be a mixture of carbon dioxide and water vapour at 1:1, the heat flux due to radiation at the theoretical flame temperature of 2900°K with 17% heat loss will amount to about 4×10^5 kcal/m²hr. Meanwhile, the heat flux due to convection heat transfer will be lower by a factor of ten. Comparison of these values with measured ones reveals that the greater part of transfer has occurred as radiation, and from this heat flux, the combustor wall temperature is estimated at about 300°C.

Concerning the cooling heat loss, it may be contended that the combustor with water-cooled wall construction is practicable enough with respect to both heat resistance and heat loss, because the 17% heat loss can be cut down to 1% or less in a practical combustor which will develop a thermal input 10^3 times and pressure several times those of the experimental one.

As already pointed out, however, this 17% heat loss was experimentally undesirable, so the combustor was lined with MgO bricks 500 mm thick. The results are as indicated in Fig. 6, thus,

Fig. 7 Oscillograms of induced voltage and current

the temperature distribution within the bricks did not attain steady state even after five minutes of operation; but it will be possible to predict the heat loss under steady state in the case of MgO brick lining, because it has been confirmed through experiment on the water-cooled wall that there is no great error in the estimation of the gas emissivity. The expected heat flux after steady state is attained is about 1×10^5 kcal/m²hr and these experiments had proved considerable effectiveness of brick lining and the subsequent power generating experiment was conducted with brick lining.

3.2 Generator characteristics

Experiments were carried out with the gas flow varied between 300 and 800 g/sec. Since the 20-segmented electrodes could be switched between open circuit, two resistances and short circuit, the relation between terminal voltage and current along the channel could be established. The voltmeter and the ammeter were photographed by a polaroid camera and thus numerous indications could be recorded during short period. Meanwhile, the time changes in typical electrodes were recorded by an electromagnetic oscillograph.

Fig. 7 illustrates an example of measurements. In this measurement after the refractory bricks of the generator channel were preheated by propane gas flame, definite amounts of fuel oil and oxygen were supplied and this supply was maintained thereafter. With start of combustion, the voltage was induced to nearly a constant value and the fluctuation was extremely small, indicating that the flow of combustion gas was stable. Meanwhile, the current took considerable time after ignition before being saturated and attaining a steady value. The time change in the short circuit current in one of the electrodes is represented in Fig. 8, which seems to show that while the main stream of gas reaches a constant temperature immediately on ignition, thus acquiring a constant velocity and inducing a constant voltage, considerable time should pass before the electrode temperature rises and the electric resistance on the electrode surface

Fig. 8 Time change in short circuit current

due to various mechanisms drops. The open circuit voltage on each electrode at varied gas flow is shown in Fig. 9 and an example of current vs. output power characteristic in Fig. 10 as a solid line.

These results are to be checked against theoretical analysis. Supposing that the electrode is divided into an infinite number of pieces, the Hall effect is neglected and all the magnitudes are assumed to change one-dimensionally only in the flow direction, the following equation will hold within the generator channel⁽¹⁾.

Equation of motion:

$$\frac{dM^2}{M^2} + \left[\frac{2}{nM^2} \frac{P}{n} \left(\frac{\partial n}{\partial p} \right)_T + \frac{P}{R} \left(\frac{\partial R}{\partial P} \right)_T \right] \frac{dP}{P} + \left[1 + \frac{T}{n} \left(\frac{\partial n}{\partial T} \right)_P + \frac{T}{R} \left(\frac{\partial R}{\partial T} \right)_P \right] \frac{dT}{T} + \left[4 \frac{C_f}{D} \frac{2}{nM^2} \frac{\sigma B^2 (1-K) M \sqrt{nRT}}{P} \right] dx = 0$$

Equation of continuity:

$$\frac{dM^2}{M^2} + \left[2 + \frac{P}{n} \left(\frac{\partial n}{\partial P} \right)_T - \frac{P}{R} \left(\frac{\partial R}{\partial P} \right)_T \right] \frac{dP}{P} + \left[-1 + \frac{T}{n} \left(\frac{\partial n}{\partial T} \right)_P - \frac{T}{R} \left(\frac{\partial R}{\partial T} \right)_P \right] \frac{dT}{T} + \frac{2dA}{A} = 0$$

Equation of energy:

$$\frac{dM^2}{M^2} + \left[\frac{2}{nM^2} \frac{P}{RT} \left(\frac{\partial i}{\partial P} \right)_T + \frac{P}{n} \left(\frac{\partial n}{\partial P} \right)_T + \frac{P}{R} \left(\frac{\partial R}{\partial P} \right)_T \right] \frac{dP}{P} + \left[\frac{2}{nM^2} \frac{1}{R} \left(\frac{\partial i}{\partial T} \right)_P + 1 + \frac{T}{n} \left(\frac{\partial n}{\partial T} \right)_P + \frac{T}{R} \left(\frac{\partial R}{\partial T} \right)_P \right] \frac{dT}{T} + \left[\frac{2}{nM^2} \frac{(1-K)(K-K_{el})\sigma B^2 M \sqrt{nRT}}{P} + \frac{2C_h \Delta H}{nM^2 DRT} \right] dx = 0$$

As already stated, in a combustion gas of nearly 3000°K considerable thermal dissociation takes place; and since the extent of this dissociation depends on temperature and pressure, it is inadequate to assume all the properties of gas constant. Therefore, from calculations of the above-mentioned properties of gas the necessary thermodynamic values and transport properties at various temperature and pressures were derived and using them the above equations were solved.

For the purpose of calculation, the total temperature of gas in the combustor was assumed 3000°K, the wall temperature of generator channel 2000°K and invariably 20 V was allowed for electrode voltage drop. The magnetic flux density in the experimental device was 14 kG at channel center, being distributed with steadily decreasing value toward both ends.

For calculation, the distribution was approximated such that the value was 14 kG in the central range of (channel length) × 0.4 and decreased parabolically toward both ends, registering 75% of the value at center; and the values of C_f , C_h were taken from ref. (1). The calculated results are indicated by dotted lines in Figs. 9 and 10. The theoretical open circuit voltage follows a trend closely resembling that of the experimental one, and the flow velocity distribution as calculated therefrom is expected to agree well with the real distribution.

Comparison of current vs. output power curves shows that there exists a substantial discrepancy between experimental and theoretical values; this is only too natural if it is taken into account that the experimental values refer to about 60 seconds after start of main combustion and, as seen from Fig. 8, they continue to increase. In Fig. 10 also indicated are the results of calculation

Fig. 9 Open circuit voltage distribution

Fig. 10 Current vs. output power characteristics

estimating the electrical conductivity of gas to be 80% of theoretical value at the corresponding temperature and pressure in consideration of the high electrical resistance which may exist on electrode surface as a transient phenomenon; in this manner the agreement with experiment is improved.

From these results, it may be concluded that, apart from the problem of electric conductivity of gas, the one-dimensional hydraulic flow analysis of channel fairly well represents the reality even on this scale of generator.

As the result of similar analysis with varied shape of generator channel, it was revealed that the output density would increase when the flow became supersonic over the entire length of generator channel. As our generator is a constant flow cross section area type, such conditions cannot be realized by choking.

As a matter of fact, in our experiment an increased gas flow resulted only in an increased pressure, and never in an increased output.

4. Summary

Some of the results of our researches centering around a 7 mW thermal input experimental MHD generator have been introduced. On this scale of experiment, the heat loss must be minimized

to preserve the high temperature of gas. This could be achieved through adoption of MgO bricks for insulation. The bricks in the combustor are subjected to relatively easy conditions, but the ones within the channel are exposed to severe conditions because of high velocity of gas flow. The durability could be vastly improved through increase of MgO purity to 99% and elevation of baking temperature. Thus, the experimental device proved sufficient for the purpose.

Much of the generator characteristic remains unknown. The one-dimensional hydraulic flow analysis as means of analysis of generator channel, though simple, can represent the reality with fairly high fidelity if the properties of high temperature gas are known as functions of temperature and pressure and calculations can be done using them.

Among the gaseous properties, electric conductivity is controversial and further study of the behaviours of electrode surface is found necessary from the standpoint of theoretical analysis of generator, too.

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