The Prospective Economics and Thermal Efficiency of Large Scale Open Cycle M.H.D. Stations

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IV. The prospective economics and thermal efficiency of large scale open cycle m.h.d. stations

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The overall thermal efficiency of several different fossil fuelled power stations is discussed using an m.h.d. generator and the conventional method of preheating the combustion with exhaust gases from the generator. Air preheat temperatures of between 1300 and 1700 °C are considered when over-all efficiencies of 51 and 61% may be attained. If the generator length is to be restricted to between 10 and 15 m in order to limit duct heat losses magnetic fields of 4 to 6 Wb/m^2 are required. The use of oxygen enrichment is found at present to be uneconomic but reacting methane with steam (an endothermic reaction) to give the fuel to be burnt is an attractive alternative process although not as good thermodynamically as air preheating. Economic considerations indicate that m.h.d. may only be useful for high cost fuels.

1. Thermal efficiency

In order to assess the economic attractiveness of prospective m.h.d. power stations it is necessary to consider both their thermal efficiency and their construction costs. Most previous studies have examined the thermodynamics of m.h.d. stations and have yielded some interesting results. The present study also attempts a thermal analysis by considering a number of similar power stations but with two key temperatures, the inlet and outlet stagnation temperatures of the m.h.d. generator itself, being changed from one calculation to the next. The calculated efficiencies can be compared and together with other factors can suggest optimum plant size and characteristics.

The normal cycle is considered in which the gases leaving the m.h.d. generator are used to preheat the air for combustion and the remaining heat is used for raising steam for a conventional turbo-alternator. It is instructive to consider the factors affecting the ratio of the power from the m.h.d. generator and from the alternator.

An important feature of such a binary cycle is that the attempt to use all the available heat not only from the hot gases but also the relatively low grade heat from the magnet and the cooling water of the m.h.d. generator necessarily restricts the use of feed water regenerative heating.

This may mean cutting out the final regenerative feed heaters in some cases and the intermediate regenerative feed heaters in others, a fact that becomes apparent when the efficiencies of the thermal cycles are analysed.

2. Basic assumptions

The fuel was taken to be natural gas with a net calorific value of 8560 kcal/m^3. The steam conditions at the turbine stop valve were 240 atm and 580 °C.

The study was applied to large units so that losses would be relatively low. A superconducting magnet system was supposed, with a power consumption of 0·5% of the m.h.d. generator power output though 0·1 to 0·2% will probably prove to be a more realistic range.

The total heat loss to the surroundings through the walls of the heat exchangers was taken as 0·5 % of the energy input to the combustion chamber. Losses due to d.c.–a.c. conversion were taken as 3·5 % of the m.h.d. generator output and the power consumption of the steam turbine auxiliaries as 4 %. Combustion was assumed to be stoichiometric and chemically complete using air as the oxidant.

Such assumptions can reasonably be applied to m.h.d. generators with power outputs between 500 and 1000 MW and estimated efficiencies of the plant compared with efficiencies of ordinary steam turbine plants. The calculations were simplified by taking, in every case, the power output of the m.h.d. generator to be 500 MW. It should be borne in mind, however, that it may be expedient to design a plant around standard sizes and types of steam turbine.

The stagnation pressure after the diffuser from the m.h.d. generator was taken as 1·2 atm although 1 atm could be used in practice. The temperature changes due to evaporation and condensation of the seed have been ignored as these processes have no significant effect on calculated efficiencies.

3. Results of calculations

The results of the main calculations are shown in table 1. The variation of inlet stagnation pressure (P_{01} atm), air preheat temperature (t_{air} °C) and over-all station efficiency ($\eta_{\text{st.}}$) with inlet stagnation temperature (t_{01} °C) is shown in figure 1. The higher the temperature fall in the m.h.d. generator the greater the station efficiency but also the greater the pressure drop in the generator.

Table 1. Over-all station efficiencies of several m.h.d. cycles

(1) stagnation temperature at duct inlet (t_{01}) (°C)	2500		2600		2700	
(2) stagnation temperature at duct outlet (t_{02}) (°C)	2250	2100	2250	2100	2250	2100
(3) air preheat temperature (t_{air}) (°C)	1340	1230	1520	1430	1760	1640
(4) total pressure at duct inlet (P_{01}) (atm)	3·3	5·0	4·8	7·7	7·2	11·2
(5) over-all station efficiency ($\eta_{\text{st.}}$) %	51·0	54·4	55·0	57·0	57·4	61·0
(6) duct length (m)	6	21	9	27	10	30

To obtain high values of t_{01} requires high air preheating temperatures but there is a practical limit on these and so on the station efficiency that may be expected for a given m.h.d. generator outlet temperature (t_{02} °C). The efficiencies given in table 1 can be regarded as close to the upper limit obtainable with the assumed values of t_{02} and available steam turbines and boilers.

The lengths of duct necessary shown in table 1 were calculated taking the electrical efficiency η_e of the m.h.d. generator as 0·9, Mach number at the input 0·85, wall temperature (t_{wall}) = 1500 °C and a magnetic field of 4 Wb/m^2.

As the duct length increases the losses, primarily owing to cooling at the wall, increase and it seems reasonable to restrict duct lengths to between 10 and 15 m. With temperatures at the m.h.d. generator inlet between 2500 and 2700 °C and with an outlet stagnation temperature of 2250 °C acceptable duct lengths can be obtained with a magnetic field of 4 Wb/m². If the outlet temperatures is reduced to 2100 °C a magnetic field of about 6 Wb/m² will probably be necessary and with t_{02} reduced to 2000 °C even higher fields will be needed.

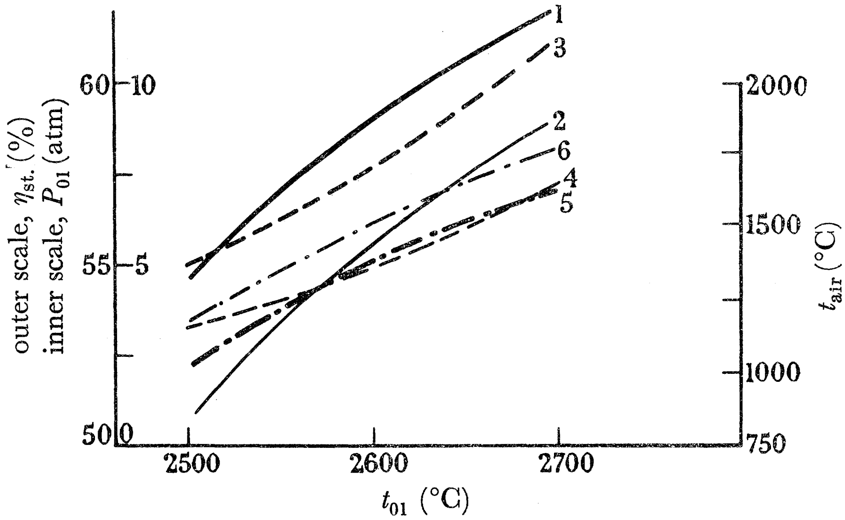

FIGURE 1. Variation of over-all station efficiency ($\eta_{st.}$), inlet stagnation pressure (P_{01} atm), air preheat temperature (t_{air}, °C) with inlet stagnation temperature (t_{01}, °C). Curve 1, $\eta_{st.}$ (t_{02} = 2100 °C); 2, $\eta_{st.}$ (t_{02} = 2250 °C); 3, P_{01} (t_{02} = 2100 °C); 4, P_{01} (t_{02} = 2250 °C); 5, t_{air} (t_{02} = 2100 °C); 6, t_{air}(t_{02} = 2250 °C).

TABLE 2. RATIOS OF POWER OUTPUTS AND CONSUMPTION OF AN M.H.D. POWER STATION

$P_{turb.}$ = power from turbo alternator; $P_{m.h.d.}$ = power from m.h.d. generator; P_c = power consumed by air compressor; t_{02} = 2250 °C.

t_{01} (°C)	2500	2600	2700
$P_{turb.}/P_{m.h.d.}$	1·37	0·76	0·50
$P_c/P_{m.h.d.}$	0·15	0·15	0·165
$P_c/P_{turb.}$	0·11	0·20	0·33
station efficiency, $\eta_{st.}$ (%)	51·0	55·0	57·4

Table 2 and figure 2 show how the power outputs of the steam turbine and the m.h.d. generator and the power input to the air compressor change relative to each other as the m.h.d. generator inlet temperature changes with a fixed outlet temperature (2250 °C in this case). With t_{01}, at 2700 °C the output of the m.h.d. generator is twice that of the turbo-alternator.

The following conclusions can be drawn from examining the calculated data:

(*a*) With large stations over-all efficiencies of between 50 and 60 % and possibly higher can be obtained using unenriched air preheated to between 1500 and 2000 °C. The upper limit of the efficiency given must be regarded as the maximum obtainable from the conditions stated, but it nevertheless far exceeds any efficiencies predictable for other types of power plant in the foreseeable future.

(*b*) The main problem to be overcome at the present stage is the development of a magnet system to produce a field of 4 to 6 Wb/m²: only then can efficient m.h.d. power be contemplated.

(*c*) As well as the problem of designing systems for the effective high temperature preheating of air, methods for obtaining high initial temperatures in combustion products with limited preheating of the air should be pursued. A few aspects of this problem can be considered here.

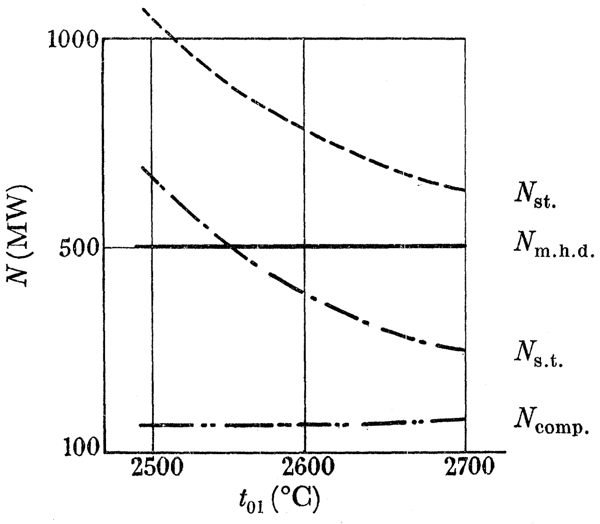

FIGURE 2. The gross output of the steam turbine section ($N_{\text{s.t.}}$) of the plant, the compressor power requirements ($N_{\text{comp.}}$) and the total useful output of a power station ($N_{\text{st.}}$) as functions of the initial temperature of the combustion products at the inlet to the m.h.d. generator (t_{01} °C) for a given constant m.h.d. generator output ($N_{\text{m.h.d.}}$) and constant gas temperature after the diffuser (in this case 2250 °C).

4. AIR PREHEATING

4·1. *Regenerative preheating*

The provision of such high temperature air as that envisaged in table 1 can probably only be made by the use of regenerative heat exchangers. Materials to withstand such high temperatures will be expensive, especially in view of the difficulties which may be expected from the potassium compounds used to seed the gases when they condense on the packing of the exchangers. The problems arising from condensing seed would be avoided by using a separate heat source to preheat the air instead of the gases from the generator. The loss of over-all station efficiency due to abandoning regenerative air preheating could be substantially compensated by the improved conditions for using a bled steam regenerative boiler feed water heating.

4·2. *Oxygen*

Oxygen additions to the combustion air allow lower oxidant preheat temperatures to be used to reach the same combustion product temperature. This advantage is more than offset by the large amounts of power required to produce the oxygen which with present large plant is about 0·4 kWh per cubic metre of oxygen. This is illustrated in table 3: air preheating to 800 °C, which can be done in metallic recuperators, was assumed before mixing with compressed oxygen.

But apart from substantially reduced efficiencies the use of oxygen will lead to considerable increases in capital investment for the oxygen producing plant. The present capital cost of oxygen plant is 100 roubles* per cubic metre of oxygen produced per hour and this

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* 2·52 roubles = £1 sterling.

would lead to an increase in the capital cost of the station of 16 to 25 roubles per kilowatt which is a significant proportion of the total.

The effectiveness of using oxygen is slightly increased if the air–oxygen mixture is all preheated and further improved if the preheat temperature is raised, yet unless the cost of producing oxygen on a large scale can be reduced it is unlikely to be economic for m.h.d. stations.

TABLE 3. EFFECT ON STATION EFFICIENCY OF OXYGEN ENRICHMENT

stagnation temperature at m.h.d. generator inlet (°C)	2500		2700	
stagnation temperature at generator outlet (°C)	2250		2250	
air preheat (°C)	1340	800	1760	800
oxygen enrichment (% by weight)	0	30·5	0	40·0
over-all station efficiency (%)	51·0	45·7	57·4	49·2
oxygen consumed per kW output of station (kg/kWh)	—	0·23	—	0·354

4·3. *Chemical regeneration*

The reaction between steam and the gaseous fuel (methane) is endothermic, and quite substantial amounts of energy can be introduced without increasing the temperature greatly. Such a reaction could be promoted by using the energy from the gases exhausted from the generator.

Suitable equipment in which a reaction of this kind could be carried out needs to be designed with the emphasis on keeping heat losses from the regenerator as small as possible. If such equipment could be designed it is probable that, for given generator inlet temperatures, a higher over-all thermal efficiency could be attained than with oxygen enrichment but not as high as by using preheated air.

5. ECONOMICS AND M.H.D. STATIONS

As m.h.d. power stations have higher thermal efficiencies than conventional steam stations there will be economic advantages on fuel consumption. On the other hand, they will entail higher initial capital costs, at least in the foreseeable future. The extent of the extra capital required cannot be accurately estimated at present since several unusual and novel types of material and equipment will be required.

The primary cost uncertainty involves the use of new types of refractory material for heat exchangers with hot gas temperatures over 700 to 900 °C, for the combustion chamber walls and the m.h.d. duct itself. Suitable refractories are presently highly priced throughout the world but some reduction may be anticipated as they become more widely used, though to what extent the prices will drop cannot be predicted.

The viability of an m.h.d. station can be determined by comparing the estimated annual expenses of such a station ($A_{\text{st.}}$) with the annual expenses of a conventional plant which it might replace ($A_{\text{sub.}}$). The m.h.d. station is useful if

$$A_{\text{sub.}} \geqslant A_{\text{st.}},$$

where

$$A_{\text{sub.}} = aC_{\text{sub.}} + R_{\text{sub.}},$$

$$A_{\text{st.}} = aC_{\text{st.}} + R_{\text{st.}};$$

$C_{\text{sub.}}$, $C_{\text{st.}}$ are the capital cost per kW installed of building a conventional and m.h.d. plant respectively; $R_{\text{sub.}}$, $R_{\text{st.}}$ are the respective annual operating costs; a is the standard coefficient of cost effectiveness.

By equating $A_{\text{sub.}}$ and $A_{\text{st.}}$ a maximum acceptable extra capital cost for m.h.d. stations

$$\Delta C = C_{\text{st.}} - C_{\text{sub.}}$$

can be found as a function of fuel costs and the ratio of efficiencies $\eta_{\text{st.}}$ to $\eta_{\text{sub.}}$.

5·1. *Seed loss*

The operating costs of an m.h.d. station include not only the normal components such as fuel, staffing, depreciation and general overhead charges but also the cost of seed lost to the environment. Assuming staffing and overhead costs are independent of the type of station installed then the extra capital cost allowable is given by

$$\Delta C = 0{\cdot}123 C_{\text{fuel}}\, h\left(\frac{1}{\eta_{\text{sub.}}} - \frac{1}{\eta_{\text{st.}}}\right)\frac{1-\alpha}{a+D} \text{ roubles/kW},$$

where C_{fuel} is the fuel cost in roubles/ton, h is the number of hours per year plant running time, D is the depreciation rate, and

$$\alpha = \frac{\text{cost of replacing lost seed}}{\text{fuel saved in m.h.d. station}}.$$

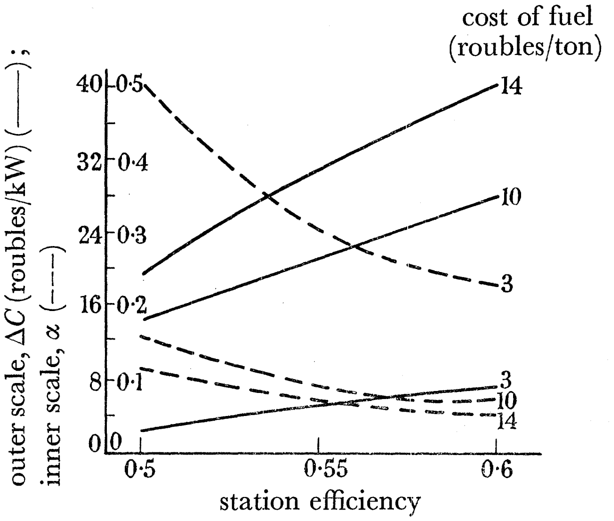

FIGURE 3. The maximum acceptable figure for the extra capital costs of m.h.d. stations (Δk) as a function of overall station efficiency ($\eta_{\text{st.}}$) and cost of fuel. a = ratio of cost of replacing lost seeding material to fuel saving. (2·52 roubles = £1.) The ratio, α, of seed costs to fuel costs is also shown.

Figure 3 shows how α and ΔC vary in relation to estimated fuel costs and $\eta_{\text{st.}}$. The following assumptions were made:

Over-all efficiency of the station to be replaced

$\eta_{\text{sub.}} = 0{\cdot}42$, being the maximum attainable for future thermal stations (using steam turbines or a steam-gas cycle),

$h = 7000$ h (i.e. assuming base load operation),

$a = 0{\cdot}125$,

$D = 0{\cdot}078$.

The seeding rate was taken to be 1 mole% of potassium in the gases.

Loss of seed is governed by atmospheric pollution requirements and the characteristics of the gas cleaning equipment. A loss of 1% of K_2CO_3 costing 150 roubles/ton was assumed. Figure 3 shows that with cheap fuel the cost of making up lost seed can be an appreciable part of the running costs. Figure 3 also indicates that m.h.d. stations should be primarily restricted to those areas where only expensive or comparatively expensive fuel is available so that the higher capital charges for an m.h.d. station can be more readily offset against the reduced fuel consumption.