PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Science of M.H.D. Generators-A Critical Survey

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A. M.H.D. CYCLES AND LARGE SCALE EXPERIMENTS

I. The science of m.h.d. generators—a critical survey

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This paper is intended to provide a general introduction to the subject and provide a background for the detailed scientific papers appearing later in the meeting.

The various types of m.h.d. generator are briefly discussed and the basic theory of m.h.d. generation is described. The open cycle fossil fuel type of m.h.d. generator system in which the exhaust gases from the m.h.d. duct are used to power a steam turbo alternator generator is discussed in more detail and the major problem areas identified. These include the stability of the flow in the m.h.d. duct, the provision of long lived electrodes, air preheaters, seed recovery apparatus and the development of a suitable superconducting magnet. The influence of the parameters of the various components on the performance of the complete m.h.d./steam turbine plant is discussed.

1. Introduction

Although basic principles of m.h.d. were suggested by Faraday as early as 1830 (Faraday 1830), apart from some early work in the 1930's (Karlovitz & Halasz 1962) it is only in the last decade that there has been a concentrated effort on m.h.d. The reason for this is that although the basic principle is very simple (namely that a hot, electrically conducting gas flows normal to a magnetic field, the induced current being collected on electrodes and fed through the load), the apparatus required for the system is difficult to construct and the practical exploitation of m.h.d. requires advances at or beyond the limits of present-day technology. For this reason some of the papers to this Symposium are concerned with subjects such as air heater design, the physical chemistry of potassium sulphate and the development of large, high field superconducting magnets.

Another reason for the interest in m.h.d. electrical power generation at this stage in time is that although there have been considerable increases in efficiency and decreases in capital cost of conventional steam turbo alternator power stations over the last thirty years, arising from the use of larger units of plant and from higher steam temperatures and pressures, this method of power generation would appear to be reaching the limits of development at an efficiency (i.e. the ratio of the electrical energy sent out to the gross calorific energy of the fuel burnt) of about 40 %. Although flame temperatures are of the order of 2000 °C the maximum economic metal temperature than can be used with a coal or residual oil fired boiler is less than 600 °C so that the steam cycle efficiency is necessarily restricted. The attraction of m.h.d. is that it enables the high temperature flame gas region in excess of 600 °C to be exploited. Figure 1 shows a scheme by which m.h.d. could be used to raise the efficiency of such a system.

The electrical conductivity of a weakly ionized gas in thermodynamic equilibrium at a temperature T varies with temperature approximately as exp $(-eV_i/2kT)$ where V_i is the ionization potential, e is the charge on the electron and k is Boltzmann's constant (see, for example, Wright 1965). Hence, in order to obtain a reasonable degree of electrical conductivity, it is normal to add a trace of low ionization potential 'seed' material (a potassium or possibly caesium compound) and to raise the combustion temperature by incorporating an air preheater. Increasing the combustion temperature by burning in oxygen has been suggested (Brogan 1962), but this does not seem to be economically attractive (Carter, Freck, Harrowell & Wright 1964). The electrical power from the m.h.d. duct is extracted as d.c. Various forms of a.c. generation have been considered (Clark, Swift-Hook & Wright 1963) but found to be unattractive at the low magnetic Reynolds numbers obtained in a combustion m.h.d. system. For other types of m.h.d. where the high magnetic Reynolds numbers might be obtained, a.c. generation could be

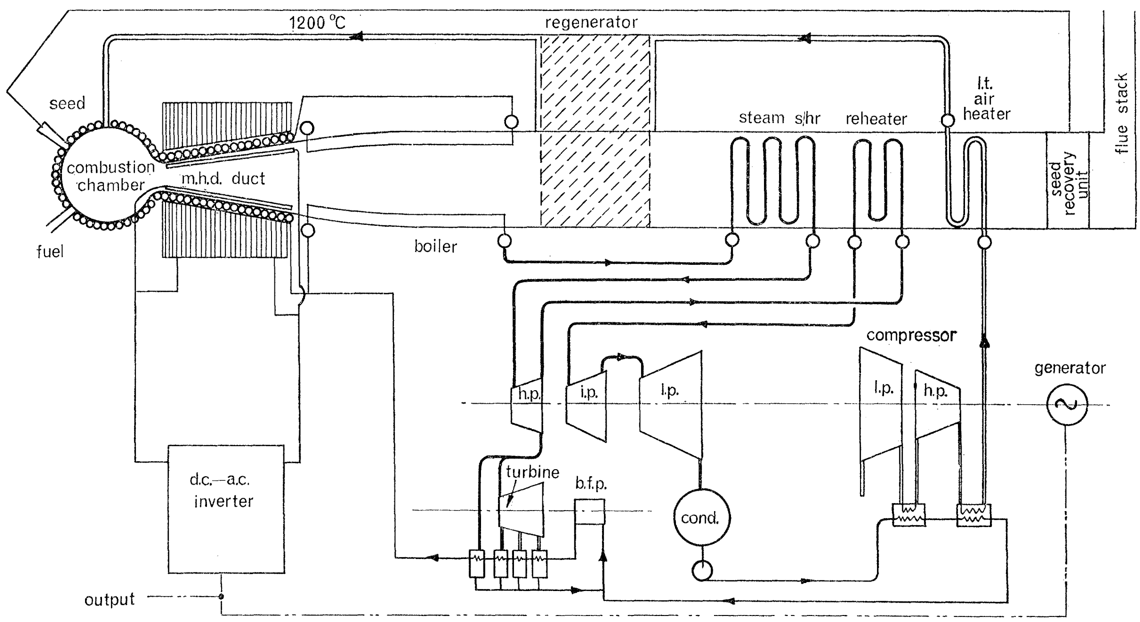

Figure 1. Typical cycle diagram of the m.h.d.-steam power plant with a directly fired air heater.

used (Fanucci 1962). After leaving the m.h.d. duct, the combustion products are still sufficiently hot to fire the air preheater and a conventional steam boiler. It is necessary to recover as much of the seed material as possible and recycle it if the cost of the seed is not to outweigh the reduction in fuel costs due to the increases in cycle efficiency. This type of m.h.d. system is often known as the open cycle fossil fuel system. It is the subject of most of the papers in this Symposium.

In another type of system, known as the closed cycle system, described below in detail by Lindley, McNab & Dunn (p. 368), a heat exchanger is used to heat the m.h.d. working fluid so the advantage of the open cycle system of having an m.h.d. fluid hotter than any solid is immediately lost. On the other hand, a wider choice of working fluid is possible since none of the gas is lost from the system. This means that gases of low collision cross-section and seed of low ionization potential may be used economically, and the use of monatomic gases makes it theoretically possible to obtain conductivities in excess of those based on the assumption of thermodynamic equilibrium. This is an area of major research interest since it would lead to an adequate electrical conductivity at a temperature

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sufficiently low to be within the range of heat exchanger technology. The method would be particularly applicable to high temperature gas-cooled reactors, although it is not clear that m.h.d. would be superior to other more conventional forms of generation such as gas turbines (Wright 1963).

Other forms of m.h.d. generator are being studied. In the liquid metal system (see, for example, Elliot 1962) the kinetic energy of an expanding gas is used to impart momentum to an electrically conducting liquid. Since liquid metal conductivities are four to six orders of magnitude greater than those of thermally raised gases as reasonable temperatures and the fluid velocities are one to two orders of magnitude less than with normal generators, the density of electrical power generation is considerably greater than with conventional m.h.d. systems and at a considerably reduced fluid temperature. The problems lie with the production of efficient two phase accelerators and separators.

Another possibility is to produce an open cycle flow system with local 'hot spots' (Thring 1962). Since the electrical conductivity rises rapidly with temperature the same mean electrical conductivity may be obtained at a lower average gas temperature. Unfortunately this system would appear to be very unstable to Rayleigh–Taylor type instabilities and is unlikely to be of practical value. Such temperature and velocity modulated systems are described below in the papers by Ibberson & Harris (p. 429) and by Devime, Lecroart, Porte & Yerouchalmi (p. 496).

Finally Jones & Blackman (1964) have used shaped explosive charges to obtain very high electrical powers for times of the order of 50 μs at conversion efficiencies of about $1\frac{1}{2}\%$.

However, this introductory paper is concerned mainly with the open cycle system since it is the type which is closest to realization and the type on which most effort is being currently expended.

2. M.H.D. DUCT PROCESSES

(a) *Duct hydrodynamics*

Over the last few years there have been a number of papers dealing with the magnetohydrodynamics of duct flows (Neuringer 1960; Coe & Eisen 1960; Sutton 1959; Brocher 1962; Swift-Hook & Wright 1962). The more elementary treatments ignore friction and heat transfer and show that, in order to obtain high densities of electrical power generation, the flow should have a speed of around that of sound in the duct gases. A consequence of this is that the duct cross-sectional area must increase in the downstream direction. For seeded combustion products the maximum power density is obtained at low supersonic speeds, but under these conditions it is possible to obtain shock waves and flow detachment (Louis & Brogan 1964). For these reasons a practical generator may well operate in the high subsonic flow region.

It seems probable that the insulating walls of an open cycle m.h.d. duct will be cooled in order to withstand the high temperature gas environment. The gas in the boundary layer close to these walls will therefore be non-conducting and magnetohydrodynamic processes in these boundary layers may be ignored. The heat transfer and wall friction effects may then be estimated using normal fluid dynamic theory taking into account the enhanced heat transfer that results from recombination of dissociated molecules in the boundary layer and on the wall. On the electrodes one must, however, allow for additional heat transfer due to the modification of the boundary layer by the passage of current.

Magnetohydrodynamic forces do play a considerable part in the hydrodynamic stability of the flow along the expanding m.h.d. duct. Boundary layer theory (Schlichting 1960) assumes that the pressure is uniform across a cross-section of the duct. When the pressure gradient along the duct is sufficiently positive the flow will separate. In extending this theory to m.h.d. flows, account must be taken of the electromagnetic forces which in a generator are equivalent to a positive pressure gradient. These forces act both on the gas in the central region of the duct and to an equal extent in the boundary layer on the electrode surface. However, they are very much reduced on the low conductivity gas adjacent to the insulating side walls and this tends to keep the side wall flows attached in a very stable manner. Any detachment of flow will, therefore, tend to occur on the electrode surfaces and particular attention must be paid to this when designing ducts.

(*b*) *Electrodynamics of ducts*

Methods of calculating the electrical conductivity of the m.h.d. working fluid are described in later papers in this Symposium. In this paper, attention is drawn to some of the consequences of the Hall effect—the name given to the fact that, in directions normal to a strong magnetic field, the electrical conductivity is a tensor quantity because of the trochoidal path of the electrons between collisions.

The electrical conductivity in directions parallel to the magnetic field (scalar), normal to the magnetic field in the direction of the electric field and normal to both the magnetic and electric fields are given by Allis (1956):

$$\sigma_0 = \mu_0 e n_e = \frac{4\pi n_e e^2}{3m}\int_0^\infty f_0(v)\,\frac{\mathrm{d}}{\mathrm{d}v}\left(\frac{v^3}{\nu_c}\right)\mathrm{d}v,$$

$$\sigma_\parallel = \frac{4\pi n_e e^2}{3m}\int_0^\infty f_0(v)\,\frac{\mathrm{d}}{\mathrm{d}v}\left(\frac{\nu_c v^3}{\nu_c^2+\omega_e^2}\right)\mathrm{d}v,$$

$$\sigma_\perp = \frac{4\pi n_e e^2}{3m}\int_0^\infty f_0(v)\,\frac{\mathrm{d}}{\mathrm{d}v}\left(\frac{\omega v^3}{\nu_c^2+\omega_e^2}\right)\mathrm{d}v.$$

In these equations $f_0(v)$ is the electron velocity distribution function taken to be Maxwellian,

$$f_0(v) = \left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}}\exp\left\{-\frac{mv^2}{2kT}\right\};$$

μ_0 is the mobility of the electrons, n_e their number density, v is the electron velocity, m the mass of the electron, e its charge, k is Boltzmann's constant, T is absolute temperature, $\nu_c = \nu_c(v)$ is the collision frequency of the electron in the gas and $\omega_e = eB/m$ is the electron cyclotron frequency in a magnetic field B.

Since the electron collision frequency is a function of energy the integrals must be evaluated for each particular pressure and temperature and magnetic field strength. However, it has been found that, over the range of conditions likely to be encountered in practice, the approximations

$$\sigma_\parallel = \frac{\sigma_0}{1+\beta^2} \quad \text{and} \quad \sigma_\perp = \frac{\beta\sigma_0}{1+\beta^2},$$

where $\beta = \mu_0 B$ are accurate to better than 2%.

Consider the two-dimensional problem of a gas flowing with velocity u along the axis of an m.h.d. duct taken to be the x direction normal to the magnetic field B taken to be in the z direction. An induced current $\mathbf{J} = (j_x, j_y, 0)$ flows through the gas and into loads, thereby giving rise to an electric field $\mathbf{E} = (E_x, E_y, 0)$.

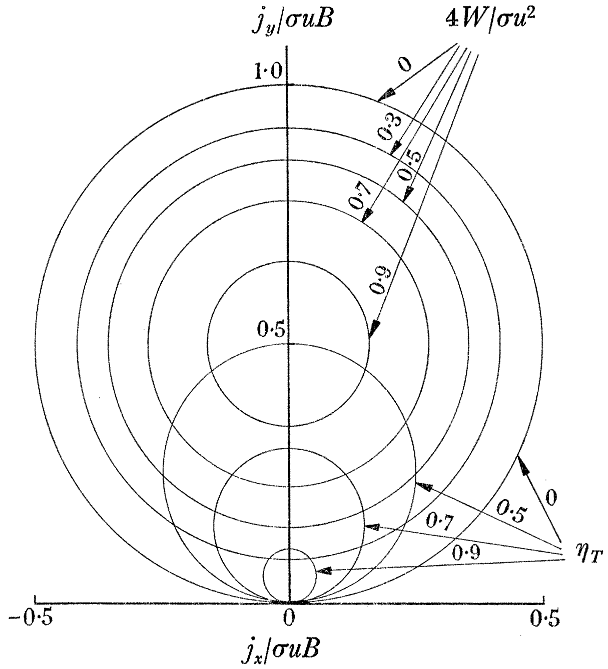

FIGURE 2

The generalized Ohm law is

$$j_x = \sigma_{\parallel} E_x - \sigma_{\perp}(E_y - uB),$$

$$j_y = \sigma_{\perp} E_x + \sigma_{\parallel}(E_y - uB).$$

The electrical power delivered to the load is $W = -\mathbf{j}.\mathbf{E}$ and an important quantity known as the 'electrical efficiency',

$$\eta_e = \mathbf{j}.\mathbf{E}/j_y uB$$

may be defined. η_e is the ratio of the electrical power generated to the work done by the fluid against the magnetic body force. Figure 2 shows contours of normalized electrical power density and electrical efficiency as a function of j_x and j_y. This type of diagram was first suggested by Burgel (1963). It will be seen that to obtain the maximum electrical efficiency for a given power density the loads should be connected in such a way as to reduce the axial current to zero.

Figure 3 shows various ways of connecting the loads. In 3 (*a*) there is a single pair of electrodes; $E_x = 0$ and hence $j_y/j_x = -1/\beta$. Such generators are sometimes called Faraday or continuous electrode generators. From figure 2, this arrangement is only satisfactory for small β. In segmented electrode generators (figure 3 (*b*)) j_x is forced to be close to zero at the expense of a multiplicity of loads. Fine segmentation must be used at high β.

In the Hall generator (figure 3 (*c*)) $E_y = 0$ and hence

$$\frac{j_y}{j_x} = \left\{\beta \frac{E_x}{\beta u B} - \frac{1}{\beta}\right\} \Big/ \left\{\frac{E_x}{\beta u B} + 1\right\}$$

and a reasonable current angle is obtained for only high values of β.

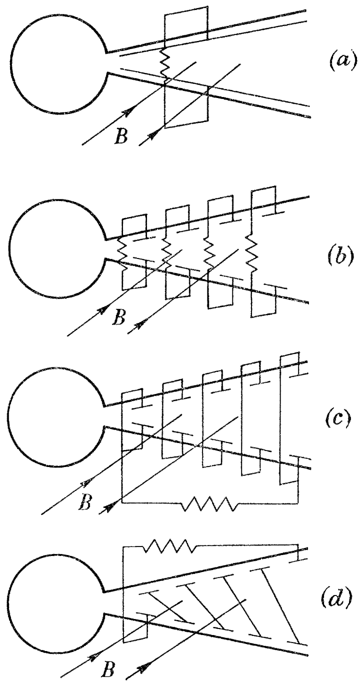

FIGURE 3

In practical combustion product generators the value of β is approximately $0.6 \times$ field strength (tesla)/pressure (atm) and might vary from 0·3 to 3 along the duct. None of the standard connexions are therefore suitable for the whole range and the arrangement in figure 3 (*d*) (variously called cross or diagonally connected or sloping tube generator) is probably preferable. In this arrangement electrical connexions are made along equipotential lines in the segmented Faraday generator (figure 3 (*b*)) and a single load or small number of loads may be used.

(*c*) *Fluid dynamics*

Consider now a complete m.h.d. duct. Assuming one-dimensional flow, the equations of continuity of mass, momentum and energy are

$$\rho u A = \text{constant},$$

$$\rho u \frac{\mathrm{d}u}{\mathrm{d}x} + \frac{\mathrm{d}p}{\mathrm{d}x} - j_y B + \frac{NS}{A} = 0,$$

$$\rho u \frac{\mathrm{d}}{\mathrm{d}x}\left(h + \tfrac{1}{2}u^2\right) - \mathbf{j}\,.\,\mathbf{E} + \frac{HS}{A} = 0;$$

A is the cross-sectional area and s the circumference of the duct, p, h and ρ are the pressure, enthalpy and density of the gas. H and N are the heat loss and frictional drag per unit area of the duct wall.

As an example of the use of these equations, consider the case of a constant velocity generator with no heat or frictional losses. The equations being

$$\frac{\mathrm{d}p}{\mathrm{d}x} - j_y B = 0$$

and

$$\rho u \frac{\mathrm{d}h}{\mathrm{d}x} - \mathbf{j}.\mathbf{E} = 0.$$

From these equations we derive immediately

$$\frac{\mathrm{d}p}{p} = \frac{1}{\eta_e}\frac{\rho h}{p}\frac{\mathrm{d}h}{h}.$$

For combustion products $\rho h/p$ is constant to a very good approximation and, for constant η_e we derive the conversion efficiency (fraction of enthalpy in the gas, not allowing for kinetic energy, converted into electricity)

$$\frac{h_{\text{in}} - h_{\text{out}}}{h_{\text{in}}} = 1 - \left(\frac{p_{\text{out}}}{p_{\text{in}}}\right)^{\eta_e p/\rho h}.$$

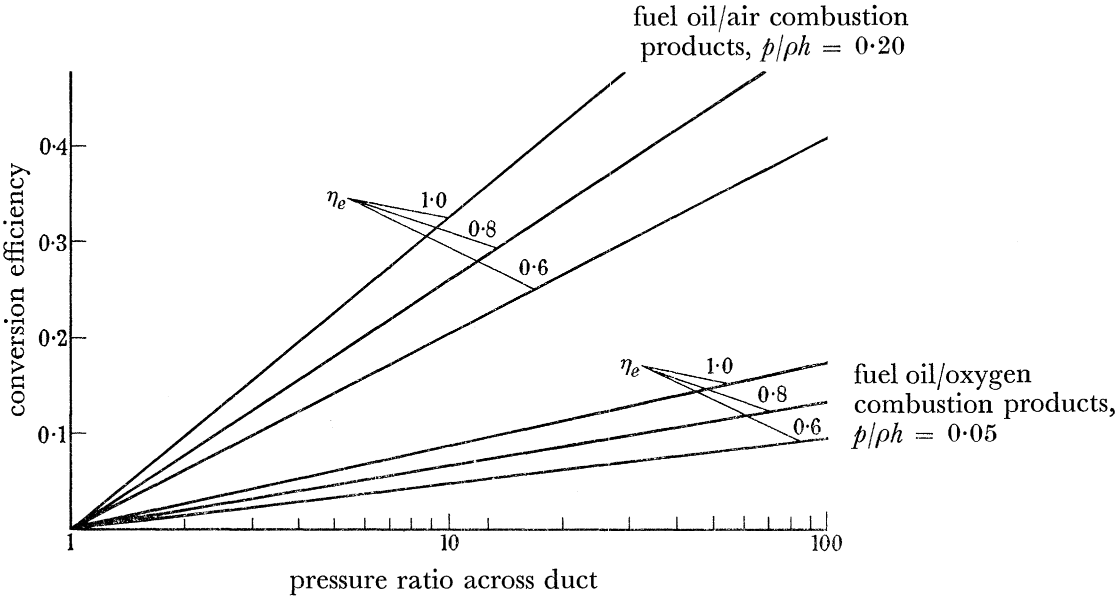

FIGURE 4

Figure 4 shows this relation and illustrates the importance of maintaining a high electrical efficiency. The electrical efficiency *in this example of no wall losses* plays the same role as the stage isentropic efficiency in a gas turbine. It should be clearly distinguished from the load parameter K which is defined as the ratio of on load to open circuit voltage. The two quantities K and η_e are equal for the Faraday generators (figure 3 (*a*) and (*b*)) but not for the general case. Figure 5 shows how the two quantities are related for the cross-connected generator (figure 3 (*d*)) where the equipotential surfaces are at 45° to the duct axis.

So far the effect of wall losses has been ignored. An approximate analytical theory including their effect has been derived by Swift-Hook (1964), but in most performance studies of the type about to be described it is customary to solve the equations numerically on a computer.

(*d*) *Duct constructional methods*

The high temperature corrosive conditions that are encountered when any surface is placed in contact with the fast moving gas stream in an m.h.d. duct makes the construction of m.h.d. ducts a critical feature of the m.h.d. problem. It seems likely that with limitations of present materials the most suitable method of making a permanent m.h.d. wall is to construct it from water cooled metal. Insulation is provided by segmenting the metal and inserting thin layers of insulator in between the metal sections. The insulator must be

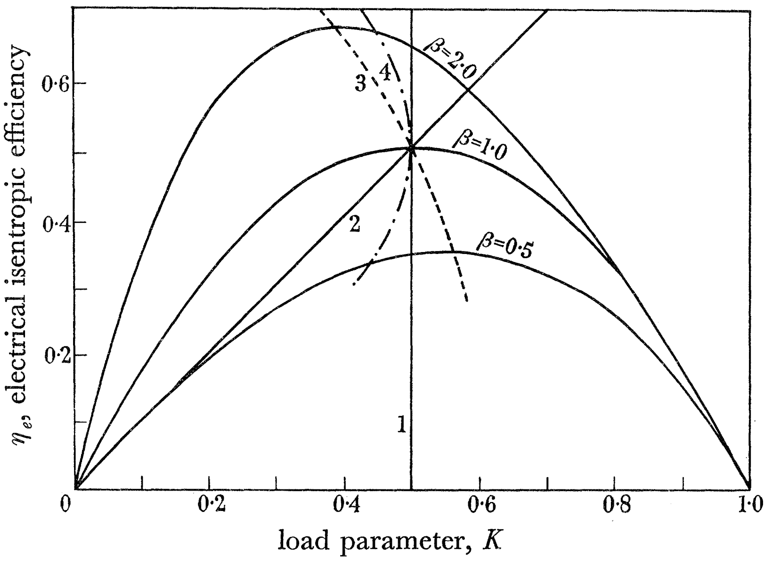

FIGURE 5. Plot of η_e against K for a fixed equipotential duct with $\alpha = 1$. Line 1 indicates the condition for small stage maximum power; 2, $\eta_e = K$ true for $J_x = 0$ type generator; 3, maximum η_e; 4, optimized condition where $J_x = 0$.

sufficiently thin to be well cooled by the metal itself. Under the influence of the high temperature gas stream the insulator tends to burn back leaving a rough surface. The voltage difference between adjacent metals at sections must be kept within about 40 V if flash-over across the insulator surface is not to occur. Using this sort of technique ducts have been constructed which have withstood tests of many hours (Sporn & Kantrowitz 1964; Dunn, Lindley & Wright 1964).

Current carrying electrodes present some problems. One technique that is being used with a fair degree of success is to use a water cooled metal surface as an electrode. This suffers from the disadvantage that as current flows some wear can take place and significant development work is required before the technique is sufficiently advanced for ducts having current densities and lives appropriate to a commercial m.h.d. generator. Another feature of cooled electrodes is that there is a voltage drop between the electrode and the main body of the m.h.d. working fluid. This voltage drop has been measured by several workers and found to be the order of 100 V.

Ceramic electrodes which may be run hot and so give a reduced voltage drop are also promising and are discussed below by Anthony & Yerouchalmi (p. 504).

Figure 6 shows one method of combining water cooled metal electrodes and water cooled metal duct construction for the cross-connected generator depicted in figure 3 (*d*).

The system is constructed from a series of water cooled metal tubes which have been bent round to form rectangular loops. The loops are then laid one on top of another in such a way that the side walls lie at an angle equal to the angle of the equipotential surfaces to the axis of the duct. In this way the top and bottom surfaces act as non-opposite electrodes. One difficulty with this type of construction lies in the large end effects that are introduced in the triangular portions between the combustion chamber and the entrance to the duct. Currents are flowing at an angle $\tan^{-1}\beta$ to the axis of the duct, whereas in a well designed system the currents in the main body of the m.h.d. generator would be flowing

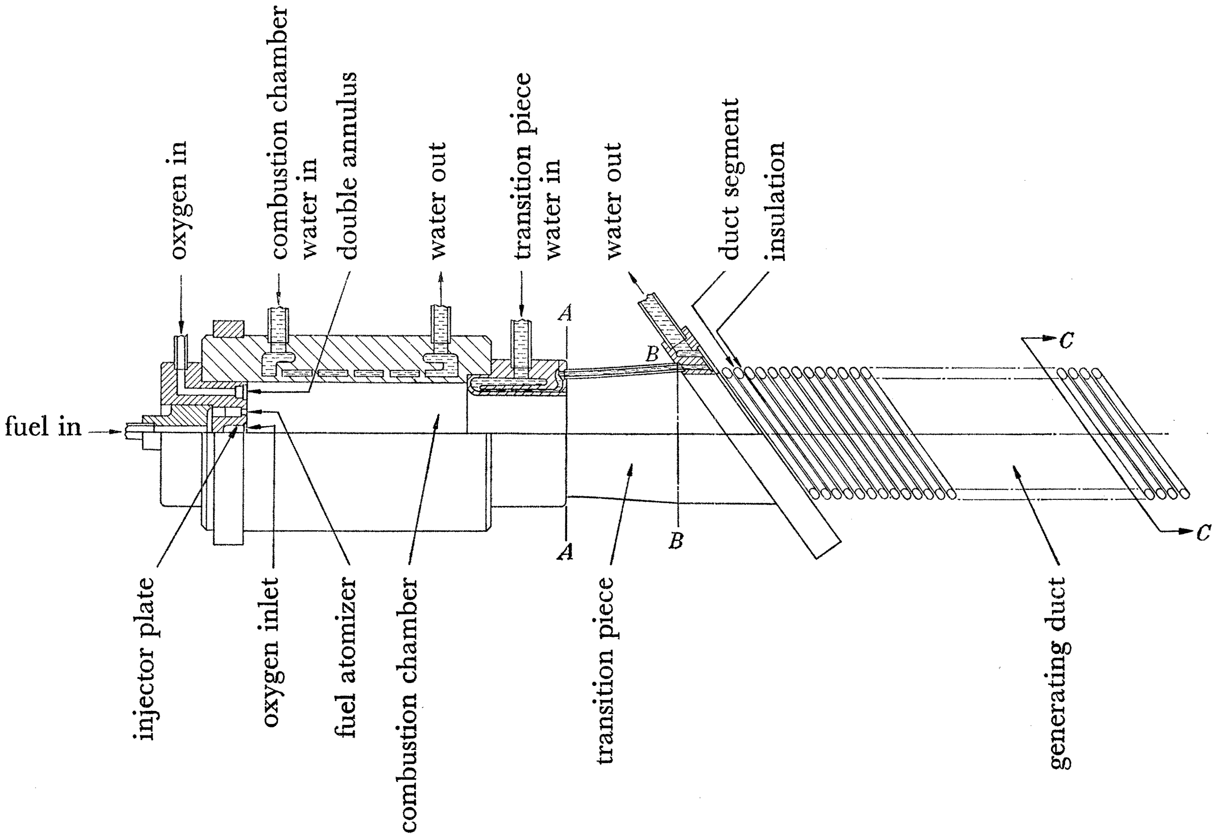

FIGURE 6

vertically. This means that there is some circulating current at the entrance of the duct in addition to the circulating current that one always obtains when conditions are changing to an m.h.d. generator. Although a good qualitative understanding of end effects has been obtained and numerical solutions have been obtained for a number of simplified geometries there is as yet no complete treatment of end effects. Each case must be investigated on its merit. In view of the importance of this subject to the over-all performance of m.h.d. ducts this is probably an area that will receive considerable attention in the future.

3. The open cycle m.h.d. system

Figure 1 shows the main features of the open cycle m.h.d. generator system. In this Symposium there are a number of papers describing the details of the technological problems associated with the major components, but here it is intended to give a brief

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review of the problems together with an indication of the effect on performance of the system as a whole.

After being compressed in a conventional compressor air goes into a high temperature preheater. The air preheat temperature should be as high as possible in order to obtain a high combustion temperature and a high conductivity of the gases which enter the duct.

The technological problems of providing high temperature pressurized air are considerable. Ideally one would like to use the exhaust gases from the exit of the m.h.d. generator as the source of heat for the air heater. Since there is a pressure drop of several atmospheres as the combustion gases pass through the m.h.d. duct there must be a comparable pressure differential between the air being heated and the combustion products supplying the heat. Moreover, the combination of seed and fuel ash makes the combustion products a highly corrosive environment and any ash deposition can cause air heater passages to block. The necessary air preheat temperatures (at least 1200 °C) put the air heater beyond the economic range of metal recuperators. The detailed research into these problems is described fully by Horn, Sharp & Hryniszak (p. 514). It may be worth noting an alternative possibility of firing the air heater with a separate pressurized burner at some loss of over-all cycle efficiency.

After leaving the air heater, the air enters the combustion chamber where it is used to oxidize the fuel which in a practical application would be residual fuel oil or coal. The combustion intensity must be extremely high in order that the heat losses through the combustion chamber walls should be kept within reasonable proportions. Research on combustion is described in the discussion by Jeffrey & Pole (p. 419). Seed is evaporated in the combustion chamber and the seeded combustion products pass through the m.h.d. duct where power is extracted as d.c. and inverted to a.c.

The magnetic field across the duct must be as high as possible and for this reason a superconducting magnet will probably be used. A balance must be reached between having a long duct which leads to an efficient cycle and a short duct where it is possible to have a magnet of lower capital cost. The papers by Brogan (p. 360) and by Chester (p. 558) describe research on magnets.

The exhaust gases leaving the m.h.d. duct are slowed down in a diffuser, pass through the air heater and a conventional steam raising boiler before being exhausted up the stack. Before they leave the system most of the seed material (probably potassium sulphate) must be recovered and passed back to the combustion chamber. Some of these points are illustrated in figures 7 to 9. The efficiencies quoted here are taken to indicate trends rather than being absolute. The independent variable is chosen to be m.h.d. duct length since the capital cost of the superconducting magnet, which is a major cost item, varies appreciably with duct length. Figure 7 shows how the cycle efficiency varies with preheat temperature. It is clear that to obtain cycle efficiencies well in excess of the efficiency of modern conventional steam plant (40 %) air preheat temperatures of at least 1200 °C must be achieved. Figure 8 shows the variation of cycle efficiency with magnetic field strength, and it is clear that magnetic fields of about 60 kG are required for reasonable efficiency. Figure 9 illustrates the importance of low heat losses through the combustion chamber walls and the advantage of preheating the seed.

4. The open cycle research programme

The programme of work leading to the development of a practical m.h.d. generator is of some interest, not only because of the diversity of scientific disciplines involved, but also as an example of the 'applied scientific method'. In 1959 the Central Electricity Generating Board set up small teams to examine the application of fuel cells, thermionic diodes, thermoelectric devices and m.h.d. generators to the large scale generation of electrical

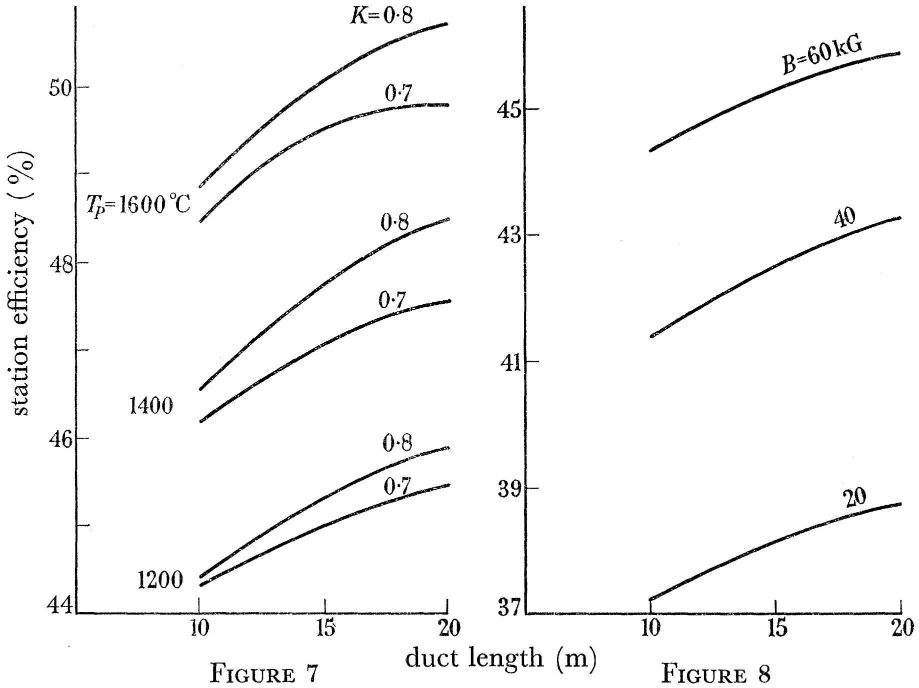

Figure 7 Figure 8

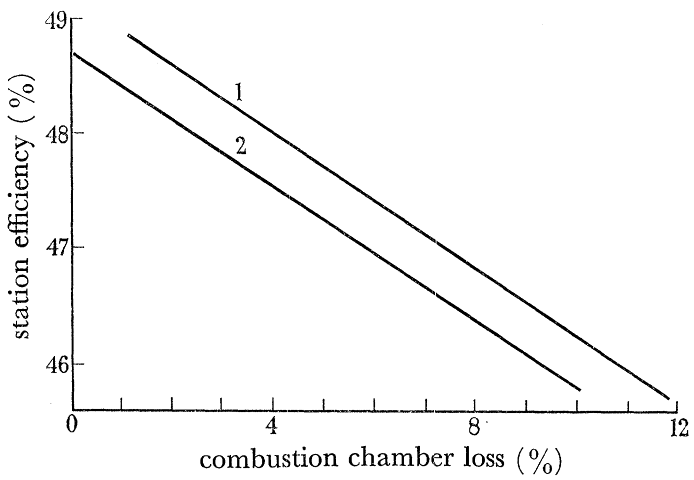

Figure 9. Curve 1, preheating seed with air; 2, unpreheated seed. Running conditions: $K = 0{\cdot}7$; $T_p = 1400$ °C; duct length ± 15 cm.

power. By 1962 the potentialities of the various methods were becoming clear and m.h.d. was chosen as the most promising. The selection was made on practical and economic grounds—fuel cells being eliminated on the grounds of too high capital cost, the thermoelectric devices on the grounds of too low efficiency and the thermionic diodes on the grounds of complexity.

The second stage was to make a concentrated attack on the remaining scientific problems of open cycle m.h.d. During this phase, which was still mainly concerned with laboratory type experiments and preliminary design studies, the major features of the ultimate station were established and a realistic assessment of the station performance obtained. However, by 1964 it was clear that, if further progress were to be made, it would be necessary to extend the experimental work beyond the small rig stage. So far the work had been expensive of scientific effort (upwards of thirty graduates had been involved) but no major capital had been expended. Large scale rigs are expensive to build, take some time to construct and are inflexible. The utmost care must therefore be taken to identify and define the objectives of any large rig before commencing construction. In 1964 the decision was taken to build:

(*a*) A 200 MW thermal input light oil/oxygen m.h.d. generator. The objects of this rig are to demonstrate that large fractions ($\sim 10\,\%$) of the enthalpy of the combustion products may be extracted as electricity, to obtain information about heat transfer at the high Reynolds numbers and to gain experience in building and operating a large m.h.d. device and thus bring out any unforseen practical details. A rig of this size is needed to demonstrate the stable extraction of electricity since, with significantly smaller rigs, the heat transfer losses from the gas are greater than the energy converted to electricity. A theory of the stability of energy extraction is presented in the paper by Heywood & Wright (p. 461), where it is shown that instabilities exist but grow too slowly to be of practical importance in an open cycle generator.

(*b*) A coal combustion chamber. This is to demonstrate that coal may be burnt at a sufficient intensity to be of interest to m.h.d.

(*c*) A rig capable of burning a coal/oil slurry or residual fuel oil. This has the dual objective of providing information on the duct and seed recovery problems associated with the use of coal in an m.h.d. generator and of providing a long duration test facility for realistic life tests on m.h.d. components—particularly ducts and electrodes.

(*d*) Rigs to enable tests on air heater systems and components.

(*e*) Exploratory work on the possibilities of building large superconducting magnets.

At that time it was agreed that the Central Electricity Generating Board should cooperate with members of the Water Tube Boiler Makers Association, the major electrical plant manufacturers and the National Coal Board in this research programme. This not only provided additional effort and expertise to the research programme but enabled the ultimate manufacturers of the m.h.d. stations, if successful, to become aware of the technological problems to be faced at an early stage.

If this phase of the research programme is successful, the 200 MW rig will be converted into a pilot plant incorporating the major features of air heaters and seed recovery apparatus. Because of the additional nitrogen content in preheated air rather than oxygen, the thermal input to the rig will be lowered to 60 MW.

A programme leading to the development of a suitable superconducting magnet will be carried out in parallel.

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