M G HAINES† and I R McNAB‡

†Physics Department, Imperial College, London SW7
‡International Research and Development Company Ltd,
Fossway, Newcastle upon Tyne, NE6 2YD

Magnetohydrodynamic power dynamics

1. Introduction

During the last 10 to 15 years interest in the generation of electrical power by magnetohydrodynamic (MHD) techniques has increased considerably particularly in the USA and USSR. The rapid growth of the subject may be judged from the power ratings of MHD generators which had risen from 10 kW in the first power experiments of 1959 to 33 000 kW by 1966, albeit for operating times of a few seconds or minutes. In parallel with the increase in power levels, operating times for smaller plant, especially of the closed loop type, have increased to hundreds of hours with improvements in technology. Combination of these two advances is the objective in the current Soviet U-25 experiment to generate 75 000 kW from a natural gas fuelled combined MHD steam plant, possibly utilizing in the future several components (duct, magnet) supplied by the USA.

The essential feature of this method of power generation is that the electrical conductors, which are moved through a magnetic field, are gaseous rather than solid, as in conventional generators. This allows the elimination of large rotating components, thereby reducing the mechanical strength requirements compared with conventional turbogenerators. This, together with the necessity to employ high temperatures to achieve an acceptable level of ionization in the gas, means that the optimum operating temperatures for MHD generation are appreciably higher than for conventional power generation systems. As a consequence the thermal efficiency of MHD generator cycle is potentially high and it is this factor, more than any other, which has led to the world-wide interest in MHD.

Two main cycle configurations are envisaged, depending on the duty to be performed. For *base load* generation in central power stations, where station efficiency is of prime concern, some power would be extracted from the plasma in the MHD section. Thereafter the gas would be passed into steam raising plant and electricity generated by conventional means, the overall efficiency being given by

$$\eta_0 = \eta_{\mathrm{MHD}} + \eta_{\mathrm{St}}\,(1 - \eta_{\mathrm{MHD}}).$$

Typical efficiency values for first generation combined MHD steam plant are expected to be $\eta_{\mathrm{St}} \simeq 0{\cdot}4$, $\eta_{\mathrm{MHD}} \simeq 0{\cdot}15$ yielding $\eta_0 \simeq 0{\cdot}5$, with capital costs approximately equal to conventional plant. Apart from the improved utilization of fuel (which is of considerable importance in view of the limited nature of the world's energy resources), the gain in efficiency would cause a substantial decrease in the waste heat from electrical power stations.

Second, MHD plants may also be competitive for *peak load* duties. In most industrialized countries there are seasonal and daily load variations which are characterized by high peak loads from time to time, generally for less than 10% of the normal working period. It is possible that simple MHD plants may be competitive with gas turbine plant for this type of duty, both in terms of capital cost and operating efficiency. One significant advantage of the MHD system is the low mechanical inertia and correspondingly fast start-up time ($\lesssim 1$ s).

MHD generator systems are generally divided into three main types which, while having much in common, have several important differences.

1.1. Open cycle combustion systems

Most of the above comments refer to these systems which utilize fossil or synthetic liquid or gaseous fuels, burned with oxygen or (preheated) air to provide combustion products at a high temperature ($\sim$2500 to 3500 K). The combustion products are seeded with a small amount (about one atomic percent) of an alkali metal, or compound thereof, to give the required plasma electrical conductivity. After passing through a nozzle in which the gas is accelerated to a high velocity ($\gtrsim$Mach 1) the plasma passes through the generator channel, which is located within the field of an electromagnet, and where electrical power is extracted from the gas. Depending on the particular cycle under consideration the gas may then be either exhausted to atmosphere or passed through conventional steam raising plant coupled to turboalternators. In addition to a reduction in thermal pollution, open cycle MHD offers the prospect of a substantial reduction in the NO_x and SO_x pollution of the atmosphere and permits the use of high sulphur content fossil fuels.

1.2. Closed cycle inert gas plasma systems

These utilize an inert gas coolant of a postulated high temperature (1500 to 2000 K) nuclear reactor as the working fluid. As with the open cycle system, alkali metal seeding is employed to give a high plasma conductivity but in this case, after passing through the generator (and, if included, the steam raising or gas turbine plant) the fluid is recycled to the reactor. At a temperature of 1500 K the electrical conductivity of an equilibrium plasma is not sufficiently high, but as a result of the use of pure monatomic gases a nonequilibrium conductivity may be induced.

1.3. Closed cycle liquid metal systems

These are similar in principle to the plasma system described in § 1.2 above but utilize a single or, more commonly, two phase liquid metal/gas mixture as the working fluid. The cycle temperatures required in this case are commonly 1000 to 1500 K, or even less depending on the working fluid, but problems relating to the acceleration, separation and maintenance of the fluid properties in these systems partly offsets the temperature advantage.

In general terms, while appreciable progress has been made during the last decade on all aspects of MHD power generation, fairly major developments are still required in several areas and it does not seem likely that a base load plant of significant size (say 400 MWe) will emerge for at least 10 years.

However, for short term power supplies either for military or civil purposes, the prospects for the earlier development of units of up to 50 MWe seem good.

2. Basic physical conditions

We will discuss in this section those physical processes that are common to both open and closed cycle power generation.

The prime requirement for a significant extraction of energy from the gas to an external electrical load is that the interaction parameter S is of the order of or a little greater than one. The interaction parameter can be taken as the ratio of the Lorentz force to the convective rate of change of momentum,

$$S \sim \frac{\boldsymbol{j} \times \boldsymbol{B}}{\rho \boldsymbol{v} . \nabla \boldsymbol{v}}$$

which, with $j \sim \sigma v B$, gives

$$S \simeq \frac{\sigma B^2 L}{\rho v} \tag{1}$$

where L is the characteristic length of the MHD duct. In contrast to high temperature controlled fusion plasmas the conductivity of the plasma envisaged for an MHD generator is low. Considering only the electron neutral collisions the electrical conductivity is

$$\sigma = \frac{n_e e^2}{m_e \nu_{en}} \tag{2}$$

with the collision frequency ν_{en} given by

$$\nu_{en} = n_n \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} q_{en} \tag{3}$$

where q_{en} is the collision cross section. For a partially ionized gas the electron density can usually be described by a thermal equilibrium at the electron temperature T_e as given by Saha's equation

$$\frac{n_e^2}{n_s - n_e} = \left(\frac{2\pi m_e k T_e}{h^2} \right)^{3/2} \exp\left(-\frac{eV_I}{kT_e} \right) \tag{4}$$

where n_s is the total number density of the alkali seed material and V_I is its ionization potential (4·34 eV for potassium and 3·89 eV for caesium). For a molecular combustion gas there is strong coupling ensuring that the electron and neutral gas temperature are essentially the same. In a noble gas, however, because it is monatomic, it is possible for the electron temperature to be significantly elevated over the neutral gas temperature. This nonequilibrium effect is discussed further in §4. In both open and closed cycle gaseous systems the operating electron temperature is expected to be in the range 2500 to 3000 K giving an electrical conductivity of 1 to 100 mho m^{-1}. As a result the magnetic Reynolds number R_m is very much less than one, ie

$$R_m = \mu_0 \sigma v L \ll 1. \tag{5}$$

This means that the magnetic field produced by the plasma current is very small compared to the applied magnetic field. It also means that the magnetic field is completely diffused and is not convected along the conducting fluid. As a consequence the skin effect is negligible in most time dependent phenomena in the plasma and we can almost always assume that

$$\operatorname{curl} \boldsymbol{E}=0 \tag{6}$$

or

$$\boldsymbol{E}=-\nabla\Phi. \tag{7}$$

We will use this assumption in the stability theory. Now equations (1) and (2) together show further that the ratio of the magnetic energy density to plasma kinetic energy density must be very large for significant magnetogasdynamic interaction

$$S=R_{\mathrm{m}}\frac{B^2}{\mu_0\rho v^2}\sim 1. \tag{8}$$

With a Mach number approaching one and a gas pressure of 1 atm the magnetic field must be much larger than 0·5 T to satisfy this condition. Hence we envisage employing a superconducting magnet of strength 5 to 8 T. As an example, for $\sigma=10$ mho m^{-1}, $v=10^3$ m s^{-1} and $L=5$ m. We have $R_{\mathrm{m}}=6{\cdot}30\times10^{-2}$, whilst for a 1 atm Mach one gas and $B=5\ T$ we obtain $S=6{\cdot}30$ ensuring significant interaction.

Another important dimensionless parameter in a magnetohydrodynamic generator is the Hall parameter. In § 4 we will show that significant nonequilibrium conductivity can only be obtained when the Hall parameter exceeds one. The Hall parameter is defined as

$$\boldsymbol{\beta}_{\mathrm{e}}=\frac{\sigma\boldsymbol{B}}{n_{\mathrm{e}}e} \tag{9}$$

where n_{e} is the electron density, and it arises principally in the generalized Ohm's law

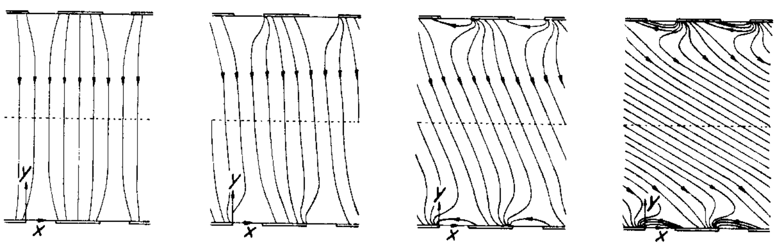
$$\boldsymbol{j}=\sigma\left(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}+\frac{\nabla p_{\mathrm{e}}}{n_{\mathrm{e}}e}\right)-\boldsymbol{j}\times\boldsymbol{\beta}_{\mathrm{e}}. \tag{10}$$

For the conditions of the above example and an electron density of $10^{20}\,\mathrm{m}^{-3}$ the Hall parameter is three. For a partially ionized gas with the electron density much less than the number density of atoms, the electron–neutral atom collisions dominate, and the electrical conductivity is proportional to $n_{\mathrm{e}}T_{\mathrm{e}}^{-1/2}$. Hence $\boldsymbol{\beta}_{\mathrm{e}}$ depends essentially only on the electron temperature, magnetic field and the neutral gas density. With the conditions imposed on the value of S and on the maximum temperature from a heat source in contact with high temperature solid materials, it is inevitable that a Hall parameter in the range 1 to 10 must be contemplated.

Writing $\boldsymbol{E}^*$ as the generalized electron field $(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}+\nabla p_{\mathrm{e}}/n_{\mathrm{e}}e)$ the generalized Ohm's law in effect states that in the plane perpendicular to $\boldsymbol{B}$ the current density $\boldsymbol{j}$ flows at the Hall angle θ $(=\tan^{-1}\beta_{\mathrm{e}})$ to $\boldsymbol{E}^*$. This is because we can write

$$\frac{\boldsymbol{E}^*\times\boldsymbol{j}}{\boldsymbol{E}^*\cdot\boldsymbol{j}}=\boldsymbol{\beta}_{\mathrm{e}}=\frac{\boldsymbol{\beta}_{\mathrm{e}}}{\beta_{\mathrm{e}}}\tan\theta. \tag{11}$$

The immediate consequence of this is that with continuous electrodes the Lorentz electric field is perpendicular to the flow velocity, and the current flows tangentially across the duct with a large component parallel to the velocity flow. This results in an increase in the plasma internal impedance by a factor $(1+\beta_e^2)$, and the magnetomotive force $\boldsymbol{j}\times\boldsymbol{B}$ has a large component driving the plasma towards the cathode. To overcome this problem the electrodes are segmented into many short electrodes separated by insulators. This in theory should permit an electric field component to exist antiparallel to the flow velocity, and the current should flow transverse to the flow direction. However, since each electrode is an equipotential the current density actually leaves or enters the electrode at the Hall angle. For a uniform conductivity and Hall coefficient the current distribution for finite sementation has been solved (see figure 1). The current density is highly concentrated on the upstream edge of the anode and downstream edge of the cathode and in extreme cases axial leakage currents can occur between adjacent electrode pairs.



(a) (b) (c) (d)

Figure 1. Current distributions between segmented electrodes. (*a*) In absence of Hall effect, (*b*) Hall effect present but no shorting, (*c*) with shorting between adjacent segment, (*d*) with extreme shorting. (London: Royal Society.)

The essential physics in the segmented Faraday generator is that the Hall electric field antiparallel to the flow opposes the ion motion, which through equation (10) is assumed to have a high collisional coupling with the neutral gas which is then also slowed down. The electrons perform cycloidal motion with a drift velocity approaching $\boldsymbol{E}\times\boldsymbol{B}/B^2$ in the high Hall parameter limit. When ion slip relative to the neutral gas is introduced the generalized Ohm's law includes an additional term on the right hand side of equation (10) but for most applications ion slip can be ignored unless the magnetic field is very large.

Because of the Hall effect two modes of operation of a linear MHD generator can be considered: the Faraday mode in which each pair of electrodes has a separate matched load; or the Hall mode in which each pair of electrodes is short circuited and a load is applied between the first and last pair of electrodes using the generated Hall voltage. A variation of the Faraday mode is the diagonal connection of those segmented electrodes that are operating at the same electrical potential. This reduces the number of independent loads and increases by several factors the total voltage output per load.

Early theoretical work on the gas dynamics of MHD generators employed quasi-one-dimensional models, and the viscous and thermal boundary layers were treated separately. With the advances in numerical simulation, fairly complete two dimensional models of both the gas dynamics and the electrodynamics together have recently been made. An interesting example is that of Argyropoulos *et al.* (1973) shown in figure 2 who computed the potential distribution across the duct from a cathode to an anode with the gas dynamic boundary layers included selfconsistently for the experimental conditions of the Avco Mark VI open cycle MHD generator. Very good agreement is

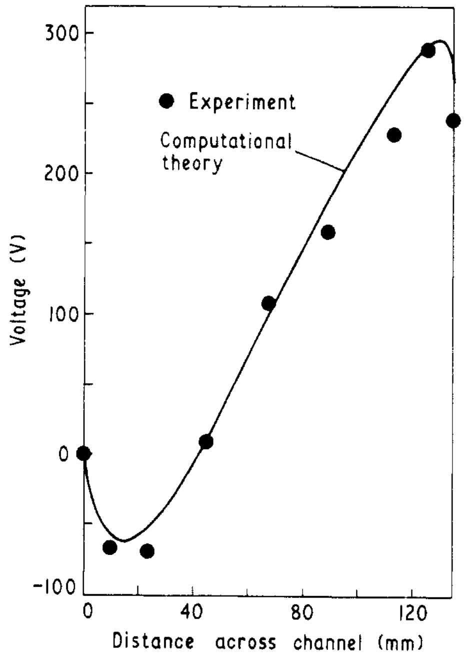


Figure 2. Comparison between experiment and theory for the electric potential variation across the Avco–APL channel (G S Argyropoulos *et al.* 1973).

found, with effective voltage drops near each electrode of about 60 V. Voltage drops in the boundary layers near electrodes form an appreciable internal dissipation, and are particularly large (over 100 V) when cold electrodes are employed.

The performance of the generator and the lifetime of electrodes is strongly affected by the onset of arcs caused by thermal instabilities particularly near the anode. Recently Rosa *et al.* (1974) have controlled the onset of this phenomenon by the construction of divided anodes connected by diodes to limit the current collected in each section of the anode. It is also possible to employ finite resistivity electrodes, proposed by Croitoru (1965), to yield a uniform current density in the plasma for a given Hall parameter and conductivity. But the electrode material must have a conductivity approximately the same as that of the plasma.

The nature of the arcing appears to be three dimensional in open cycle combustion generators and two dimensional in closed cycle noble gas generators. The maximum Hall voltage per electrode pair is determined by the breakdown of the gas in the neighbourhood of the insulator walls and varies from 30 to 200 V depending on conditions. Due to the convection by the gas flow, arc spots, particularly on the cathode, are not stationary and so the electrode erosion is reduced compared to a stationary gas with the anode being damaged more than the cathodes.

Finally we turn to the stability of the MHD gasdynamic generator. Besides considering the ionization instability present in nonequilibrium generators, Velikhov (1962) examined the magnetoacoustic instabilities in an equilibrium generator. We will discuss the nonequilibrium electrothermal instability in §4. Because of the decoupling of the electron temperature from the gas temperature, the characteristic time for this instability is approximately 10^{-6} s whilst in the equilibrium (open cycle) generator in which all the species are coupled it results in a time scale of approximately 10^{-3} s, essentially comparable with the transit time of the gas flow through the duct. It is generally considered that the thermal instability is responsible for the onset of arcing, and here it is important to include the proper geometry and boundary conditions of the segmented electrodes. Argyropoulos *et al.* (1973) have studied the onset of arcs in this situation and predict that even in open cycle MHD power generators an elevation of electron temperature can occur in the arc itself.

3. Open cycle MHD power generation

The order of magnitude calculations of § 2 indicate that the enthalpy extraction efficiency, and hence the overall combined plant efficiency, depends strongly on the plasma electrical conductivity and magnetic field strength through the expression σB^2.

The plasma conductivity is controlled largely by the combustion temperature of the working fluid which in turn is determined by the type of fuel and the nature and temperature of the oxidant being used.

Experimental MHD plants have generally employed refined and relatively expensive fuels, often with oxygen as the oxidant. While this has a number of advantages in terms of the ease of operation (and may therefore be acceptable for peak loading or short duration special purpose plants) there is no doubt that for large scale base load operation coal should be the basic fuel. This does not necessarily imply that coal should itself be burned in the combustion chamber, since a devolatilization process could be undertaken to produce gas from coal (Gannon *et al.* 1974) but clearly there is an economic incentive to reduce the number of steps in the cycle.

For a given fuel the combustion temperature may be controlled either by varying the air preheat temperature or by oxygen enrichment of the air. Both courses require capital expenditure on plant and, certainly for the former, also some R and D effort.

Figure 3 shows how the plant thermal efficiency may be expected to vary with the degree of air preheat. The ideal preheater would heat compressed air (say 5 to 10 atm) to the highest possible temperature by utilizing the combustion products leaving the MHD channel at a temperature $\gtrsim 2000$ °C and pressure of one atm. However, condensation of seed and or slag material from the coal on the preheater surfaces could cause severe damage to the preheater materials as well as adversely affecting the heat transfer rates. As a result most attention to date has been given to indirect techniques for air preheating, that is, using unseeded and relatively clean fuel to preheat air. In the Soviet U-25 facility the air is preheated in this way in Cowper heaters to a temperature of 1250 °C at a pressure of three to four atmospheres. In separate experiments with the smaller U-02 facility a high temperature pebble bed has been developed which has now operated for over 15 000 h at air preheat temperatures of 1500 to 1700 °C, and for several hundred hours at about 2000 °C (Kirillin and Scheindlin 1974). Similar temperatures (1650 °C) have been achieved in cyclic air preheater experiments using high density alumina blocks and these are shortly to be extended to include fly ash and seed additives to simulate direct fired operation.

Whether the alternative of oxygen enrichment would be economically viable for a large scale base load plant is not clear at present although it is possible that the recent discovery in Germany of a new method of achieving oxygen enrichment by selective adsorption may prove beneficial.

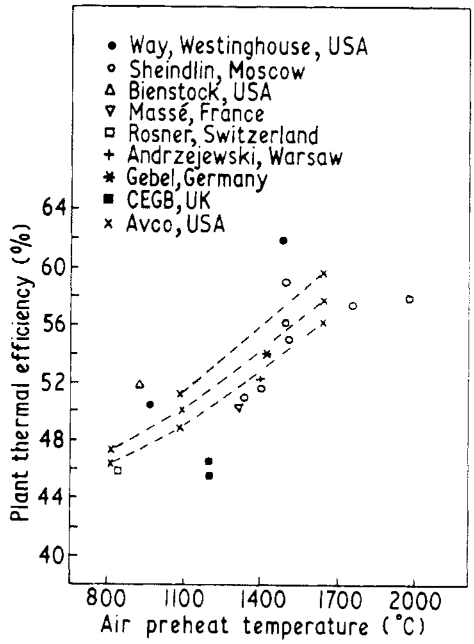


Figure 3. Thermal efficiency of base load MHD electrical power station (Vienna: IAEA).

In addition to dealing with the oxidant, attention must also be given to the efficient and complete combustion of the fuel, and the vaporization and uniform mixing of the seed material with the combustion products. Heat losses from combustion chambers may be minimized by employing ceramic linings and efficiencies of up to 97% have been claimed for the U-25 combustion chamber, which utilizes natural gas as the fuel. For coalburning systems the high proportion of noncombustible material (up to 20%) presents a significant problem especially in that it may erode or corrode not only the combustor but also downstream components such as the duct, air preheater, steam generator, etc. While there is some evidence that the slag could be used to advantage for protecting the generator walls, it seems likely that a more elaborate combustor design in which the majority of the slag is rejected will prove a better approach. At present a three stage combustor is under development at the Bureau of Mines Research Centre at Pittsburgh which will burn 1000 lb wt coal h^{-1} with liquid slag rejection rates of greater than 90% and ash content in the working fluid of less than 10%. The extra complexity (and hence cost) of the multistage combustion process is partially offset by the fact that less of the air required for combustion is compressed to 6 to 8 atm, most being put in at 1 atm.

Several seed injection techniques have been used by different groups, including solution in (liquid) fuels and water solutions. However it has recently been claimed that the best technique (in terms of obtaining high conductivity) is to inject the seed material (commonly potassium carbonate) as a dry powder. Seeding devices capable of doing this have been developed and operated reliably for tens of hours (Rosa *et al.* 1974). These employ a pressurized hopper with an internal vibrator and variable speed feeder together with a nitrogen carrier line which entrains the powdered seed and delivers it to the oxidizer supply line to the burner.

Improved performance would be achieved by the use of a caesium compound rather than potassium. However, in general the higher cost of caesium compounds makes this unattractive unless highly efficient seed recovery can be assured (see below).

The most essential feature of the MHD plant is the generator duct itself, since it is in this that electrical power is extracted from the high temperature plasma. Early experiments were devoted to understanding the power extraction process and evaluating the influence of the parameters which are important in this type of system. By and large this has now been successfully completed and the detailed design of generator ducts in two and even three dimensions has been undertaken with a good degree of success. Most workers have employed linear generators of the segmented or Hall types, in some cases the former being connected as diagonal systems for use at particular values, but there has also been some experimental work on large (25 MWe) disc geometries, especially for (pulsed) Hall operation.

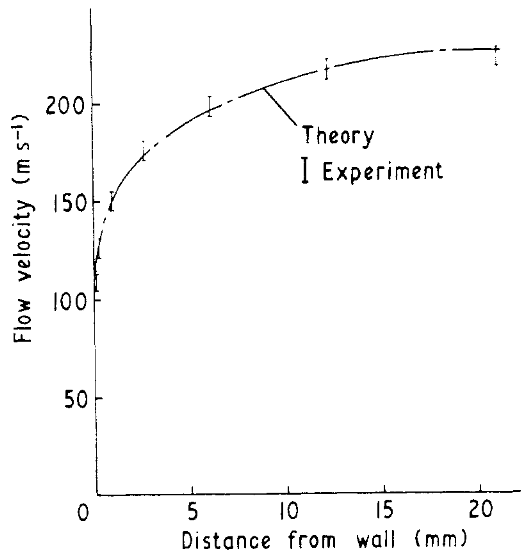


Figure 4. Experimental and theoretical velocity profiles (S J Morris *et al.* 1973).

As mentioned in §2; two and even three dimensional models of the flow behaviour have been successfully developed and compared with experiment. A recent example is a two dimensional code describing the flow effects caused by transverse pressure gradients resulting from Hall currents which has shown good agreement with experiment.

Experimental and theoretical work on MHD generator boundary layer properties has involved the use of a laser Doppler velocitometer to obtain experimental data on the boundary layer profile, with good agreement as shown in figure 4 (Morris *et al.* 1973). Time dependent solutions of the quasi-one-dimensional equations for flow in the generator section have been used to examine the response of generators to load changes and the influence of finite amplitude magnetoacoustic fluctuations.

Many of the problems which have been encountered in operation relate to materials, either electrical conductors or insulators. The requirements for electrodes is that they should provide the plasma with (or accept from it) electrons in sufficient quantities that no space charge limitations arise and so that there are minimum losses. With cold electrodes, generally of metal, voltage drops at the electrodes are high and the electrodes

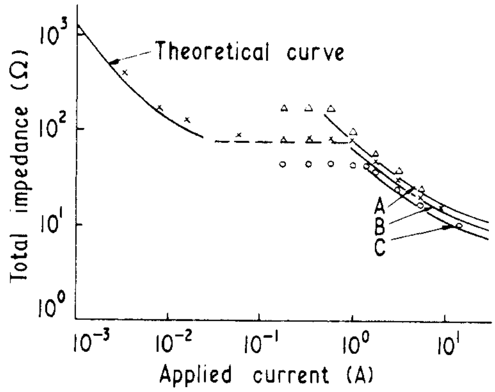


Figure 5. Comparison of experimental and theoretical cross channel impedances. Experimental wall temperature: △ 1273 K, × 1373 K, ○ 1473 K. Theoretical: A 1300 K, 360 m s^{-1}; B 1400 K, 470 m s^{-1}; C 1500 K, 560 m s^{-1} (M S S Hsu 1973).

operate in the arc mode with, in many cases, damaging erosion due to arc spots. Several workers have evaluated the mechanisms involved in arc formation in MHD generators. In general the overall picture seems unclear at present with electrostatic, fluid dynamic and discharge phenomena all interacting to play a part in these processes. A model including (*a*) a 10^{-5} m thick sheath region, (*b*) a thermally unstable breakdown region extending across the boundary layer and (*c*) a diffused discharge region, gave good agreement with experimental data obtained with the Vegas generator (Hsu 1973, figure 5). Much effort has been devoted to improving the design of the electrode and the resulting design may be quite complex. For example, the use of a zirconia cement set in a copper matrix with an Inconel stainless steel screen insert has been shown to be reasonably effective, with interelectrode insulation being provided by alumina. In this way satisfactory operation is achieved whilst standing off some 40 V per electrode in the Hall direction. More recently operation at up to 120 V per electrode in the axial direction has been demonstrated. Insulator walls consisting of cooled alumina-insulated hexagonal metal ' pegs ' have been shown to operate reasonably satisfactorily, as have diagonally connected water cooled ' window frame ' systems. In this latter case matching of the optimum diagonal connections with the metal combustion chamber inlet and diffuser exit sections is provided by a graduated change in the diagonal angle.

Prevention of catastrophic disintegration of the ceramic sections in situations where multiple short burst operation is required is achieved by operating the combustion chamber on standby with a pilot flame to provide preheating, and this may also be required if more exotic electrode materials, such as lanthanum chromite, are employed.

Protection of the interior of the generator duct has been achieved in cases where clean fuels, toluene for example, have been used by ' seeding ' the combustion products with refractory powders such as zirconia or alumina. These form coatings on the channel wall which protect it from further damage. The coating has to be electron emitting so as not to inhibit the electrode performance, but should not short out electrodes in the Hall or transverse directions. These two apparently contradictory requirements are resolved by the use of thin deposits. In coal burning systems it may be possible to turn to advantage the presence of the coal slag by having this condense out on the generator wall to provide a protective layer of this type. However it is questionable whether an adequate degree of control over the layer thickness can be achieved by this means over a long term.

Operation under realistic conditions with the type of duct structure described above has been achieved by several groups for up to 10 h, and with 10^2 to 10^3 multiple starts. Attention has also been given to the design of lightweight and low cost channels suitable for use for power peaking.

Another essential part of the MHD unit is the magnet. As indicated by equation (1) the power output and efficiency of the MHD system is proportional to B^2. Iron cored magnets are limited, by saturation of the iron, to field levels of up to about 2·3 T. Values above this can be achieved by using water cooled copper coils, systems in current use yielding up to a maximum of about 3·5 T. At this level, for a large system the magnet power consumption becomes a significant factor in the overall cycle economics and it is advantageous to turn to cryogenic and superconducting systems. Liquid nitrogen cooled magnets have been operated satisfactorily during short duration MHD tests for periods of about one minute at fields up to 4·0 T, however the use of superconducting systems seems essential to ensure that the full economic benefit is obtained from MHD systems. Most design studies for full scale or even power peaking plant envisage magnetic field levels of 5 T or more with the highest value at present being 8 T over a working volume (ambient temperature) of $0{\cdot}14 \text{ m} \times 0{\cdot}34 \text{ m} \times 1{\cdot}3$ m (Purcell and Wang 1974). Considerable discussion has taken place as to the ' best ' magnet configuration. The saddle has the best winding effectiveness but is more expensive than the simple solenoid, which has the best record of success in magnets built to date. The circular winding is only economic for relatively short generator linear ducts or disc geometries. An intermediate design, the racetrack, has intermediate properties and has been selected for the Avco Mk VI channel test facility. This coil has a length of 2·3 m (straight section) with an exit warm bore aperture of $1 \text{ m} \times 1$ m (Hatch *et al.* 1974).

Operation of superconducting magnets in conjunction with MHD generators has been achieved by German and Japanese groups with no significant adverse interactions, although fluctuations in the magnet current caused by the plasma have been observed.

Recovery of the material used for seeding the combustion gases is an important factor in the economics of open cycle MHD plant. As mentioned earlier, the use of caesium (generally as Cs_2O from pollucite) has considerable advantage over the use of potassium (as K_2CO_3) in terms of the plasma conductivity. This results, for a given plant output, in smaller generator ducts and superconducting magnets, but the higher cost of caesium (by a factor of about five) requires that the caesium loss in the seed recovery system can only be a fifth of that with potassium, thereby necessitating a greater investment in seed recovery plant.

When coal is the fuel, spent seed in the form of K_2SO_4 and K_2CO_3 contaminated with fly ash condenses from the MHD exhaust in the temperature range 1370–1810 K (in the high temperature air preheater and superheat and reheat sections of the steam bottoming plant). Following collection the next step is extraction and at present recovery values of about 98% for potassium are thought realistic (and have been achieved in Soviet and American experiments).

The achievement of the comparable (economic) value for caesium recovery of 99·6% seems a much more difficult target and one attractive solution propounded by Bergman and Bienstock (1973) is that of mixed caesium/potassium seeding.

Apart from ensuring that the amount of seed material discharged to the environment is small, the emission of other pollutants from the MHD plant has to be kept to a minimum. Fortuitously it happens that at potassium seeding levels typical of open cycle MHD plant, the seed (K_2CO_3) itself removes all the sulphur contained in typical (USA) coals, so that the effluent is practically free of SO_2. For example (see figure 6) 1·5 g mol K_2O kg^{-1} of coal is sufficient to remove all the sulphur from coal containing 4 wt % of sulphur, which is well above most (USA) coals.

Because MHD is a high temperature process it has been implied that this will necessarily cause high NO_x emissions. However, experiments have shown that with two stage combustion techniques using less than stoichiometric air ratios, the MHD exhaust gas nitrogen oxides level will be well below the USA Environmental Pollution Agency (EPA) standard emission rate of 500 ppm, and at a small economic penalty (< 2% on capital cost). Radiant cooling techniques can also help to reduce NO_x levels through gas phase decomposition reactions, at least down to 100 ppm, while further reductions in nitrogen oxides can be achieved by catalytic effects using refractory materials, in pebble beds for example.

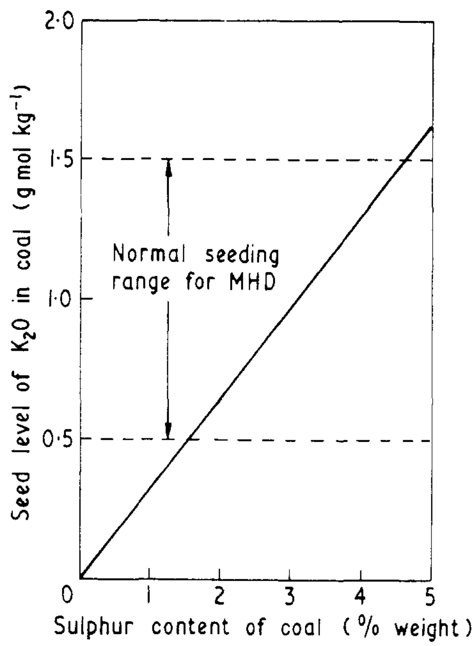


Figure 6. MHD plasma seeding levels for eliminating sulphur from coal (D Bienstock *et al.* 1973).

Recently much interest has been shown in the hydrogen ' economy ' and several authors have pointed out that this could be of interest for MHD systems. For example, Townsend (1974) has suggested that in a nuclear based economy, overall savings may result by using electricity generated during off peak periods to electrolyse water to H_2 and O_2 which is then stored for use in MHD generators during periods of high demand. An alternative (Nakamura and Riedmuller 1974) proposes a continuously operating (closed) cycle using thermochemical reactions promoted by a nuclear reactor with an operating temperature in the range approximately 800 °C. After passing through the MHD generator section the combustion products (water vapour) are condensed and returned to the thermochemical reaction chamber. An essential feature of this proposal is the development of the thermochemical decomposer, which has yet to be proven.

In addition to open cycle MHD power generation of the type discussed above there has been some interest in short duration explosively driven systems for pulsed power supplies. Typical operating conditions in systems of this type using caesium picrate seeded PBX explosive charges for a 1 in$\times$4 in cross section channel with $B\sim 2$ T, are an open circuit voltage of 1000 V, a short circuit current of 20 kA and a pulse length of approximately 100 μs; ie an output energy of 2 kJ (Jones 1973). Larger units (up to 6 in$\times$8 in) have also been tested, with currents of up to 0·5 MA. There is evidence for several interesting effects in such generators: not only is the magnetic Reynolds number of order unity, but high conductivity (10 000 mho m^{-1} or greater) regions at the front of the plasma slug are thought to exist, together with internally circulating currents.

4. Closed cycle MHD power generation

In closed cycle MHD power generation an inert noble gas is circulated in a closed loop from a heat source, eg nuclear reactor or heat exchanger coupled to a combustion plant, through the MHD generator channel to a diffuser, regenerator and compressor and returned to the heat source. The gases considered are usually helium or argon, and these are seeded with up to 1 atom per cent of alkali metal vapour such as caesium or potassium in order to make them reasonably conducting electrically.

There are several advantages to closed cycle MHD power generation over open cycle. One is that a very pure gas system can be used, thereby ensuring that erosion of the duct materials by chemical action is kept to a minimum. Secondly the operating gas temperature can be comparatively low, say 1500 to 2000 K, and it is possible to have an electron temperature elevated over the gas temperature. As pointed out in § 2 the degree of ionization in this nonequilibrium state is determined in the steady state by Saha's equation at the temperature of the electrons. This is conditional on the electron energy distribution being maxwellian and that the electron density is high enough for electron collisional processes to dominate over atomic and radiative processes. It would appear that the most practical method of obtaining nonequilibrium ionization is through the ohmic dissipation arising either from a preionizing discharge or through the magnetically induced current. The elevation of electron temperature T_e over the neutral gas temperature T_n is determined by the balancing of ohmic dissipation with electron–neutral energy relaxation term, ie

$$\frac{j^2}{\sigma} = \frac{3m_e}{m_n} \nu_{en} n_e k(T_e - T_n) \tag{12}$$

where σ and ν_{en} are defined in equations (2) and (3) and the electron density is determined by Saha's equation (equation (4)). Because of the exponential factor in Saha's equation the electron density varies very strongly with electron temperature in the temperature range of interest. If we replace the current density in equation (12) by the component of the generalized electric field $\boldsymbol{E}^*$ which is parallel to $\boldsymbol{j}$, namely E_j^*, then we find that in the steady state the terms in electron density cancel and there is a direct relationship between E_j^* and T_e given by

$$E_j^* = \frac{m_e \nu_{en}}{e}\left[\frac{3k(T_e - T_n)}{m_n}\right]^{1/2} \tag{13}$$

Since E_j^* is of order vB in magnitude, and, for an optimum gasdynamic interaction, the Mach number is of order unity, it can be shown that for a significant elevation of electron temperature the Hall parameter β_e should be greater than one. Using equation (2) we have

$$\beta_e^2 = \left(\frac{\sigma B}{n_e e}\right)^2 \sim \frac{3k(T_e - T_n)}{m_n v^2}. \tag{14}$$

For a Hall parameter greater than one or two the nonequilibrium electron plasma is unstable to the ionization instability, one of the general class of electrothermal instabilities, as shown below.

Before examining this we will consider the time dependence of the nonequilibrium processes. Employing the three body collisional-radiative recombination theory we can write down a time dependent Saha equation

$$\frac{\partial n_e}{\partial t} = A_1 n_e (n_s - n_e) - A_2 n_e^3 \tag{15}$$

where

$$A_2 = 1{\cdot}1 \times 10^{-20} T_e^{-9/2}\ \mathrm{m^6\,s^{-1}}$$

and

$$A_1 = \left(\frac{2\pi m_e k T_e}{h^2}\right)^{3/2} \exp\left(-\frac{eV_I}{kT_e}\right) A_2.$$

By linearizing equation (15) for a small perturbation we find that the time τ_s for reaching Saha equilibrium is $(2n_e^2 A_2)^{-1}$. Since n_e varies approximately as T_e^{12} in this range τ_s is a sensitive function of electron temperature being significant for $T_e < 2000$ K but is negligibly small for $T_e > 2500$ K.

In the electron energy equation, the dominant terms are

$$eV_I \frac{\partial n_e}{\partial t} = \frac{j^2}{\sigma} - 3\nu_{en} \frac{m_e}{m_n} n_e k (T_e - T_n) \tag{16}$$

giving a characteristic time τ_E for energy balance

$$\tau_E = \frac{eV_I}{3\nu_{en} k (T_e - T_n)} \cdot \frac{m_n}{m_e}. \tag{17}$$

This is the controlling time scale for the change in electron density at higher temperatures.

If the electron temperature is quickly reduced to below 2000 K by a rapid expansion of the gas as it passes through a hypersonic nozzle, then, because τ_s is large, a degree of ionization corresponding to the initial electron temperature can be frozen in. This method of attaining an increase in electrical conductivity was proposed independently by Lindley (1960) and others.

At a temperature greater than 2500 K under MHD generator conditions we can assume Saha equilibrium, with the electron density related to the electron temperature as given in equation (4). This is the regime we will consider to be applicable in a simplified account of the ionization or electrothermal instability to which we now proceed.

The ionization instability has been considered by many authors, including Nelson and Haines (1969). In this paper finite ionization rates, energy convection, radiation transfer and thermal conduction, finite degree of ionization and Coulomb as well as

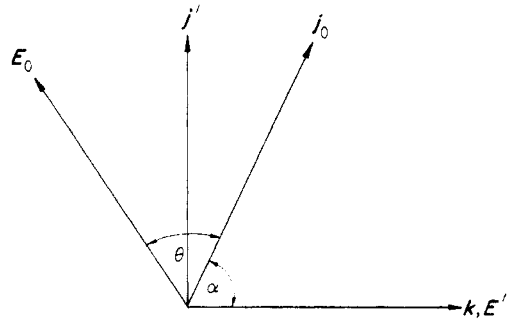


Figure 7. Relative directions of the steady state and perturbed current density and electric field.

neutral collisions were included for various gas mixtures. In the simplest model which can describe the phenomenon, we consider a homogeneous steady state with a current density $\boldsymbol{j}_0$ flowing at an angle θ to $\boldsymbol{E}_0$ and add a plane wave perturbation with the wave vector $\boldsymbol{k}$ at an angle α to $\boldsymbol{j}_0$ as shown in figure 7. It follows from equation (6) and from charge conservation that $\boldsymbol{k}\times\boldsymbol{E}'=0$ and $\boldsymbol{k}\cdot\boldsymbol{j}'=0$, where the prime indicates a perturbed variable. It follows that $\boldsymbol{E}'$ is parallel to $\boldsymbol{k}$, and $\boldsymbol{j}'$ is perpendicular to $\boldsymbol{k}$. From the perturbed time dependent electron energy equation (equation (16)), and the perturbed Ohm's law (equation (10)) we are led to an expression for the growth rate γ, given by

$$\gamma = \frac{j_0{}^2}{\sigma_0 n_{e0} e V_I} (\beta_e \sin 2\alpha - 1 - \cos 2\alpha) \tag{18}$$

showing that there is a growth for $\beta_e > 1$ with a maximum value at $\alpha=\frac{1}{4}\pi$. In a partially ionized gas the role of the Hall effect in the electrothermal instability is to ensure that the perturbed ohmic heating can exceed the perturbed equipartition term thus leading to an excess energy for ionization. The terms that contribute to the $\beta_e \sin 2\alpha$ term which drives the instability are the perturbed ohmic heating, which maximizes if $\boldsymbol{j}'$ is parallel to $\boldsymbol{j}_0$ (ie $\alpha=\pi/2$) for constant $|\boldsymbol{j}'|$, and the contribution to $\boldsymbol{j}'$ from $\sigma'\boldsymbol{j}_0\times\boldsymbol{\beta}_e$ which maximizes at $\alpha=0$. Hence the optimum angle for growth is $\pi/4$. Inclusion of convective terms in the energy equation leads to complex γ, ie an electrothermal wave.

With a growth rate of 10^6 s^{-1} it is important to consider the nonlinear effects of the instability and the effect of boundary conditions, particularly segmented electrodes which themselves cause nonuniform current density and ohmic heating. Nelson (1971) showed that for a weakly unstable plasma confined between insulating walls, steady striations at 45° could occur in agreement with experiment. A definitive time dependent two dimensional theory with segmented electrodes by Uncles (1973 a and b) shows that the streamers are formed transverse to the gas flow and positioned opposite the insulator gaps in the segmented electrodes. Figure 8 illustrates the development of the electrothermal instability when the initial Hall parameter exceeds the critical value for the instability to occur. The figure shows the current density stream lines for four electrode pairs when the instability is fully developed. This example is for a coarse segmentation of electrodes and gives the important result that the effective plasma conductivity in the presence of well developed streamers is *increased* by a factor of about two over a uniform conductivity case for the same geometry and average values of conductivity and Hall parameter. That is, the streamers in effect provide a hot high conductivity path for the current, so that the current flow is mainly in and parallel to the highly ionized streamer. This is in contrast to the linear theory which predicts an angle of 45° for the wave sector. In the time dependent simulation the linear theory is indeed followed at first, but after 10 or so growth times the streamer develops.

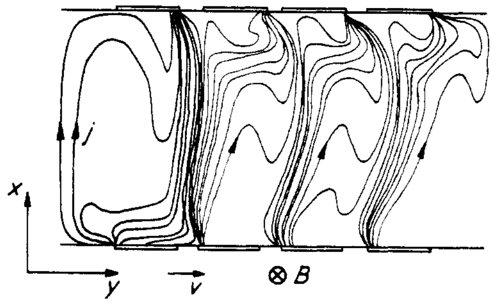


Figure 8. Current discharge structure at 5×10^{-5} s. The contours are the current density stream function lines (R J Uncles 1973).

Contrary to earlier predictions there is in the simulation a marked reduction in the leakage current between adjacent electrodes when it is unstable to the electrothermal instability, although at early times there is some leakage at the cathodes. This asymmetry is due to the ∇p_e term in Ohm's law. Other asymmetries occur in the theory when gas dynamic effects are introduced due to the $\boldsymbol{j} \times \boldsymbol{B}$ forces (see § 3) and experimentally more electrode erosion has been found at the anode (see § 2).

Brederlow and Witte (1974) have recently published experimental measurements of effective conductivity and Hall parameter together with electron temperature and density. They show that the effective conductivity agrees well with various theories, particularly that of Solbes (1968), even though these theories assume a discharge structure very different from the streamers that have been observed with image convertor photographs.

Finite ionization rates can affect the growth of electrothermal instabilities and it has been shown experimentally that streamers do not occur when the ionization relaxation length is less than the streamer separation. Further experimental results by McNab *et al.* (1974) show that under these conditions the conductivity is a very sensitive function of the seeding fraction.

The experiments dealing with closed cycle MHD power generation are generally of three kinds: shock tunnel (operating time $\sim 10^{-3}$ s), blow down (~ 10 s), and closed loops ($\sim$h). A larger volume and mass flow can be more easily obtained in a short duration experiment, and so in shock tunnels surface-to-volume effects have been reduced but the experiments may be operated at unrealistically cold wall temperatures. Zauderer and Tate (1973) employ a shock tunnel with the MHD generator section having an entrance and exit area of 9·8 cm × 16·5 cm and 19·1 cm × 25·4 cm, respectively, and a generator length of 75 cm with a magnetic field of 1·2 T. Stagnation temperatures are generally higher in this type of experiment than in the envisaged closed cycle system, but for their lowest operating temperature of 2150 K in neon + 1·2 % caesium, 0·44 MWe of MHD power was generated which represented 8·5 % of the 5·2 MWe heat input and an isentropic efficiency of approximately 30 %. In this experiment 37 pairs of hot wire electrodes (less than 1600 K) were employed, and the electrode voltage drops were reduced from 90 to 120 V with cold flush plate electrodes to 60 to 100 V. The wire electrodes were mounted to protrude into the gas stream, away from the wall boundary layers. Nevertheless the power dissipated in the electrode boundary layers represented an equivalent amount of energy to that delivered to the external load. This, together with the occurrence of oblique shocks at high values (more than 0·4) of the electromagnetic interaction parameter S, limited the isentropic conversion efficiency.

In the longer duration blowdown facilities the energy is stored typically in a pebble-bed heater, and gas is passed through this for a fraction of a minute, giving useful experimental times of the order of 10 s. Thus, phenomena representing more closely those occurring in a steady generator might be found. The most important of these are the heating of the walls and electrodes of the channel which affects the gasdynamic boundary layer, the emission properties of the electrodes, particularly the onset of arcs, and the reduced electrical insulation of the alumina or boron nitride walls. This last effect together with gas leakage between joints has been the main cause of the severe reduction in Hall potential which had been a common feature of most experiments until 1971. Then the Frascati groups (Anzidei *et al.* 1971) showed that by a carefully designed sprung and interlocking modular construction, the MHD duct could have the desired gas tightness and electrical insulation. In figure 9 is shown the measured Hall potential which had a maximum of 1100 V and was twice the value obtained earlier with a poorer design of channel.

The continuously flowing closed loop experiments tend to be technologically more difficult and at present are of smaller scale. Apart from the problems involved in a

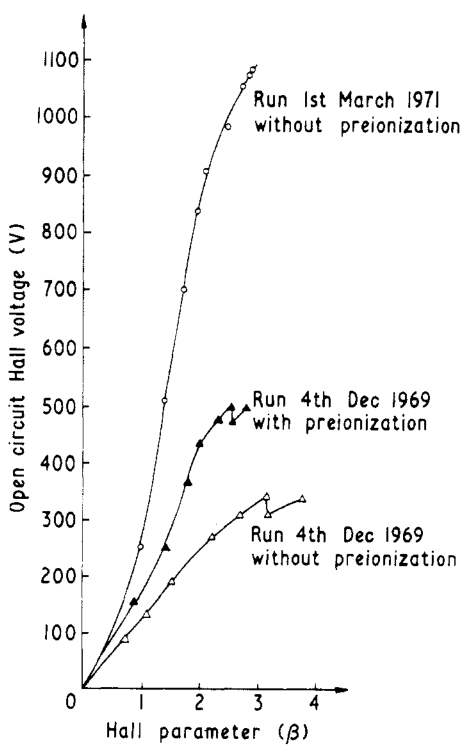


Figure 9. Overall induced Hall voltage (L Anzidei *et al.* 1971 Paris: OECD).

continuously operating high temperature heater, compressor, purification plant, seed injection with recovery before the compressor, the electrical insulation problems are much greater because of the need to electrically float each section so that the developed Hall voltage does not lead to current flow to earth or to other parts of the loop. Recently at NASA–Lewis a successful measurement of 250 V Hall potential was made (Sovie and Nichols 1974) showing that this problem had been overcome. At IRD, Newcastle upon Tyne, in a collaborative experiment with Imperial College, recent measurements have been made of an increase in effective plasma conductivity by a factor of 10 due to an elevated nonequilibrium electron temperature (McNab *et al.* 1974). Confirmation of ionization and delay times and preliminary measurements of the electrode voltage drops as a function of current were also made. In this experiment progress was made on the technological problem of building an efficient tantalum heater element (figure 10) which is compatible with caesium so that the seed can be injected and thoroughly mixed before the generator section.

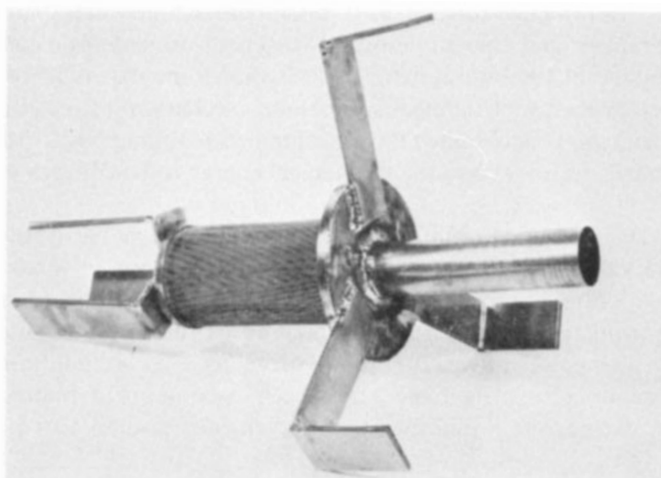


Figure 10. Tantalum mesh heater for International Research and Development Company Ltd closed loop facility.

Finally, there are two main areas for the application of closed cycle MHD power generation. The first lies in the use of a high temperature gas cooled reactor (HTR) with a coolant gas temperature of at least 1500 K. Such a reactor has yet to be developed, and indeed would be a far more expensive project than the MHD generator to which it would be coupled. In Dragon type reactors the nuclear fuel, operating at a temperature of 2000 K for several months, has shown satisfactory mechanical strength, but considerable diffusion of fission products occurs. In the NERVA space reactor which operates for 10 h with a hydrogen outlet temperature of 2500 K and pressure of 40 atm, a specific power of 1500 MW m^{-3} was obtained. The fuel element is basically uranium carbide particles coated with pyrolytic graphite. Such a reactor concept could be adapted to a helium cooled system at 2000 K making it suitable for closed cycle MHD. The pressure matching from a reactor to a generator is not a major problem with the advent of high magnetic fields from superconducting magnets, the main problem being the development of suitable fuel elements. The second application is to couple a closed cycle MHD generator to a fossil fuelled heat source via a heat exchanger. The advantages of this over direct open cycle MHD are that an operating temperature of 2000 K with nonequilibrium ionization allows room temperature rather than preheated or oxygen enriched air to be used for combustion, and there should be very little erosion of duct materials at the lower temperature and in the comparatively pure gas of the closed loop. Zauderer *et al.* (1973) are designing an experimental facility to test this application.

5. Closed cycle liquid metal systems

The study of the interaction of a liquid metal with a magnetic field preceded that of an ionized gas by over a hundred years, Faraday being the first to conduct experiments, using mercury, in 1832. The advantage of a liquid metal for MHD cycles compared with plasmas is its high electrical conductivity and the (relative) independence of this quantity on temperature. In principle this makes it possible to achieve high cycle efficiencies at moderate temperatures and also to consider AC generators based on inductive effects.

The disadvantage of the liquid metal cycle is that some means has to be found to transfer the thermal energy of the heat source into mechanical (directed) energy of the liquid metal stream. Having obtained this, the interaction taking place with the magnetic field in the generator region allows the mechanical energy to be converted into electrical energy.

During the last decade a number of different liquid metal systems have been investigated. Initial interest centered around cycles for use in space vehicles and operated under conditions rather different from those for ground based systems. Thus the cycle rejection temperature is generally high so as to minimize radiator area and optimize the system power-to-weight ratio. More recently as public interest in the space programme has diminished there has been a consequent redirection of effort towards topper or complete liquid metal MHD cycles for ground based or mobile but high efficiency cycles.

The main cycle concepts which have been studied are the separator cycle, the condensing cycle and the two phase cycle.

The *separator cycle* has probably received the most attention to date. In a cycle of this type (see figure 11) two components are used. One, the liquid metal electrodynamic working fluid, is the coolant of the nuclear reactor, while the other, the compressible thermodynamic working fluid, may be a gas, or a vapour. The thermodynamic fluid is mixed with liquid metal and the resulting two phase mixture expanded through a nozzle to obtain a high kinetic energy. Thereafter the mixture enters a separator where the liquid is separated and directed on towards the MHD generator, while the gas or vapour is cooled or condensed and pumped back to the mixer. The liquid leaves the MHD section with sufficient velocity to return through a diffuser to the heat source. A system of this type has been successfully operated at Jet Propulsion Laboratory at power outputs of up to 31 kW AC using sodium-potassium alloy and nitrogen as the working fluids (Cerini 1973). The maximum measured generator net efficiency in this case (ie useful electrical output/output plus losses in generator) was 26%.

The *condensing cycle* has been studied in both its single stage and multistage forms. While extensive calculations have been performed on the multistage arrangement, little experimental work is available. The concept relies upon an attempt to improve

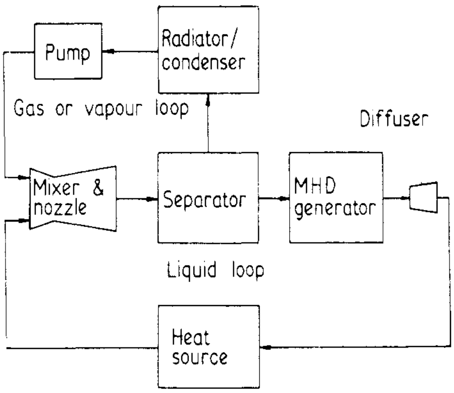


Figure 11. Liquid metal MHD separator cycle (M Petrick 1973).

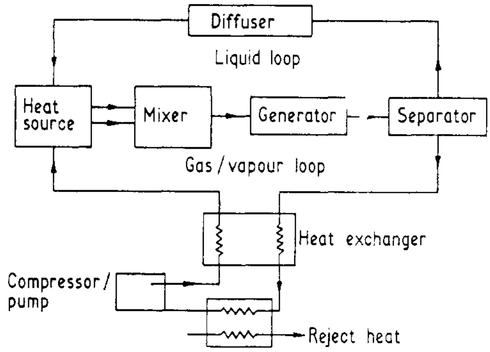


Figure 12. Basic two phase liquid metal MHD generator cycle (M Petrick 1973).

the overall efficiency of the thermal to kinetic energy transformation by making the expansion take place in stages. In this way the flow velocity is kept at a moderate level so that frictional losses are minimized. After expansion in the first nozzle and passage through the generator section, the fluid stream is slowed by the injection of cooled fluid prior to entering the next stage. The final stage of a system of this type is essentially that occurring in a single stage condensing cycle, where all the vapour is condensed by the injection of cooled fluid before the liquid stream enters the generator. The main problem with a system of this type is that large losses may occur in sections where condensation of the vapour takes place, thereby leading to low efficiencies. Methods of improving this which have been suggested include the hollow core jet condenser. The construction of a 1000 kW unit of this type having 60 parallel two phase nozzles has recently been completed in Berlin.

The third type of liquid metal generator utilizes a *two component two phase emulsion* as the working fluid, for example NaK–N_2 (see figure 12). Because of the presence of the gaseous phase the electrical conductivity of such systems is lower than that of the pure liquid metal, but, provided the void fraction does not exceed about 0·8, the fluid retains a bubble structure, with an electrical conductivity close to that of the metal. In contrast to the two steps required by the previously mentioned liquid metal systems the emulsion flow system allows a one step conversion process, but necessitates the use of a DC generator. The main advantages of a system of this type are that friction losses may be reduced by suitable design of the generator section and that separation (and condensation if appropriate) take place at the lower velocities pertaining to the diffuser, rather than at the higher values required in the nozzle separator cycle.

On the whole, while much work has been carried out on the nozzle separator cycle and rather less on the condensing cycle, and while the associated AC induction generators are reasonably well understood, it seems at present as though the two phase emulsion system with its (relatively) simpler DC generator offers a better prospect for future development. Since heat is transferred to the gas from the liquid metal, the expansion in the MHD generator section takes place almost isothermally. This, together with the use of recuperative heat exchangers and multistage compression results in a potentially high cycle efficiency.

Improvements seem possible in a dual cycle using gas turbines, but perhaps the most significant improvement in this cycle could be made if the thermodynamic working fluid could be operated at above its critical temperature and pressure in the MHD generator, while compression was made below the critical temperature. This would greatly reduce the compression work, thereby improving cycle efficiency.

The main areas of experimental work have been devoted to reducing end losses by the use of vanes (to prevent circulating currents) or by grading the magnetic field. Theoretical expressions have been obtained and compared with experiment (see figure 13) for variation of two phase conductivity with void fraction. Generally, the generator efficiency falls off rapidly for void fractions above about 0·8. A crucial factor affecting the generator performance is the relative velocity (slip) of the liquid and gaseous phases during expansion through the generator, and present effort in this area is devoted to contouring the generator so as to generate a constant velocity expansion (Amend *et al.* 1974).

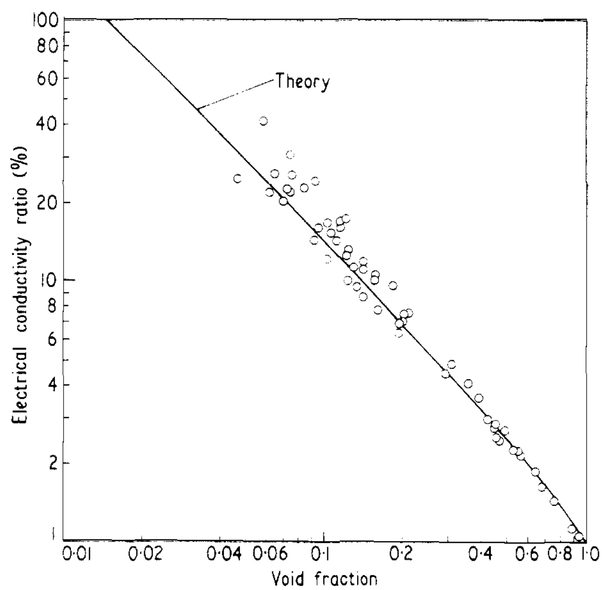


Figure 13. Ratio of two phase to single phase electrical conductivity as a function of the volume void fraction, and comparison with theory (M Petrick 1973).

Drops in efficiency caused by lower velocity fluid boundary layers which shunt the output have been eliminated by the injection of gaseous nitrogen to break up the boundary layers (Cutting *et al.* 1974).

Finally, some interest has been shown, but little experimental work undertaken, on the slug flow or liquid piston MHD systems in which the two working fluids are not intimately mixed as in the other cases, but remain as separate or discrete bodies.

Summary

In open cycle MHD power generation the emphasis is now towards practical application with interest in the MHD generator centering on materials problems, electrode wear, and gas dynamics. Detailed multidimensional numerical simulation is employed to show a good understanding between experiment and theory. Air preheaters are being

successfully developed, and the large U–25 facility in the Soviet Union has employed both this technique and oxygen enrichment for obtaining a combustion temperature of 2500 °C. Besides the possibility of achieving an overall electrical efficiency of 50% (compared to conventional power generation of about 40%) open cycle power generation can lead to a substantial reduction in emission of sulphur oxides and nitrogen oxides. Thus there could be a reduction in fuel costs, thermal pollution and chemical pollution with MHD. These arguments are being used to effect in the USA and USSR where expanding programmes are under way.

In closed cycle MHD, the research has been directed mainly to an understanding of the physics of nonequilibrium ionization and electrothermal instabilities. Much progress has been made on this, and the emphasis is changing towards achieving a stronger interaction parameter with a substantial extraction of energy and a solution of the materials and insulation problems in long duration tests. A major problem is the development of a suitable heat source (eg HTR with a coolant temperature > 1500 K), and attention is being directed also to the application of closed cycle MHD to fossil fuelled systems.

Finally liquid metal MHD, whilst suffering from large viscous losses is making steady progress and has an obvious application to liquid metal cooled fast breeder reactors. Research is concentrating on the fluid dynamics of two phase systems particularly the relative slip of the liquid and gaseous phases.

Acknowledgment

Copies of the *Proceedings of the 13th and 14th Engineering Aspects of MHD Symposia*, held in Stanford and Tullahoma, USA, respectively, are available from Dr J Fox, Department of Mechanical Engineering, University of Mississippi, Mississippi 38677, USA.

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