THE MAGNETOGASDYNAMIC GENERATOR

by

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NOMENCLATURE

A	Cross-section area of the channel
A_e	Area of the electrodes
A_w	Area of the channel walls
B	Magnetic flux density
c	Velocity of light
C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
D	Electric flux density (electric displacement)
d	Distance between electrodes
E	Electric field intensity
e	Electron charge
f	Friction coefficient
	Collision frequency of electron
H	Magnetic field intensity
H_s	Total enthalpy influx
h	Enthalpy per unit mass
h_s	Stagnation enthalpy per unit mass
I	Electric current
i	Electric current in the magnetizing coil
J	Electric current density
K	Thermal conductivity
k	Boltzmann's constant
	Ratio of specific heat
ℓ	Mean length of the magnetizing coil
	Mean free path

L	Length of the generator
m	Mass
M	Molecular weight
	Mach number
n	Number density
	Number of turns of magnetizing coil
n_e	Number density of electrons
n_i	Number density of ions
n_o	Number density of gas atoms
n_s	Number density of seed atoms
P	Electric power
p	Pressure
p_d	Electric power density
Q	Heat
Q_e	Collision cross section of electrons
Q_i	Collision cross section of ions
Q_o	Collision cross section of gas atoms
	Ohmic heating loss
Q_h	Heat loss through the walls
Q_m	Resistance loss of the magnetizing coil
q	Gas velocity
R	Gas constant
	Resistance
r	Resistivity
S	Entropy
s	Entropy per unit mass
T	Temperature
t	Time

U	Internal energy
$\bar{U}$	Velocity vector in x-direction
u	Gas velocity in x-direction
V	Voltage
w	Width of electrode
x) y) z)	Cartesian coordinate
α	Degree of ionization
ϵ	Permittivity
ϵ_o	Permittivity of free space
η	Total efficiency of the MGD generator
η_e	Electrical efficiency of the MGD generator
η_t	Equivalent turbine efficiency of the MGD generator
η_c	Conversion efficiency of the MGD generator
λ_d	Debye shielding length
μ	Permeability
μ_o	Permeability of free space
ν	Kinematic viscosity
σ	Electrical conductivity
τ	Mean free time between gas particle collision
ω	Electron cyclotron frequency
ρ_e	Electron charge density
ρ	Gas density
ρ_o	Gas density of standard atmospheric conditions
Φ	Potential energy
-	Indicates the vector quantity

INTRODUCTION

Magnetogasdynamics, as applied to the magnetogasdynamic generator, is the study of the flow of a compressible, conducting gas in the presence of a magnetic field. When a conducting gas moves through the magnetic field, the gas acts like a copper bar in the conventional electric generator. An electromotive force is induced in the body of the gas which, in turn, induces an electric current. At the same time there are electromagnetic forces which are caused by the induced currents and the magnetic field intensity. These forces have components which are opposite in direction to the flow of the conducting gas and tend to retard its motion. (In the case of an accelerator, or magnetogasdynamic propulsion unit, these forces have components which are in the same direction as the gas flow and tend to accelerate the motion of the conducting gas.)

Usually gases are not good electrical conductors except at very high temperatures. When the temperature is higher than 10,000 degrees K, all gases will be sufficiently ionized to be considered an electrically conducting gas. The ionized gas is called a "plasma". In general, the plasma should be considered as a mixture of various species--positive and negative ions, electrons and neutral particles. In practice, the plasma may be considered as a single gas of definite composition (1), and also may be assumed to be a perfect gas. Then the fundamental equations of magnetogasdynamics will be greatly simplified. Because the high temperatures required for ionization are beyond the temperature limits of the materials which can be used in the construction of magnetogasdynamic generators, it is necessary to seed the gas with a small amount of some easily ionized alkali metal, such as potassium or cesium. When this is done a sufficient degree of electrical conductivity can be obtained at lower temperatures, which are in the range of 4000 to 5000 degrees F (3).

Today the conversion of heat to electricity by the method of magnetogasdynamics is of great interest to engineers because the thermal efficiency of the magnetogasdynamic cycle shows promise of exceeding 50 per cent for bulk power generation (3), and because there are no moving parts involved in the generator. The wear and tear caused by moving parts found in the conventional turbo generator will be eliminated. Besides, the magnetogasdynamic generator can be combined with the modern steam or gas power plant which uses chemical fuels or nuclear reactors. At present the estimated cost of the electricity produced by this method is higher than that of the conventional method (3). However, the writer expects that the magnetogasdynamic generator will be competitive in the near future.

The purpose of this report is to study the principles of magnetogasdynamics and to investigate the application of these principles to the design of the magnetogasdynamic generator--a new kind of device for direct conversion of thermal energy to electric energy by means of the interaction between electromagnetic fields and the conducting gases. The fundamental equations for one-dimensional magnetogasdynamic flow are discussed. The principle of the magnetogasdynamic generator and its design considerations are explained. The efficiency of the magnetogasdynamic generator is defined with an explanation of the losses. The calculation of the generator size (both constant cross-section and varying cross-section area) is also given in this report.

FUNDAMENTAL EQUATIONS

In a general discussion of magnetogasdynamics, the plasma is assumed to be a single fluid. The fundamental equations are obtained by the combination of the fundamental gasdynamic equations with the electromagnetic equations. Therefore the equations to be considered are as follows.

1. The equations of the electromagnetic field (Maxwell's equations).
2. The conservation of mass, or continuity equation.
3. The momentum equation.
4. The conservation of energy, or energy equation.
5. The equation of state.

Electromagnetic Field Equations

The electromagnetic field is described by Maxwell's equations which apply to a system in which there are moving charges in the magnetic field. These equations are called field equations (1, 2, 3, 13, 14). Using the mks system,

$$\text{curl } \bar{H} = \bar{J} + \epsilon \frac{\partial \bar{E}}{\partial t} \qquad (1)^{1}$$

$$\text{curl } \bar{E} = -\mu \frac{\partial \bar{H}}{\partial t} \qquad (2)$$

$$\text{div } \bar{B} = 0 \qquad (3)$$

$$\text{div } \bar{D} = \rho_e \qquad (4)$$

where H = magnetic field intensity, amp/m

E = electric field intensity, volt/m

B = magnetic flux density, weber/m^2

D = electric displacement (electric flux density), coulomb/m^2

J = electric current density, amp/m^2

ρ_e = electric charge density, coulomb/m^3.

The electric field intensity, E, and the magnetic flux density, B, determine the electrical force on a charged particle in the conducting field. The electric displacement, D, and the magnetic field intensity, H, are the fields created which are related to the electrical force exerted on a particle.

The electric flux density, E, is related to the electric field intensity, D, by the expression

$$\bar{D} = \epsilon \bar{E} \qquad (5)$$

where ϵ is the permittivity. (The term $\epsilon \frac{\partial \bar{E}}{\partial t}$ in Eq. (1) is the displacement current.) If the medium is a vacuum, or free

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[1]The term $\rho_e \bar{q}$, which is called the convection current, is omitted from Eq. (1) because it is of importance only when rapid electrical oscillations are present (23). In magnetogasdynamic generators rapid electrical oscillations do not occur.

space, the permittivity is denoted by ϵ_0, where

$$\epsilon_0 = 10^7/4\pi c^2 \quad \text{coulomb}^2 - \text{sec}^2/\text{kg} - \text{m}^3 \quad (1)$$

or

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ farad/m}$$

The magnetic flux density, B, is related to the magnetic field intensity, H, by the expression

$$\bar{B} = \mu \bar{H} \qquad (6)$$

where μ is the permeability. If the medium is a vacuum, μ_0 is used instead of μ, and

$$\mu_0 = 4\pi \times 10^{-7} \text{ kg - m/coulomb}^2$$

or

$$\mu_0 = 1.257 \times 10^{-6} \text{ henry/m}$$

In magnetogasdynamic approximations, it is assumed that both and μ are the values in a vacuum.

The current density, $\bar{J}$, is related to the electric field, E, by the electrical conductivity, σ,

$$\bar{J} = \sigma \bar{E} \qquad (7)$$

Equation (7) is a statement of Ohm's law. The electrical conductivity, σ, is the reciprocal of the resistivity, which is a scalar number. Actually the electrical conductivity of the plasma is a tensor, but in practice the conductivity is assumed to be a scalar quantity.

When the plasma moves with velocity $\bar{q}$ through a magnetic field of intensity $\bar{H}$, there is a magnetic force acting on the plasma, and the magnitude of this force is equal to the vector product of the velocity $\bar{q}$ and the magnetic field intensity, $\bar{H}$. If the system is considered by an observer moving with the ionized gas, the observer will see the gas at rest, and he will see that the magnetic field moves with velocity $\bar{q}$ toward the observer. The total electromagnetic force, or total electric intensity, $\bar{E}'$, is the sum of electrical and magnetic forces acting on the ionized gas when the gas is at rest and when the gas is moving with velocity $\bar{q}$ (8).

$$\bar{E}' = \bar{E} + \mu\bar{q} \times \bar{H} \tag{8}$$

or

$$\bar{E}' = \bar{E} + \bar{q} \times \bar{B} \tag{8a}$$

From Eq. (7), the total electric current density is

$$\bar{J} = \sigma(\bar{E} + \mu\bar{q} \times \bar{H}) \tag{9}$$

or

$$\bar{J} = \sigma(\bar{E} + \bar{q} \times \bar{B})$$

The last electromagnetic equation is the equation of conservation of electric charges. This may be written as

$$\nabla \cdot \bar{J} + \frac{\partial \rho_e}{\partial t} = 0 \tag{10}$$

Conservation of Mass Equation

The equation of conservation of mass is the same as the continuity equation in gasdynamics, which states that the rate of mass entering a region equals the rate of mass leaving the region plus the rate of change in mass stored within the region This equation can be written in the differential form as

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}\ (\rho\bar{q}) \tag{11}$$

where ρ is the density of the ionized gas.

Momentum Equation

For a given direction the net momentum efflux from a region plus the time rate of change of momentum within the region equals the net force acting on the fluids within the region. This equation (1, 2, 26) can be written as

$$\rho \frac{D\overline{q}}{Dt} = -\nabla p + \mu\overline{J} \times \overline{H} + \rho \nu\left[\nabla^2\overline{q} + \frac{1}{3} \nabla (\nabla \cdot \overline{q})\right] \qquad (12)$$

where p = the gas pressure

ν = the kinematic viscosity

The force due to gravity per unit volume in Eq. (12) is neglected. The term on the left side represents the rate of change of momentum stored in the region plus the excess momentum flux from the region. The first term on the right side is the pressure force acting per unit volume. The second term is the force due to the magnetic field or Lorentz force. The last term represents the shearing force or viscosity effect of the ionized gas.

Energy Equation for Gas

The energy equation for the gas involves the conservation of energy principle as applied to the kinetic, potential, and internal energies of the gas, as well as the flow of work and heat to and from the gas.

For the kinetic energy, the equation is obtained by taking the scalar product of Eq. (12) and the gas velocity $\overline{q}$.

$$\rho \frac{D}{Dt}\left(\frac{\bar{q}^2}{2}\right) = -(\bar{q} \cdot \nabla p) + \bar{q} \cdot (\rho \nu \nabla^2 \bar{q})$$

$$+ \bar{q} \cdot \frac{1}{3}\left[\rho \nu \nabla(\nabla \cdot \bar{q})\right] + \bar{q} \cdot (\mu \bar{J} \times \bar{H}) \qquad (13)$$

The rate of change of internal energy per unit mass is the sum of the rate of work done by the pressure forces, the rate of heat transfer by conduction and the thermal energy generated by the electrical conduction current passing through the gas. The equation is

$$\rho \frac{DU}{Dt} = -p(\nabla \cdot \bar{q}) + \nabla \cdot (K \nabla T) + \frac{J^2}{\sigma} \qquad (14)$$

where K is the coefficient of thermal conductivity. The term J^2/σ is called the joule heat per unit volume per unit time (1, 2).

If Φ denotes the potential energy per unit volume due to elevation, the sum of the kinetic, internal, and potential energies gives the total energy of the gas.

$$\rho \frac{D}{Dt}\left(U + \frac{\bar{q}^2}{2} + \Phi\right) = -\nabla(\bar{q}p) + \bar{q} \cdot (\rho \nu \nabla^2 \bar{q})$$

$$+ \bar{q} \cdot \frac{1}{3}\left[\rho \nu \nabla(\nabla \cdot \bar{q})\right] + \nabla \cdot (K \nabla T)$$

$$+ \bar{q} \cdot (\mu \bar{J} \times \bar{H}) + \frac{J^2}{\sigma} \qquad (15)$$

The last two terms of Eq. (15) may be written as

$$\bar{q} \cdot (\mu \bar{J} \times \bar{H}) + \bar{J} \cdot \bar{E}' = \bar{q} \cdot (\mu \bar{J} \times \bar{H}) + \bar{J} \cdot (\bar{E} + \mu \bar{q} \times \bar{H})$$

$$= \bar{q} \cdot (\mu \bar{J} \times \bar{H}) + \bar{J} \cdot \bar{E} + \bar{J} \cdot \mu \bar{q} \times \bar{H} = \bar{J} \cdot \bar{E}$$

Therefore the energy equation can be written as

$$\rho \frac{D}{Dt}\left(U + \frac{\bar{q}^2}{2} + \Phi\right) = -\nabla\cdot(\bar{q}p) + \bar{q}\cdot(\rho\nu\nabla^2\bar{q})$$

$$+ \bar{q}\cdot\frac{1}{3}\left[\rho\nu\nabla(\nabla\cdot\bar{q})\right] + \nabla\cdot(K\nabla T) + \bar{J}\cdot\bar{E} \quad (16)$$

From the first two Maxwell's equations, Eqs. (1) and (2), the electromagnetic energy equation can be derived as follows.

$$\bar{E}\cdot\nabla\times\bar{H} = \bar{E}\cdot\bar{J} + \bar{E}\cdot\epsilon\frac{\partial\bar{E}}{\partial t} \quad (17a)$$

$$\bar{H}\cdot\nabla\times\bar{E} = -\bar{H}\cdot\mu\frac{\partial\bar{H}}{\partial t} \quad (17b)$$

Subtracting Eq. (17a) from Eq. (17b) gives

$$\bar{H}\cdot\nabla\times\bar{E} - \bar{E}\cdot\nabla\times\bar{H} = -\bar{H}\cdot\mu\frac{\partial\bar{H}}{\partial t} - \bar{E}\cdot\bar{J} - \bar{E}\cdot\epsilon\frac{\partial\bar{E}}{\partial t} \quad (17c)$$

$$\nabla\cdot(\bar{E}\times\bar{H}) = -\bar{H}\cdot\mu\frac{\partial\bar{H}}{\partial t} - \bar{E}\cdot\bar{J} - \bar{E}\cdot\epsilon\frac{\partial\bar{E}}{\partial t}$$

$$\bar{E}\cdot\epsilon\frac{\partial\bar{E}}{\partial t} + \bar{H}\cdot\mu\frac{\partial\bar{H}}{\partial t} = -\nabla\cdot(\bar{E}\times\bar{H}) - \bar{J}\cdot\bar{E}$$

$$\epsilon\frac{\partial}{\partial t}\left(\frac{\bar{E}^2}{2}\right) + \mu\frac{\partial}{\partial t}\left(\frac{\bar{H}^2}{2}\right) = -\nabla\cdot(\bar{E}\times\bar{H}) - \bar{J}\cdot\bar{E} \quad (18)$$

The terms on the left side of Eq. (18) are the time rate of change of the electrical and magnetic energies within the unit volume, respectively. The first term on the right side is the net rate of electromagnetic energy inflow to the unit volume, and the $\bar{J}\cdot\bar{E}$ term is the electrical resistive work done per unit volume per unit time by the field $\bar{E}$ on the charges in moving them within the unit volume.

When the energy equation of gasdynamics, Eq. (16), is combined with the electromagnetic energy equation, Eq. (18), the rate of change of the total energy per unit volume will be obtained.

$$\rho \frac{D}{Dt} \left(U + \frac{\bar{q}^2}{2} + \bar{\Phi}\right) + \frac{\partial}{\partial t} \left(\epsilon \frac{\bar{E}^2}{2} + \mu \frac{\bar{H}^2}{2}\right) = - \nabla \cdot (\bar{q}p)$$

$$+ \bar{q} \cdot (\rho \nu \nabla^2 \bar{q}) + \bar{q} \cdot \frac{1}{3} \left[\rho \nu \nabla (\nabla \cdot \bar{q})\right]$$

$$+ \nabla \cdot (K \nabla T) - \nabla \cdot (\bar{E} \times \bar{H}) \qquad (19)$$

The Equation of State

As a first approximation in magnetogasdynamics, a plasma may be considered as a single fluid and a perfect gas (1). Therefore within this assumption, the equation of state, which is the relation between the pressure, p, density, ρ, gas constant, R, and temperature, T, is

$$p = \rho R t \qquad (20)$$

The fundamental equations of magnetogasdynamics are then Eqs. (1), (2), (9), (10), (11), (12), (19), and (20).

ONE-DIMENSIONAL MAGNETOGASDYNAMIC FLOW

In order to bring out the essential features of the flow of a compressible ionized gas, the one-dimensional case will be discussed first. The necessary assumptions are:

1. The flow of the gas is in the direction of the

x-axis and has the component of velocity u only.

2. The flowing gas is assumed to be a perfect gas with constant specific heats and chemical composition.

3. The flow is steady, all variables are functions of coordinate x only, and all terms which are a function of time are zero.

4. There is no shaft work.

5. The thermodynamic properties and velocity of the gas are uniform across any given cross section of the flow passage.

6. There is no change in potential energy.

For magnetogasdynamics there is the additional assumption:

7. The magnetic field, $\overline{H}$, is always perpendicular to the direction of the gas flow. (If the magnetic field, $\overline{H}$, is parallel to the velocity of the gas, and if the flow is one-dimensional, the magnetic field term will be zero in Eqs. (9), (13), and (15)). (1)

8. Viscosity effects are assumed negligible (3).

In the above assumptions the flow variables are independent of the y and z coordinates. For engineering application the one-dimensional flow analysis is useful for the flow inside conduits or nozzles. Therefore one-dimensional flow can be used to analyze the performance of the magnetogasdynamic power generator. An application to magnetogasdynamic jet propulsion is quite similar; there is a net electric power input to the system instead of a net outflow of electric power.

Figure 1 shows the vectors involved in one-dimensional magnetogasdynamics. The velocity vector, $\overline{U}$, is in the x-direction. The magnetic flux density, $\overline{B}$, is in the z-direction. The induced electric field, $\overline{U} \times \overline{B}$, which is produced by the velocity vector, $\overline{U}$, and the magnetic flux density, $\overline{B}$, is in the negative y-direction. The current density vector, $\overline{J}$, obtained by the conductivity, σ, and the induced electric field, $\overline{U} \times \overline{B}$, is in the same direction as the induced electric field, $\overline{U} \times \overline{B}$. If there is an externally applied current density an electric field will be produced, and these quantities are in the opposite direction to the induced current density and induced electric field, or in the positive y-direction.

Electrodynamic Equations

For steady flow all the terms with respect to time are zero. Then Maxwell's equations are for a neutral gas

$$\text{curl } \overline{H} = \overline{J} \tag{21}$$

$$\text{curl } \overline{E} = 0 \tag{22}$$

$$\text{div } \overline{B} = 0 \tag{23}$$

$$\text{div } \overline{D} = \rho_e \tag{24}$$

The magnetic flux density, $\overline{B}$, is related to the magnetic intensity by the permeability μ.

$$\overline{B} = \mu \overline{H} \tag{25}$$

The value of the free-space permeability is used as an approximation for the actual value (1, 3, 5, 6, 8).

From Ohm's law, which represents the relation between the electric field strength and the current flow per unit area,

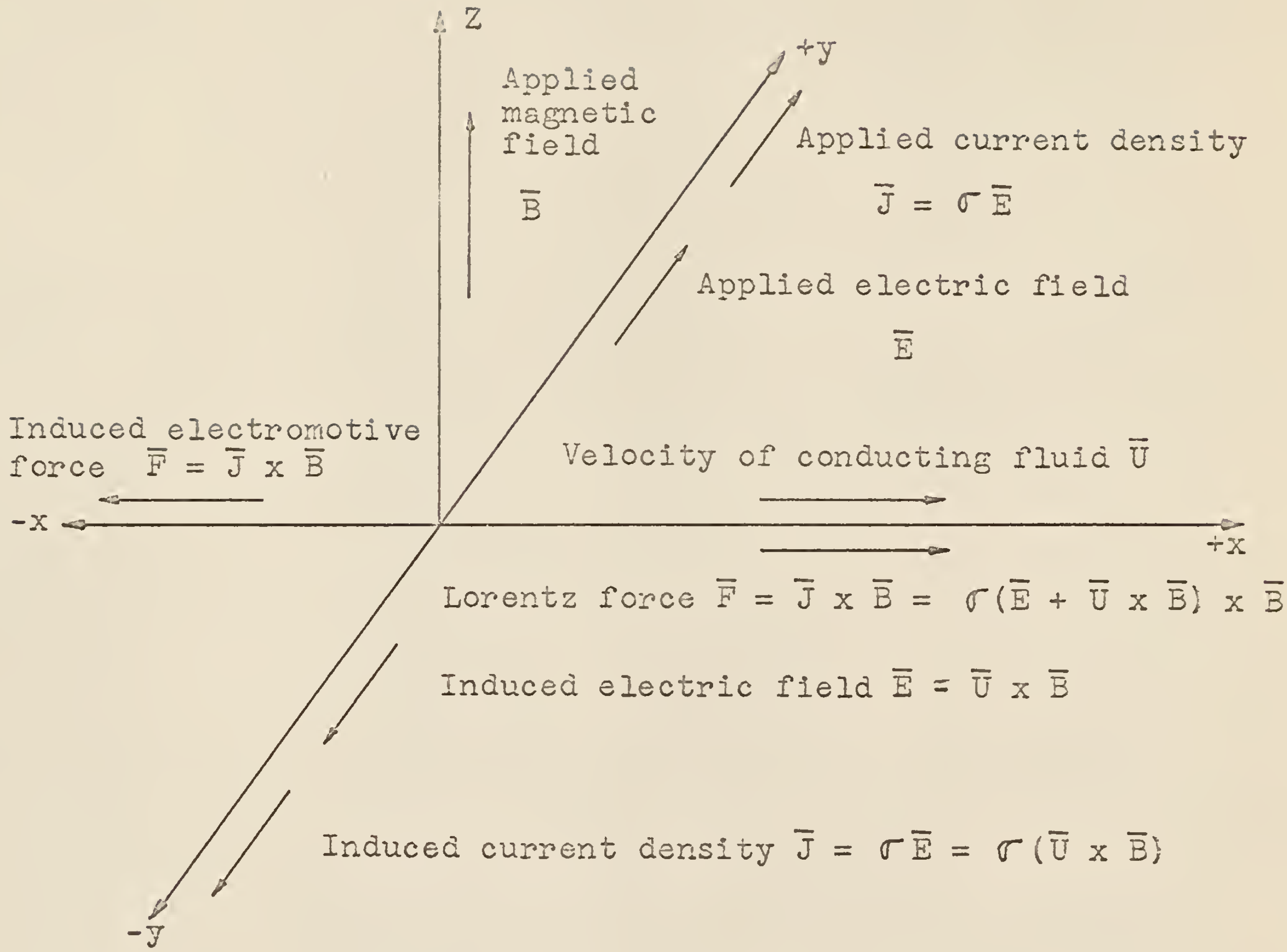

Fig. 1. Vector diagram for one-dimensional magnetogasdynamics.

$$\bar{J} = \sigma(\bar{E} + \bar{U} \times \bar{B}) \tag{26}$$

Thermodynamic Equations

It is assumed that the fluid is a continuum. When the conducting gas is ionized, it is composed of electrons, ions, and neutral atoms. The electrons are mainly the current-carrying portion of the gas. The conducting gas is assumed to be a single phase and a perfect gas although it is a mixture of several types of particles. Therefore the equation of state can be applied.

$$p = \rho R t \tag{27}$$

where p = pressure of the gas

ρ = density of the gas

R = gas constant

T = temperature.

The entropy, S, of the conducting gas is independent of the electromagnetic fields, and is a function of the temperature and pressure. The entropy of the conducting gas per unit mass can be written

$$dS = C_p \frac{dT}{T} - R \frac{dp}{p} \tag{28}$$

where

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p \tag{29}$$

or $\quad dh = C_p \, dT$

and $\quad h_2 - h_1 = C_p(T_2 - T_1)$

As $$C_p = \frac{k}{k-1} \cdot R \tag{30}$$

then $$h_2 - h_1 = \frac{k}{k-1} R(T_2 - T_1) \tag{31}$$

where C_p = specific heat at constant pressure

C_v = specific heat at constant volume

k = specific heat ratio = C_p/C_v

h = enthalpy

In gasdynamics it is very convenient to express the velocity of the gas stream in terms of the Mach number, M, which is defined as the ratio of the gas velocity, u, to the local velocity of sound

$$M^2 = \frac{u^2}{k\,R\,T} \tag{32}$$

Magnetogasdynamic Equations

From the fundamental equation derived in the previous article, the basic magnetogasdynamic equations are

Continuity $$\nabla \cdot \rho \bar{U} = 0 \tag{33}$$

Momentum[1] $$\rho(\bar{U} \cdot \nabla)\bar{U} + \nabla p = \bar{J} \times \bar{B} \tag{34}$$

Energy $$\rho \bar{U} \cdot \nabla (h_s - Q) = \bar{J} \cdot \bar{E} \tag{35}$$

where h_s is the total or stagnation enthalpy defined by

$$h_s = h + \frac{u^2}{2} \tag{36}$$

and Q is the heat addition per unit mass of fluid.

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[1]Viscosity effects are assumed negligible (3).

The continuity equation can be integrated and written as

$$\rho_1 u_1 A_1 = \rho_2 u_2 A_2 = m \tag{37}$$

where subscripts 1 and 2 denote the initial and final conditions, respectively, and A is the cross-section area normal to the flow. For a rectangular cross section,

$$A = w\ d \tag{38}$$

where w is the distance between the walls in the direction of the magnetic field, $\overline{B}$, and d is the distance between electrodes in the direction of current density, $\overline{J}$.

The momentum equation can be written in the differential form as

$$\rho u \frac{du}{dx} + \frac{dp}{dx} = JB_z \tag{39}$$

The energy equation for steady-state conditions can be written

$$\rho u \frac{d}{dx} (h_s - Q) = JE \tag{40}$$

Ohm's law equation can be written

$$\overline{J} = - \sigma(\overline{B} \times \overline{U} - \overline{E})$$

$$\overline{J} = - \sigma\overline{E}(\lambda - 1) \tag{41}$$

where $$\lambda = \frac{\overline{B} \times \overline{U}}{\overline{E}} = \frac{uB_z}{E} \tag{42}$$

is defined as the lag ratio (3) or the ratio of induced electric field ($\overline{B} \times \overline{U}$) to static electric field $\overline{E}$. For magnetogasdynamic propulsion λ is less than unity, which means that the electric field produced by the motion of the conducting gas is smaller than the supplied electric field and that $\overline{J}$ and $\overline{E}$ have the same direction. For the magnetogasdynamic generators λ is greater than unity, which means that the induced electric field of the moving gas is larger than the electric field supplied to the external load (because of internal voltage drop between the electrodes) and that $\bar{J}$ and $\bar{E}$ are in opposite directions to each other. This explains why there is a minus sign in Ohm's law, Eq. (41) above.

The electrical power supplied to or extracted from the flow is given by

$$P = - \int_{x_1}^{x_2} \bar{J} \cdot \bar{E} \, A \, dx \tag{43}$$

where the electrical power is positive in the case of current generation and negative in the case of propulsion. This electrical power can be expressed in terms of thermodynamic properties as

$$\bar{P} = m \left[(h_{s_1} - h_{s_2}) + Q \right] \tag{44}$$

PRINCIPLE OF THE MAGNETOGASDYNAMIC GENERATORS

The magnetogasdynamic power generator extracts electrical current from the motion of an ionized gas heated to about 5000 degrees F (3,033 degrees K) as it passes through a magnetic field. The process is quite the same as the electrical phenomenon found in the conventional generator; voltage is created when a conductor is moved through a magnetic field.

In the conventional electrical generator, the conductor is usually a copper wire or bar that is spun through a magnetic field by a turbine or engine. In the magnetogasdynamic power generator, a very hot ionized gas, such as superheated air, steam, argon, or helium, is used as the conductor and is moved through the magnetic field. An induced voltage is obtained and current is drawn off by electrodes. There are no moving machine parts involved. The energy contained in a high temperature, ionized gas, or plasma, which consists of ionized atoms and electrons, is converted directly into electrical energy.

The principle of the magnetogasdynamic generator is very simple. This generator consists of two plate electrodes, P_1 and P_2. There is a magnetic flux density, $\overline{B}$, between the electrodes, and in Fig. 2 its direction is perpendicular to and pointing into the paper. A charged particle, ρ_e, is moving in the magnetic field at velocity $\overline{U}$ from left to right, as shown in Fig. 2. From electromagnetic theory, the magnetic force $\overline{F}$ acting on the particle is

$$\overline{F} = \rho_e \, \overline{U} \times \overline{B} \tag{45}$$

or

$$\frac{\overline{F}}{\rho_e} = \overline{U} \times \overline{B} \tag{45a}$$

where $\overline{F}$, $\overline{U}$, and $\overline{B}$ are vectors. By definition the magnetic force per unit charge (Eq. 45a) is called the induced electric field intensity $\overline{E}$. If the charged particle, ρ_e, is negatively charged, the force acting on the particle has its direction downward. If the charged particle, ρ_e, is positive, the force acting on the particle has its direction upward, as shown by the broken line arrows in Fig. 2. Therefore the positively charged particle has a tendency to drift toward plate P_1 and the negatively charged particle has a tendency to drift toward plate P_2.

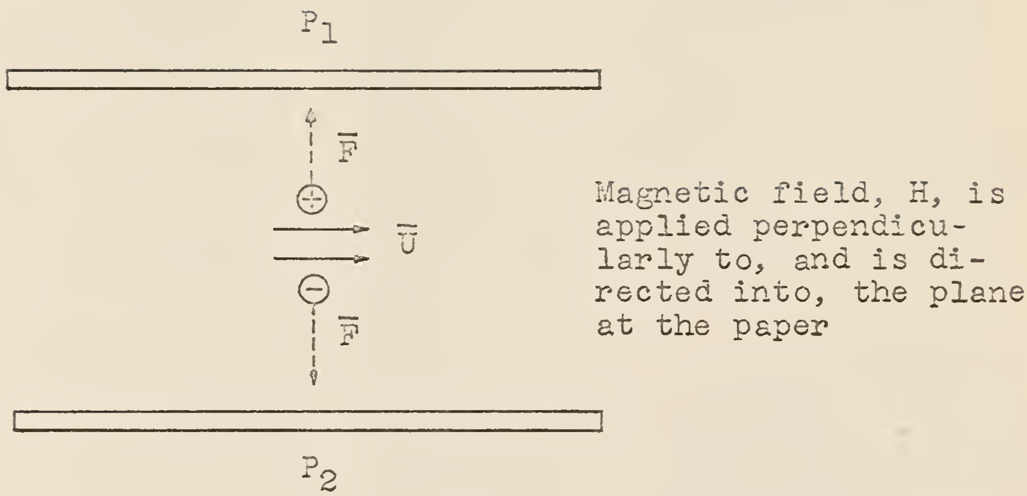

Fig. 2. Motions of charges particles in the presence of a perpendicular magnetic field.

Instead of the two particles shown in Fig. 2, there is actually an ionized gas, or plasma, in which the molecules are moving at velocity $\bar{U}$ from left to right. The positive ions will be forced toward electrode P_1 and the negative ions will be forced toward electrode P_2. There are many ions and nonionized molecules in the ionized gas. Before the positive ions and negative ions reach the electrodes P_1 and P_2, respectively, the ions will collide with the nonionized molecules and with each other. However, an average drift of the positive ions toward P_1 and of negative ions toward P_2 is still going on between collisions. If an electric conductor is connected from electrode P_1 to electrode P_2 through an external electrical load, an electric current will flow from P_1 through the external load to P_2. This is the basic principle of the magnetogasdynamic generator.

Thus a magnetogasdynamic generator extracts energy from the flow of ionized gas and converts it to electrical energy. The process can be reversed. If instead of a load, there is an external source of electrical power supplying the current in a direction opposite to the direction of the current produced, the process can be reversed, and energy is fed to the gas stream. This is a basic principle of the magnetogasdynamic propulsion or pump.

A simple form of a magnetogasdynamic generator is shown in Fig. 3. It consists of a channel through which the gaseous working fluid flows, coils which produced a magnetic field across the channel, and electrodes at the top and bottom of the channel. These electrodes serve much the same purpose as the brushes in

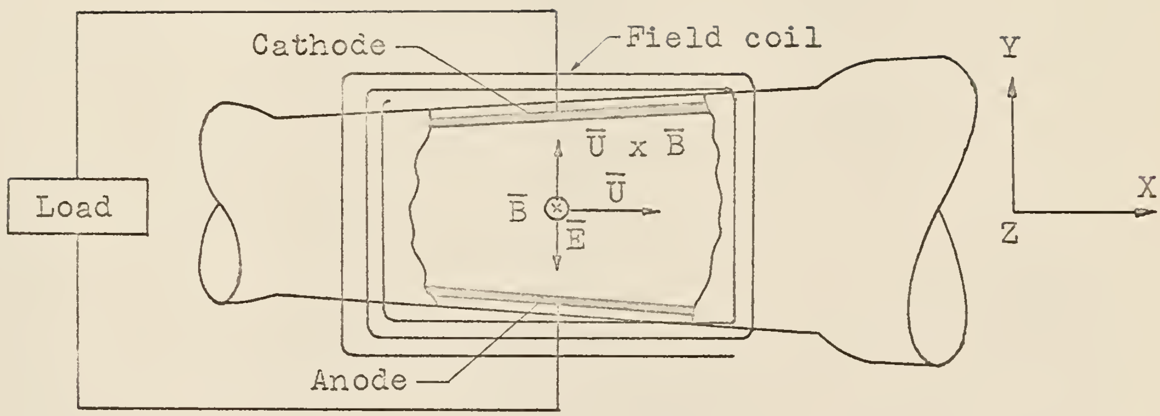

Fig. 3. A linear magnetogasdynamic generator.

a conventional generator. The gas moves through the magnetic field and has an electromotive force generated in it which drives a current through it, the electrodes, and the external load. The magnetogasdynamic generator can be used in a heat cycle, replacing both the turbine and generator in such a cycle, or it can be combined with conventional electric power plants.

DESIGN CONSIDERATIONS

In designing a magnetogasdynamic generator, the effects of the following factors should be considered first.

1. Gas conductivity
    a. Ionization method
    b. Temperature requirement
    c. Optimization of seed concentration.
2. Efficiency of MGD generator
    a. Ohmic heating of gas
    b. Eddy-current losses
    c. Boundary layer losses
    d. Anode and cathode voltage losses
    e. Friction losses
    f. Heat loss at the walls
    g. I^2R loss of magnetizing coil.
3. Hall effects.
4. Optimum flow velocity.
5. Geometric considerations
    a. Constant area MGD generator
    b. Varying cross section MGD generator.

Gas Conductivity

The difference between the magnetogasdynamic generator and the conventional generator is that the MGD generator uses an ionized and conducting gas. One of the most important quantities in design is the electrical conductivity, σ , which is the reciprocal of the electrical resistivity, R. The value of gas conductivity will determine the size of the generator because the volume of the generator varies inversely with the value of the conductivity. If the conductivity is too low, the generator will become large and uneconomical. The conductivity depends upon the degree of ionization, the elastic electron-scattering cross section, or electron-collision cross section, and temperature. The value of conductivity will be increased with an increase of temperature and degree of ionization.

Ionization Method. Ionization is the separation of an electron from an atom which leaves the atom with a positive charge or ion. In magnetogasdynamics there are two available ionization methods. The first one is ionization by thermal collision. This method is obtained by heating the gas to a high temperature. Molecules of the gas will then move with high velocities. This means that the kinetic energies of the molecules are very high, and this energy is sufficient to ionize these molecules when they collide. The second method is the ionization caused by collisions between electrons and molecules. For thermal equilibrium the electrons have the same kinetic energy as the molecules. As the mass of an electron is much smaller than that of a molecule, its velocity will be very high. The collisions of these electrons with neutral particles will cause ionization. The energy required to remove completely an electron from its normal state in a neutral molecule to a distance not influenced by the nucleus is called the ionization potential (1). Usually the ionization potential is expressed in electron volts. For example, the ionization potentials of potassium and cesium are 4.34 and 3.89 ev, respectively (5).

Temperature Requirement. Most gases, such as air, CO, and CO_2, have a relatively high ionization potential (14.0 electron volts for CO and 13.7 electron volts for CO_2) (5, 9), but they do not ionize until high temperatures are reached. If about 0.1 to one per cent of some easily ionizable material, such as an alkali metal vapor (potassium or cesium), is added to the gas, a sufficient degree of ionization can be obtained at a temperature which is below the temperature limits of some materials used in the construction of magnetogasdynamic generators (19). (Small laboratory units have been tested at temperatures slightly over 2500 degrees K.) (19)

Figure 4 shows a graph of a result obtained from an estimation of a 100,000-kilowatt magnetogasdynamic generator, in which a linear dimension is plotted as a function of gas conductivity and field strength (7). This graph also indicates the temperatures required to obtain the conductivities in seeded gases. A rough idea of conductivities and temperatures required may be obtained from this graph. For example, if a practical field strength is 10,000 gauss, or one weber per square meter, and

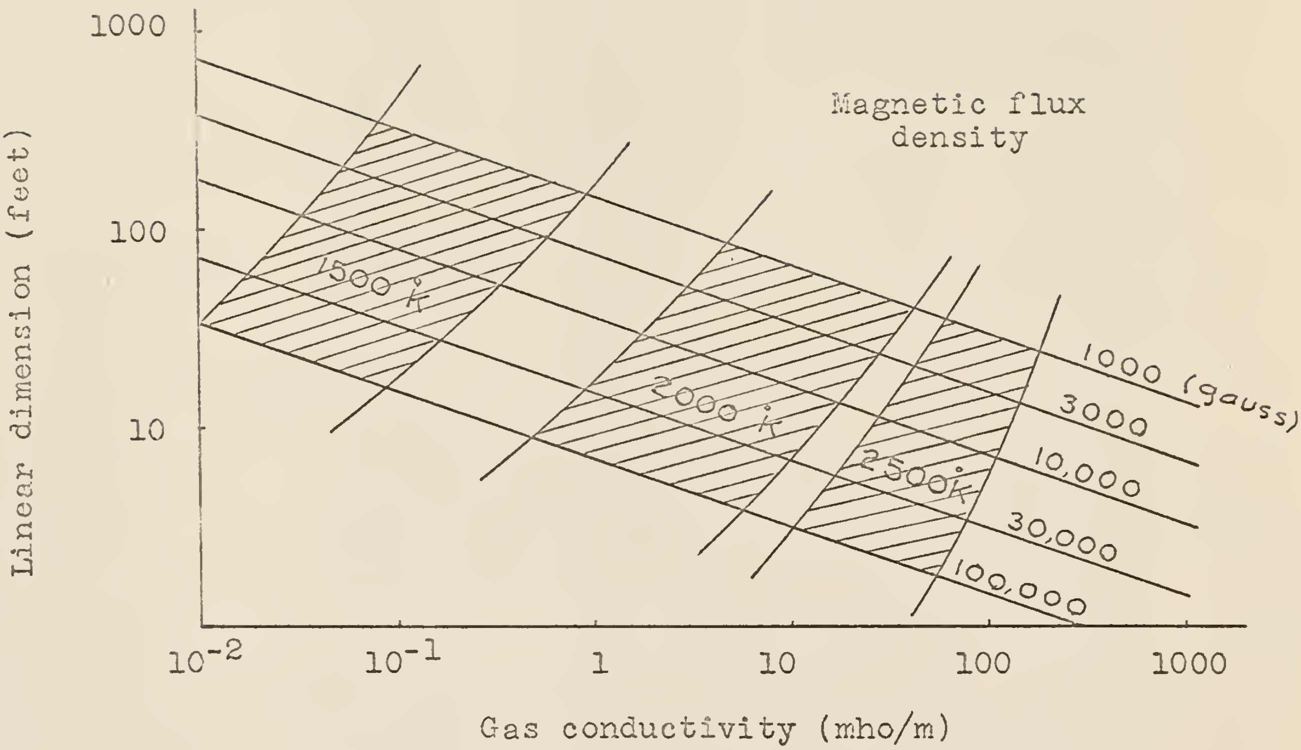

Fig. 4. Approximate size of a 100-mw magnetogasdynamic generator as a function of gas conductivity and magnetic field strength. Shaded regions indicate, roughly, the gas temperatures required (7).

the reasonable estimate for the maximum practical size is 10 feet, the gas conductivity is at least of the order of 50 mhos per meter and the temperature of the gas is 2500 degrees K.

Optimization of Seed Concentration. The alkali metals which are proposed (potassium, cesium, sodium, and so forth) have only one electron in the outermost shell. This single electron is rather loosely bound to the atom and the energy required to separate it from the atom is rather small. This is the reason why the ionized gas used in the magnetogasdynamic generator is either an evaporated alkali metal or an ordinary gas seeded with a small amount of alkali metal. For instance, by seeding air with about one per cent of potassium vapor at a temperature of 2000 degrees K, a conductivity of about 10 mhos per meter can be obtained. In order to get the maximum value of the conductivity, there is an optimum value of seed concentration, which for most gases is only one per cent or less (19, 20). The level of seed concentration will be obtained by considering the collision cross sections of the neutral seed atoms, the neutral gas atoms, and the ions in the electrical conductivity equation.

The electrical conductivity of a gas (20) is given by

$$\sigma = 0.532 \frac{e^2}{(m_e kT)^{\frac{1}{2}}} \cdot \frac{n_i}{n_i Q_i + n_s Q_s + n_0 Q_0} \tag{46}$$

where e = electron charge = 1.602×10^{-19} coulomb

m_e = electron mass = 9.108×10^{-31} kg

k = Boltzmann's constant

T = temperature, °K

Q_i = collision cross section of ions, m^2

Q_s = collision cross section of seed atoms, m^2

Q_0 = collision cross section of gas atoms, m^2

n_i = number density of ions, particles/m^3

n_s = number density of seed atoms, particles/m^3

n_0 = number density of gas atoms, particles/m^3

For alkali metal vapors the number density of the ions n_i (which is defined as the number of ions per unit volume) will be quite small and is proportional to the square root of the number density of the seed atoms $(n_s)^{\frac{1}{2}}$. The collision cross section, Q_s, is very large as compared with the collision cross section of an electron. Approximately the electrical conductivity (20) can be expressed as

$$\sigma \propto \frac{n_s}{n_s Q_s + n_0 Q_0} \tag{47}$$

The maximum value of the electrical conductivity, from Eq. (47), is obtained when

$$n_s Q_s = n_0 Q_0 \tag{48}$$

or

$$n_s / n_0 = Q_0 / Q_s \tag{48a}$$

For argon with potassium seeding, the collision cross section of the argon atom, Q_0, is about 6×10^{-17} cm^2. The collision cross section of the potassium atom, Q_s, is about 3×10^{-14} cm^2. For maximum electrical conductivity, the per cent of seed gas is determined as

$$\frac{Q_0}{Q_s} = \frac{6 \times 10^{-17}}{3 \times 10^{-14}} \times 100 = 0.2 \text{ per cent}$$

In a simple analysis, the electrical conductivity, σ, is given by the following formula (1, 5, 12).

$$\sigma = \frac{e^2 \, n_e}{f \, m_e} \tag{49}$$

where f = the collision frequency of electrons.

$$f = n_0 Q_e \left(\frac{8kT}{\pi m_e} \right)^{\frac{1}{2}} \tag{50}$$

Substituting in Eq. (49), gives

$$\sigma = \sqrt{\frac{\pi}{8}} \cdot \frac{e^2}{\sqrt{m_e kT}} \; \frac{1}{Q_e} \cdot \frac{n_e}{n_0} \tag{51}$$

or

$$\sigma = 0.532 \cdot \frac{e^2}{\sqrt{m_e kT}} \; \frac{1}{Q_e} \cdot \frac{n_e}{n_0} = \sigma_c \tag{51a}$$

where n_e = number density of electrons, particles/m^3

n_0 = number density of gas atoms, particles/m^3

Q_e = the electron atom collision cross section, m^2

The ratio n_e/n_0 is defined as the degree of ionization. Equation (51a) was given by Chapman and Cowling (22, 1, 12) for the case of a slightly ionized gas.

For the case of a fully ionized gas, Spitzer (17) gave the following formula for the electrical conductivity.

$$\sigma = \frac{0.591(kT)^{3/2}}{m_e^{\frac{1}{2}} e^2 \; \ln\left(\frac{\lambda d}{b_0}\right)} = \sigma_d \tag{52}$$

where λ_d = Debye shielding distance[1]

$= \left[(kT)/(8\pi \, n_e e^2)\right]^{\frac{1}{2}}$

b_0 = impact parameter = $e^2/3kT$

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[1]The Debye shielding distance is "the distance from a charge beyond which the influence of the charge becomes negligible" (5).

For the intermediate case no theoretical analysis is available. Kantrowitz suggested the following formula (1).

$$\frac{1}{\sigma} = \frac{1}{\sigma_c} + \frac{1}{\sigma_d} \tag{53}$$

Efficiency of the MGD Generator

There are two types of efficiencies used for the magnetogasdynamic generator: (1) an electrical efficiency that describes how much of the generated power is actually delivered to the load and how much is dissipated in the internal resistance of the generator; and (2) an equivalent turbine efficiency which is the ratio of actual enthalpy drop to the isentropic enthalpy drop. The equations of efficiencies are derived below with the assumption that the velocity is constant. Actually the velocity is not constant, but the assumption is useful in simplifying the equation of motion. The derivation of the equations is as follows (7, 20).

From Eq. (37), the continuity equation,

$$\rho A = \text{constant} \tag{54}$$

From Eq. (39), the momentum equation,

$$dP/dx = JB \tag{55}$$

From Eq. (40), the energy equation,

$$\rho u \frac{dh}{dx} = JE \tag{56}$$

If Eq. (55) is multiplied by the flow velocity u, the rate at which work is done by the ionized gas pushing itself through the magnetic field is obtained as

$$u \frac{dP}{dx} = u\ J\ B \tag{57}$$

The rate at which the enthalpy of the gas is converted into electrical energy is given by Eq. (56). Dividing Eq. (56) by Eq. (57) gives

$$\eta_e = \frac{\rho u\ dh/dx}{u\ dp/dx} = \rho \frac{dh}{dp} = \frac{E}{uB} \tag{58}$$

where η_e is the electrical efficiency of the magnetogasdynamic generator which is defined as the ratio of load voltage, E, to the open-circuit voltage, uB, or ratio of electric power output to electric power input. Equation (58) shows that a decrease in electrical efficiency results in a decrease in change of enthalpy for a given pressure drop. According to the assumption of constant specific heat and velocity, the ratio of the actual pressure ratio across the generator to the isentropic pressure ratio will be calculated as follows.

From Eq. (58),

$$dp = \frac{\rho}{\eta_e} dh = \frac{p}{\eta_e RT} c_p\ dT$$

$$dp = \frac{1}{\eta_e} \frac{k}{k-1} \frac{p}{T} dT$$

$$\frac{dp}{p} = \frac{1}{\eta_e} \frac{k}{k-1} \frac{dT}{T}$$

Integrating,

$$\ell n \frac{p_2}{p_1} = \frac{1}{\eta_e} \frac{k}{k-1} \ell n \frac{T_2}{T_1} = \ell n \left(\frac{T_2}{T_1}\right)^{k/\eta_e(k-1)}$$

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{k/\eta_e(k-1)} = \left(\frac{c_pT_2}{c_pT_1}\right)^{k/\eta_e(k-1)}$$

$$\frac{p_2}{p_1} = \left(\frac{h_2}{h_1}\right)^{k/\eta_e(k-1)} \tag{59}$$

For isentropic flow $\eta_e = 1$.

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{k/k-1}$$

$$\frac{p_2}{p_1} = \left(\frac{h_2}{h_1}\right)^{k/k-1} \tag{60}$$

Dividing Eq. (59) by Eq. (60),

$$\frac{p_1/p_2 \text{ (actual)}}{p_1/p_2 \text{ (isentropic)}} = \left(\frac{h_1}{h_2}\right)^{k/\eta_e(k-1)} \cdot \left(\frac{h_2}{h_1}\right)^{k/k-1}$$

$$\frac{p_1/p_2 \text{ (actual)}}{p_1/p_2 \text{ (isentropic)}} = \left(\frac{h_1}{h_2}\right)^{k(1-\eta_e)/(k-1)\eta_e} \tag{61}$$

where h_1 and p_1 are the enthalpy and pressure at the entrance of the generator, and h_2 and p_2 are the same quantities at the exit. From this relationship the equivalent turbine efficiency of the magnetogasdynamic generator can be obtained.

$$\text{Equivalent turbine efficiency} = \frac{(h_1 - h_2)\text{(actual)}}{(h_1 - h_2)\text{(isentropic)}}$$

$$\eta_t = \frac{(1 - h_2/h_1)\text{(actual)}}{(1 - h_2/h_1)\text{(isentropic)}}$$

$$\eta_t = \frac{1 - (p_2/p_1)^{\eta_e(k-1)/k}}{1 - (p_2/p_1)^{(k-1)/k}} \tag{62}$$

The total efficiency of the magnetogasdynamic generator will be defined as the product of the electrical efficiency and the equivalent turbine efficiency.

$$\eta = \eta_e \cdot \eta_t \tag{63}$$

From Eq. (43) and Eq. (58), the power output per unit volume, or power density, will be written as follows:

Eq. (43) $P = \int_{x_1}^{x_2} \bar{J} \cdot \bar{E} \, A \, dx$

Power density $P_d = \bar{J} \cdot \bar{E} = JE$

Ohm's law $J = \sigma (uB - E)$

Therefore $p_d = \sigma(uB - E)E = \sigma(uBE - E^2)$

But $E = \eta_e uB$

$$p_d = \sigma(\eta_e u^2B^2 - \eta_e^2 u^2B^2)$$

$$= \sigma u^2B^2 \eta_e(1 - \eta_e) \tag{64}$$

The maximum power density, p_d, will be obtained when $dp_d/d\eta_e$ equals zero.

$$\frac{d\,p_d}{d\,\eta_e} = \sigma u^2B^2 \frac{d}{d\,\eta_e}(\eta_e - \eta_e^2)$$

$$= \sigma u^2B^2 (1 - 2\eta_e)$$

$$\sigma u^2B^2(1 - 2\eta_e) = 0$$

$$1 - 2\eta_e = 0$$

$$2\eta_e = 1$$

$$\eta_e = 1/2$$

This means that the power density of a magnetogasdynamic generator is a maximum when the electrical efficiency, η_e, equals 0.5, or 50 per cent. In other words, the external load, or resistance, must be equal to the internal resistance of the magnetogasdynamic generator.

The generator length L can be obtained by integrating Eq. (55). Assuming σ, u, η_e, and B are constant,

$$d_p = JB\,dx$$

$$d_p = \sigma(uB - E)B\,dx$$

$$d_p = \sigma(uB - \eta_e uB)B\,dx$$

$$d_p = \sigma(1 - \eta_e)uB^2\,dx$$

$$\int_{p_1}^{p_2} d_p = \sigma(1 - \eta_e)uB^2 \int_{x_2}^{x_1} dx$$

$$= -\sigma(1 - \eta_e)uB^2 \int_{x_1}^{x_2} dx$$

$$p_2 - p_1 = -\sigma(1 - \eta_e)uB^2(x_2 - x_1)$$

$$L = x_2 - x_1$$

$$p_2 - p_1 = -\sigma(1 - \eta_e)uB^2L$$

$$p_1\left(\frac{p_2}{p_1} - 1\right) = -\sigma(1 - \eta_e)uB^2L$$

$$p_1\left(1 - \frac{p_2}{p_1}\right) = \sigma(1 - \eta_e)uB^2L$$

$$L = \frac{p_1}{(1 - \eta_e)\sigma uB^2}\left(1 - \frac{p_2}{p_1}\right) \qquad (65)$$

$$L = \frac{p_1}{(1 - \eta_e)\sigma uB^2}\left[1 - \left(\frac{h_2}{h_1}\right)^{k/(k-1)\eta_e}\right] \qquad (65a)$$

Losses

The equivalent turbine efficiency of the magnetogasdynamic generator can be determined by Eq. (62). The major losses that tend to decrease this efficiency are as follows.

Ohmic Heating of Gas. Ohmic heating of the conducting gas, or I^2R loss inside the plasma, is caused by its electrical conductivity. If Q_0 is the loss

$$Q_0 = \int \frac{J^2}{\sigma} \, d\tau \qquad (66)$$

where τ = the average time interval between collisions.

Eddy-current Losses, (as the flow passes into and out of the magnetic field). These entering and leaving losses have been analyzed and calculated by Fishman and Sutton. It appears that they will be roughly 10 per cent of the entrance stagnation pressure (20).

Boundary Layer Losses. For viscous flow, there is a viscous force that causes the stagnation pressure loss. But these losses are small and will be neglected.

Anode and Cathode Voltage Losses. These losses occur due to the sheath of space charges near the electrodes. The loss due to the anode and cathode voltage drop may be given by the ratio of this voltage drop to the voltage appearing between electrodes. The voltage between electrodes is given by $\eta_e uBd$, where d is the distance between electrodes. For example, $\eta_e uBd$ is of the order of 1000 volts when u = 1000 m/sec, B = 1 weber/m^2 (10,000 gauss), d = 1 m, and η_e lies between 1/2 and

1. The electrode drops should represent a loss of not more than about one per cent (20).

<u>Friction Loss at the Walls</u>. If f is the coefficient of friction, the rate of loss for a wall area A_W is (21)

$$F = f\rho u^2 A_W \cdot u = f\rho u^3 A_W \tag{67}$$

<u>Heat Loss at the Walls</u>. If the allowed temperature of the material used to construct the magnetogasdynamic generator is equal to or lower than the static gas temperature, external cooling is required. The heat transfer through the walls by conduction is

$$Q_h = -kA \frac{dT}{dx} \tag{68}$$

The heat transfer through the wall is one of the largest sources of loss in the magnetogasdynamic generator. For effective design it is necessary to minimize this loss. For a linear configuration generator, the duct-length-to-diameter ratio should not be greater than 20 (20).

<u>i^2R Loss of the Magnetizing Coil</u>. If the coil has n turns with total copper cross section, A_c, and mean length per turn, ℓ, the resistance of the coil is (21)

$$R = \frac{r\,\ell n^2}{A_c}$$

where r is the resistivity of the wire material, and

$$Q_m = i^2R = \frac{r\ell}{A_c}(ni)^2$$

If ℓ_m denotes the length of the magnetic path, then

$$ni = \frac{B\ \ell_m}{\mu_0}$$

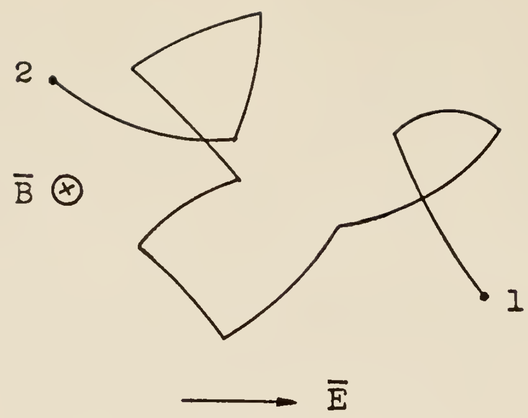
and
$$Q_m = \frac{r \ell \ell_m^2}{A_c \mu_0^2}\ B^2 \tag{69}$$

For a sufficiently large magnetogasdynamic generator, the wall friction, loss of heat at the walls, and the i^2R loss in the magnetizing coil are small compared to the energy converted. Thus these losses can be neglected (21).

Hall Effects

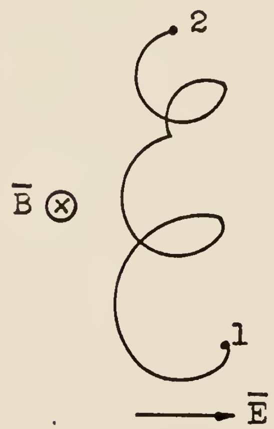
The Hall effect is the effect of the magnetic field upon the electrons. In the presence of the magnetic field, the electrons no longer follow straight-line paths while they drift to the electrode. The electrical field accelerates the electrons in the opposite direction to the electrical field. As the electrons move in this direction, the magnetic field causes them to be accelerated in the direction normal to their trajectories, and the electron paths become curves as shown in Fig. 5a and Fig. 5b. The Hall effect also causes the electrical conductivity to be a tensor rather than a scalar, and the electrical conduction current is not in the same direction as the electric field intensity. The product of the electron cyclotron frequency, ω_e, and the electron mean collision time, $\mathcal{T}_e$, is used as the measure of the Hall effect.

The magnitude of the Hall effect depends upon the magnitude of the quantity $\omega_e\ \mathcal{T}_e$($\omega_e\ \mathcal{T}_e = 2\pi$ x electron-cyclotron frequency



(a)

Perpendicular electric and magnetic fields are present; mean free path << mean radius of path.



(b)

Same as (a) but mean free path >> mean radius.

Fig. 5. Typical paths of electrons in a gaseous plasma.

times the mean free time between collisions). This quantity will be expressed in terms of the ratio of gas densities, ρ/ρ_0, and the magnetic flux density, B(20).

$$\omega_e \tau_e = \frac{WB}{(\rho/\rho_0)}$$

where W is a function of the degree of ionization, electron temperature, and the gas composition. As $\omega_e \tau_e$ approaches and exceeds unity, an electric field (Hall field) is parallel to the direction of the flow. In practice, the value of $\omega_e \tau_e$ lies between 2 and 7 for a generator with continuous electrodes.

One method to overcome the Hall effect is the use of segmented electrodes. Each pair of electrodes is connected through its own load. Then the generator power is independent of the value of $\omega_e \tau_e$ and the loss due to the Hall effect is not important. This is the reason why segmented electrodes are used.

Optimum Flow Velocity

From the experiments of Neuringer (7) for the magnetogasdynamic generator in which the entrance Mach number is less than one, the optimum exit Mach number must be unity. For supersonic operation, which means that the entrance Mach number is greater than unity, the optimum exit Mach number is also unity. The efficiency of the magnetogasdynamic generator will be increased if the subsonic and supersonic entrance Mach number have values far from unity, i.e., for M = 0.3 and 3, efficiencies greater than 20 per cent were obtained by Neuringer in his experiments (7).

Geometric Considerations

<u>Constant-area MGD Generator</u>. In designing the constant-area MGD generator (Fig. 6), the following assumptions are made.

1. The cross section of flow, A, of the channel or duct is constant.

2. The pressure, p, velocity, u, and temperature, T, of the ionized gas are functions of x only. For steady flow all properties are independent of time, t.

3. The friction and heat losses at the walls are negligible.

4. The magnetic flux density, B, is a constant. (Actually B varies slightly owing to the flow of electric current between P_1 and P_2. The variations are negligible when compared to the magnitude of B.)

5. The ionized gas obeys the perfect gas law.

$$p = \rho R\ T \tag{70}$$

From the continuity equation,

$$m = \rho_1\ Au_1 = \rho_2\ Au_2 \tag{71}$$

From the momentum equation,

$$p_1 + \rho_1\ u_1^2 = p_2 + \rho_2\ u_2^2 + JBL$$

But $\quad J = \frac{I}{A_e}$, A_e = area of electrode

$$(p_1 + \rho_1 u_1^2) - (p_2 + \rho_2 u_2^2) = \frac{IBL}{A_e}$$

$$(p_1 - p_2) + (\rho_1 u_1^2 - \rho_2 u_2^2) = \frac{IBL}{wL}$$

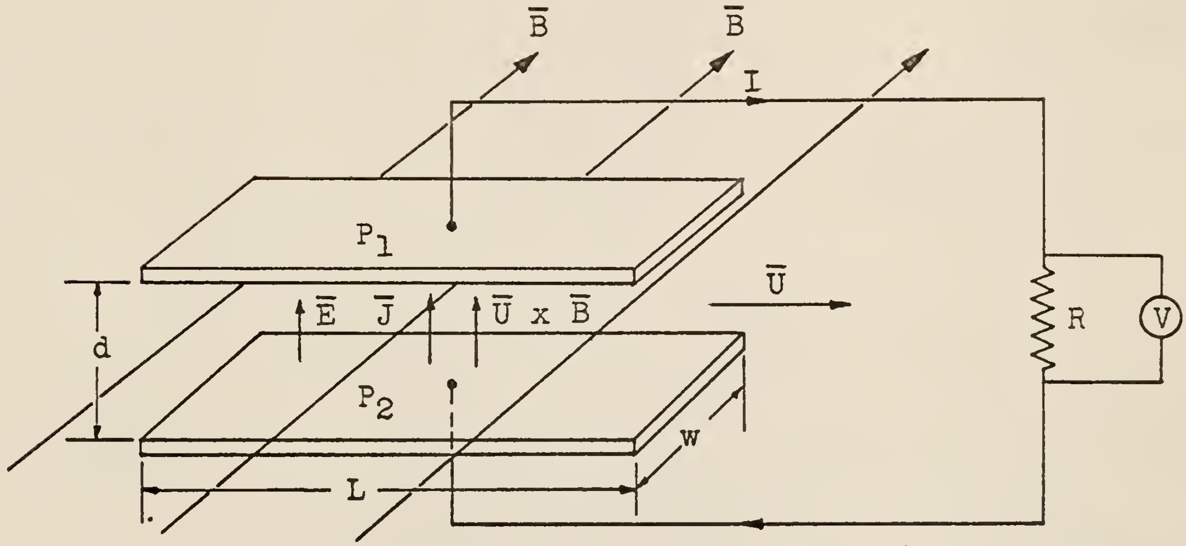


Fig. 6. Constant-area MGD generator.

$$(p_1 - p_2) + (\rho_1 u_1^2 - \rho_2 u_2^2) = \frac{IB}{w} \tag{72}$$

In making an energy balance, it is assumed that the process is adiabatic.

$$\rho u(h_{s_2} - h_{s_1}) = JEL$$

$$\rho u(h_{s_2} - h_{s_1}) = -\sigma u^2 B^2 \eta_e (1 - \eta_e) L$$

Multiplying both sides by the cross-section area, A,

$$\rho A u(h_{s_2} - h_{s_1}) = -\sigma u^2 B^2 \eta_e (1 - \eta_e) AL$$

$$m(h_{s_2} - h_{s_1}) = -VI$$

$$m(h_{s_1} - h_{s_2}) = VI \tag{73}$$

where I is the current flow from electrode, P_1, through the load, R, to electrode, P_2, and V (= IR) is the voltage developed across the load.

Equation (73) can be written in terms of the specific heat, C_p, temperature, T, and velocity, u, as follows.

$$m\left[(h_1 + \frac{u_1^2}{2}) - (h_2 + \frac{u_2^2}{2})\right] = VI$$

$$m\left[(C_p T_1 + \frac{u_1^2}{2}) - (C_p T_2 + \frac{u_2^2}{2})\right] = VI$$

$$m\left[C_p(T_1 - T_2) + (\frac{u_1^2}{2} - \frac{u_2^2}{2})\right] = VI \tag{73a}$$

$$m\left[\frac{k}{k-1} R(T_1 - T_2) + (\frac{u_1^2}{2} - \frac{u_2^2}{2})\right] = VI \tag{73b}$$

$$m\left[\frac{k}{k-1} (\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}) + (\frac{u_1^2}{2} - \frac{u_2^2}{2})\right] = VI \tag{73c}$$

Another equation gives the current, I, as a function of the gas variables

$$J = \sigma(uB - E) = \sigma(uB - V/d)$$

$$I = \int J \, dA_e$$

A_e = area of electrode

$$I = \int w \, J \, dx = w \int_{x_1}^{x_2} \sigma(uB - V/d)dx$$

$$= \sigma(uB - V/d)wL \tag{74}$$

Equations (70), (71), (72), (73), and (74) give a complete description of the conversion process. Given any set of initial conditions, p, ρ, u, T, and I, the subsequent values of these variables are completely determined.

The conversion efficiency of an MGD generator is defined as the ratio of the electric power output to the enthalpy flux at the input end (21).

$$\eta_c = VI/H_{s_1} \tag{75}$$

where H_{s_1} = total enthalpy influx = $\dot{m}(CvT_1 + \frac{P_1}{1} + \frac{1}{2} u_1^2)$, V, and I are the voltage and conduction current between the two electrodes, P_1 and P_2. From Eq. (73), Eq. (75) can be written as

$$\eta_c = \frac{h_{s_1} - h_{s_2}}{h_{s_1}} \doteq 1 - \frac{h_{s_2}}{h_{s_1}} \tag{76}$$

It is noted that h_{s_1} is the total gaseous power input to the MGD generator, and h_{s_2} is the unused gas energy at the exhaust end per unit mass. The conversion effectiveness is quite similar to the thermal efficiency, defined as the ratio of the useful energy output to the total energy input.

Example. An MGD generator with constant cross section uses argon ($k = 1.67$, $M = 40$) seeded with one per cent potassium as the working gas. The following data are given.

$$B = 1 \text{ weber/m}^2$$
$$T_1 = 2500° \text{ K}$$
$$p_1 = 0.5 \text{ atm}$$
$$u_1 = 2800 \text{ m/sec}$$
$$p_2 = 1.0 \text{ atm}$$
$$\dot{e} = 0.5$$

The output voltage is 250 volts and the required power generated is 15×10^6 watts. Assume that the average conductivity is 100 mho/m and determine the dimensions of the generator.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\eta_e(k-1)/k}$$

$$\frac{T_2}{2500} = \left(\frac{1}{0.5}\right)^{0.5(1.67-1)/1.67} = (2)^{0.20} = 1.149$$

$$T_2 = 2500 \times 1.149 = 2870° \text{ K}$$

$$\rho_1 = p_1/RT_1 = \frac{0.5 \times 100 \times 100 \times 40}{847 \times 2500} = 0.0944 \text{ kg/m}^2$$

$$\rho_2 = p_2/RT_2 = \frac{1 \times 100 \times 100 \times 40}{847 \times 2870} = 0.170 \text{ kg/m}^2$$

$$\rho_2 u_2 = \rho_1 u_1$$

$$u_2 = \frac{\rho_1 u_1}{\rho_2} = \frac{0.0944 \times 2800}{0.17} = 1555 \text{ m/sec}$$

$$\eta_e = E/uB$$

$$0.5 = \frac{E}{2800 \times 1}$$

$$E = 0.5 \times 2800 = 1400 \text{ volts/m}$$

$$E = V/d$$

where d = distance between electrodes

$$d = \frac{250}{1400} = 0.1785 \text{ m}$$

From the energy equation,

$$m(h_{s_1} - h_{s_2}) = VI$$

$$h_{s_1} = \left[\frac{k}{k - 1} \cdot RT_1 + \tfrac{1}{2} u_1^2\right]$$

$$= \left[\frac{1.67}{1.67 - 1} \times \frac{8314}{40} \times 2500 + \tfrac{1}{2}(2800)^2\right]$$

$$= 1{,}300{,}000 + 3{,}920{,}000 = 5{,}220{,}000 \text{ joules/kg}$$

$$h_{s_2} = \left[\frac{k}{k - 1} RT_2 + \tfrac{1}{2} u_2^2\right]$$

$$= \left[\frac{1.67}{0.67} \times \frac{8314}{40} \times 2870 + \tfrac{1}{2}(1555)^2\right]$$

$$= 1{,}490{,}000 + 1{,}210{,}000 = 2{,}700{,}000 \text{ joules/kg}$$

$$h_{s_1} - h_{s_2} = 5{,}220{,}000 - 2{,}700{,}000 = 2{,}520{,}000 \text{ joules/kg}$$

Energy equation,

$$m(h_{s_1} - h_{s_2}) = VI$$

$$m \times 2.52 \times 10^6 = 15 \times 10^6$$

$$m = \frac{15 \times 10^6}{2.52 \times 10^6} = 5.96 \text{ kg/sec}$$

$$m = \rho A u$$

$$A = \frac{m}{\rho u} = \frac{5.96}{0.0944 \times 2800} = 0.0226 \text{ m}^2$$

$$A = wd$$

where w = width of flow channel

$$w = A/d = \frac{0.0226}{0.1785} = 0.1265 \text{ m}$$

$$I = P/\dot{V} = \frac{15 \times 10^6}{250} = 60{,}000 \text{ amp}$$

From the current equation,

$$I = \sigma uB(1 - \eta_e)wL$$

$$60{,}000 = 100 \times 2800 \times (1 - 0.5) \times 0.151 \times L$$

where L = length of the generator

$$L = \frac{60}{28 \times 5 \times 0.151} = 2.84 \text{ m}$$

Therefore the generator dimensions are 0.15 x 0.151 x 2.84 m.

$$\eta_c = \frac{h_{s_1} - h_{s_2}}{h_s} = \frac{2{,}520{,}000}{5{,}220{,}000} = 0.483 = 48.3\%$$

The power density

$$\dot{P} = \frac{15 \times 10^6}{17.85 \times 12.65 \times 284} = \frac{15 \times 10^6}{6.42 \times 10^4} = 234 \text{ watt/cm}^3$$

Varying Cross-section MGD Generator. This type of generator improves the conversion efficiency, which can be realized by allowing B and the cross section of the conversion chamber to vary in such a way that the generated emf is kept constant throughout the conversion path as the velocity u approaches a final value.

In considering the dimensions of the conversion path of this type of MGD generator, the initial condition of the plasma, or ionized gas, should be known first. The final conditions of velocity and temperature will be selected with values that are neither too low nor too high. A very low final temperature

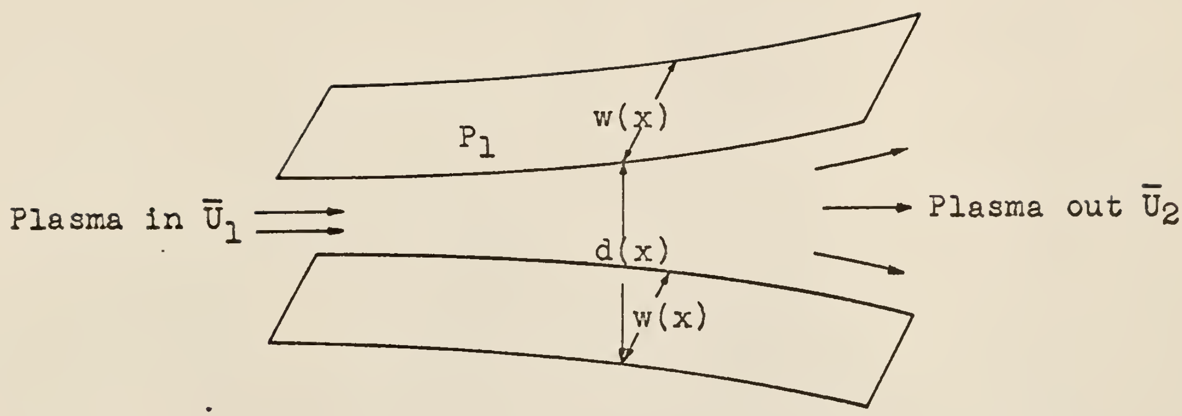


Fig. 7. A conversion chamber with varying cross section.

results in a great variation of temperature between inlet and outlet, which causes a large decrease in the electrical conductivity of the working fluid. A high final temperature gives a small decrease in the enthalpy of the working fluid, thus decreasing the power flow. If the total power to be generated, or the electrical efficiency, is given, the inlet and outlet areas of the conversion path can be determined from the thermodynamic properties by using the continuity and energy equations. The given value of conductivity will determine the length of the conversion path, and from this the power density will be obtained.

Example. An MGD generator with variable cross section uses the combustion gases of liquid fuel $(CH_2)_x$ seeded with one per cent potassium as its working fluid. The following data are given.

$$P_1 = 10 \text{ atm}, \; P_2 = 1 \text{ atm}$$

$$T_1 = 2500° \text{ K } (4500° \text{ F})$$

$$u_1 = 2500 \text{ m/sec}$$

$$B = 1 \text{ weber/m}^2$$

$$\eta_e = 0.50$$

The output voltage is 250 volts. Assume that the electrical conductivity is 100 mho/m and determine the size of the generator.

$$\left(R = 53.45 \frac{\text{ft - lb}_f}{\text{lb}_m \text{ F° abs}} = 29.3 \frac{\text{kg - m}}{\text{kg° K}} = 297.5 \frac{\text{joules}}{\text{kg° K}}\right.$$

$$\left. k = 1.27, \; C_p = 0.329 \frac{\text{Btu}}{\text{lb}_m\text{° F}}, \; C_v = 0.259 \frac{\text{Btu}}{\text{lb}_m\text{° F}}\right)$$

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{k/(k-1)\eta_e}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)\eta_e/k}$$

$$\frac{T_2}{2500} = \left(\frac{1}{10}\right)^{(1.27-1)0.50/1.27}$$

$$T_2 = 2500(1/10)^{0.1061} = 2500 \times 0.692 = 1955° \text{ K}$$

For the maximum flow rate, the Mach number at the exit should be unity and no shocks should occur in the chamber (7).

$$C_2 = \sqrt{kRT_2} = \sqrt{1.27 \times 297.5 \times 1955} = 860 \text{ m/sec}$$

$$u_2 = M_2\, C_2 = 1 \times 860 = 860 \text{ m/sec}$$

$$\eta_e = E/u_1B$$

$$E = \eta_e\, u_1B = 0.50 \times 2500 \times 1 = 1250 \text{ volt/m}$$

$$E = V/d$$

$$d_1 = V/E$$

$$d_1 = 250/1250 = 0.200 \text{ m} = 0.20 \times 3.28 = 0.656 \text{ ft}$$

Let A_1 be square cross section; therefore

$$w_1 = 0.200 \text{ m} = 0.656 \text{ ft}$$

$$A_1 = (0.200)^2 = 0.04 \text{ m}^2 = 0.43 \text{ ft}^2$$

$$m = \rho_1 A_1 u_1 = \frac{p_1 A_1 u_1}{RT_1}$$

$$= \frac{10.3 \times 100 \times 100 \times 0.04 \times 2500}{29.3 \times 2500} = 140.5 \text{ kg/sec}$$

$$m = \rho_2 A_2 u_2$$

$$A_2 = \frac{m}{\rho_2 u_2} = \frac{mRT_2}{p_2 u_2} = \frac{140.5 \times 29.3 \times 1955}{1.03 \times 100 \times 100 \times 860} = 0.908 \text{ m}^2$$

$$= 9.77 \text{ ft}^2$$

Let A_2 be a square cross section; therefore

$$d_2 = \sqrt{A_2} = 0.953 \text{ m} = 3.13 \text{ ft}$$

$$w_2 = 0.953 \text{ m} = 3.13 \text{ ft}$$

$$h_{s_1} = \left[\frac{k}{k - 1} RT_1 + \frac{u_1^2}{2} \right]$$

$$= \left[\frac{1.27}{1.27 - 1} \times 297.5 \times 2500 + \tfrac{1}{2}(2500)^2 \right]$$

$$= 3,500,000 + 3,125,000 = 6,625,000 \text{ joules/kg}$$

$$h_{s_2} = \left[\frac{k}{k - 1} RT_2 + \frac{u_2^2}{2} \right]$$

$$= \left[\frac{1.27}{1.27 - 1} \times 297.5 \times 1955 + \tfrac{1}{2}(860)^2 \right]$$

$$= 2,735,000 + 370,000 = 3,105,000 \text{ joules/kg}$$

$$h_{s_1} - h_{s_2} = 6,625,000 - 3,105,000 = 3,520,000 \text{ joules/kg}$$

Power generated,

$$P = m(h_{s_1} - h_{s_2}) = 140.5 \times 3.52 \times 10^6 = 495 \times 10^6 \text{ watts}$$

$$\text{Length } L = \frac{p_1}{(1 - \eta_e)\,\sigma u B^2} \left(1 - \frac{p_2'}{p_1}\right)$$

$$= \frac{10.3 \times 100,000}{(1 - 0.5) \times 100 \times 2500} \left(1 - \frac{1}{10}\right)$$

$$= 37.1/5 = 7.42 \text{ m}$$

$$= 7.42 \times 3.28 = 24.4 \text{ ft}$$

Conversion efficiency η_c

$$\eta_c = \frac{h_{s_1} - h_{s_2}}{h_{s_1}} = \frac{3,520,000}{6,625,000} = 0.531 = 53.1\%$$

Power density P_d

$$P_d = \sigma u^2 B^2 \eta_e (1 - \eta_e)$$

$$= 100 \times 2500^2 \times 1^2 \times 0.5(1 - 0.5)$$

$$= 156.25 \times 10^6 \text{ watt/m}^3$$

Volume of conversion chamber

$$V = \frac{495 \times 10^6}{156.25 \times 10^6} = 3.17 \text{ m}^3 = 112 \text{ ft}^3$$

CONCLUSIONS

Magnetogasdynamic generators are a new type of machine used to convert heat energy into electric energy and are suitable for large scale generation of direct-current power. The principle of the magnetogasdynamic generator is quite similar to the conventional generator except that a hot ionized gas is used instead of a metallic conductor. The hot ionized gas moves through a magnetic field which is applied at right angle to the flow, and past electrodes which are in contact with the stream of gas. Electrons in the gas are deflected by the magnetic field, and between collisions with other particles, such as ions and atoms in the gas, they make their way diagonally to one of the electrodes. An electric current is produced as the electrons move from the anode, through the load, to the cathode, and back again to the gas stream.

Magnetogasdynamic power generation requires a conducting gas or ionized gas as a working fluid. For the gas to be sufficiently conducting, a certain number of free electrons must be present together with an equal number of ions and the atoms of nonionized gas. The most direct method to ionize a gas partially, and make it conducting, is to heat it sufficiently. However, the temperatures of partially ionized gas are still beyond the limits of materials used to construct the magnetogasdynamic generator.

When the gas is "seeded" with a small amount of an element, such as potassium or cesium, adequate electrical conductivity can be obtained at somewhat lower temperatures (in the range of 4000 to 5000 degrees F). The induced voltage at the terminals of a magnetogasdynamic generator is directly proportional to the intensity of the magnetic field, the velocity of the gas, and the distance between the electrodes. A generator will supply maximum power when the external load connected to its terminals has a voltage drop equal to one-half of the open-circuit voltage. In other words, the external load resistance is equal to the internal resistance.

Reference (21) describes a disadvantage of the MGD generator with constant cross section. A part of the kinetic energy is used to compress and heat up the gas when the entrance Mach number is greater than unity. This happens because the velocity of the gas decreases and the pressure of the gas increases. If the entrance Mach number is less than unity, the constant cross section MGD generator will speed up the gas unnecessarily owing to the higher Mach number of the exit. In both cases the conversion efficiency is low. This difficulty can be avoided by making the cross-section area increase with the length of the MGD generator. Therefore the MGD generator with increasing cross section is recommended. For both types of conversion chambers, constant cross section and varying cross section, operating with either supersonic or subsonic speeds at the entrance, the optimum exit velocity (corresponding to the maximum efficiency) is equal to the acoustic velocity. This is the lower limit of velocity for supersonic operation and the upper limit for subsonic operation. Magnetogasdynamic generators have their lowest efficiency if the entrance Mach number is near unity, according to the experiments of Neuringer (7). The efficiency is increased when the entrance Mach number is far removed from unity. For subsonic operation ($M < 1$), most of the electric power delivered to the load is produced near the exit region of the MGD generator because the high velocity there increases the electromagnetic induction. For supersonic operation ($M > 1$), most of the electric power generated comes from the increased electromagnetic induction occurring near the entrance of the MGD generator where the velocity is high.

The conversion of thermal to electrical energy by this method is very attractive to engineers because of the predicted high efficiencies and because there is no moving component that can cause mechanical wear and tear. At the present, magnetogasdynamic generators are under development. Further research needs to be done to obtain more reliable data on the conduction of electricity in gases and to provide a better understanding of this conduction. Materials used to construct magnetogasdynamic generators must be developed to better withstand high temperatures, sudden temperature changes, and chemical interaction with alkali metal seeding materials.

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THE MAGNETOGASDYNAMIC GENERATOR

by

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The magnetogasdynamic generator is a new kind of electrical machine which is used to convert thermal energy into electric energy by means of the interaction between electromagnetic fields and a conducting gas. Usually gases are not good electrical conductors except at very high temperature. When the temperature is higher than 10,000 degrees K, all gases will be sufficiently ionized to be considered an electrically conducting gas. The ionized gas is called a "plasma", and is composed of electrons, ions, and neutral particles. In practice the plasma may be considered as a single gas of definite composition and also may be assumed to be a perfect gas. The conducting gas moves through a channel or duct with a magnetic field applied in a direction perpendicular to the flow and past electrodes which are located at the top and bottom of the channel. The ionized gas performs the same function as the copper conductor in the conventional generator. The negatively charged electrons in the gas are deflected by the magnetic field, and between collision with other particles, such as ions and atoms in the gas, they make their way diagonally to one of the electrodes. An electromotive force is induced in the body of the gas which, in turn, induces an electric current. An electric current is produced as the electrons move from the anode, through the load, to the cathode, and back again to the gas stream.

The magnetogasdynamic power generator requires a conducting gas or ionized gas as a working fluid. The most direct method to ionize a gas partially, and make it conducting, is to heat it sufficiently. However, the temperatures of partially ionized gas are still beyond the limits of materials used to construct the magnetogasdynamic generator. When the gas is "seeded" with a small amount of an element, such as potassium or cesium (because of economics potassium is used more than cesium), adequate electrical conductivity can be obtained at somewhat lower temperatures, in the range of 4000 to 5000 degrees F. A generator will supply maximum power when the external load connected to its terminals has a voltage drop equal to one-half of the open-circuit voltage. In other words, the external load resistance is equal to the internal resistance.

The direct conversion of thermal to electrical energy by this method is very attractive to engineers because the predicted thermal efficiencies of the magnetogasdynamic cycle are better than the present efficiencies of steam and gas power cycles now used for bulk power generation. Also there are no moving parts that can cause mechanical wear and tear as is the case for the conventional turbo generator. The magnetogasdynamic cycle can be combined with the modern steam or gas power plant, which uses chemical fuel or nuclear reactors, in order to improve the plant efficiency. At the present, magnetogasdynamic generators are under development. Further research needs to be done to obtain more reliable data on the conduction of electricity in gases. Materials used to construct magnetogasdynamic generators must be developed to better withstand high temperatures, sudden temperature changes, and chemical interaction with alkali metal seeding materials.