OPEN CYCLE M.H.D. POWER GENERATION

Edited by

J. B. HEYWOOD and G. J. WOMACK

OPEN-CYCLE MHD POWER GENERATION

RESULTS OF RESEARCH CARRIED OUT BY MEMBERS OF THE BRITISH MHD COLLABORATIVE COMMITTEE

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FOREWORD

Many readers will be aware that for several years a very considerable research and development effort has been devoted by the Central Electricity Generating Board to the study of Magnetohydrodynamic Power Generation. Since 1964 the Board has been joined by the manufacturers of heavy electrical equipment (Associated Electrical Industries Limited, C. A. Parsons Limited, the English Electric Company Limited, the General Electric Company Limited), the Water Tube Boilermakers' Association and the National Coal Board in a programme of collaborative research. This collaboration became known as the British MHD Collaborative Committee, and it is the results of this research programme which are described in this book.

Work on this project began in 1959, when the C.E.G.B. set up a small study group to examine the possible application of the direct conversion method of electrical generation to central power station use. Preliminary and small-scale experiments were begun on fuel cells, on thermionic and thermoelectric devices, as well as on MHD. Obviously, a number of small-scale studies such as this could not all be taken through to large-scale development, and thermionic and thermoelectric devices were abandoned first. Both fuel cells and MHD were continued, and the laboratory experiments increased in scale to involve installations costing a few tens of thousands of pounds.

The continuing studies on MHD indicated by 1964 that many of the research problems had been identified, and that further progress towards a competitive source of power generation would require large-scale experimental work. An outline design of an MHD power station indicated that it would be competitive with nuclear stations (on the price assumptions current at that time) for several years provided it could be brought into commission in the period 1975–9. The difficulties in achieving this were recognized, but in spite of the risk, the profit to be gained from a successful outcome was sufficient to persuade us to make the effort. At this point the collaborative programme was initiated under the technical leadership of Dr. P. R. Howard. A very remarkable spirit of unity has prevailed since the first coming together of the collaborating groups all of whom have made substantial financial and technical contributions to the project. This is reflected in the number of contributors to this book. It has been a constant stimulation and encouragement to me as chairman of the main committee to have the support which has been so loyally provided.

The problems to be dealt with are described in detail in the following pages. Most of the small-scale work has been successfully completed, and although several outstanding problems remain, the stage has been reached where a detailed efficiency and cost estimate for an MHD power station can be given. Thus the research stage of the project has been completed, and at present we cannot see any economic justification in the United Kingdom for the large expenditure which the development stage would require. The main reason for this is that in this country the cost of nuclear power stations of the A.G.R. type is still tending to fall, while costs of fossil-fuel-fired plant are now tending to rise. This has brought closer the date at which an MHD station must be commissioned and has reduced the period of time when it would be competitive with a nuclear station practically to zero.

The main purpose of this book is to collect together and present in a logical sequence the information which has allowed this appraisal to be made. In this way an up-to-date picture of the prospects for open-cycle MHD power generation is given. While this appraisal has led, in the United Kingdom, to the termination of large-scale research on this topic, this is not the case elsewhere in the world where different economic conditions may prevail. For this reason the presentation of the results of our research to a wider audience than has hitherto been possible seems well justified.

L. ROTHERHAM

PREFACE

THIS book describes the results of studies on open-cycle MHD power generation which were carried out by the British Collaborative Team over the 3–4-year period ending in 1968. Since the scope of the work embraces studies within the spectrum from fundamental research to engineering design, differences in approach to the basic studies and solution of technical problems have occurred. Also, since this book is compiled from the work of many contributors there are, inevitably, differences in style in the presentation of the various sections. Every effort has been made by the Editors to achieve uniformity whilst retaining the individual character of the reported work, but some sacrifice in consistency has been necessary in the integration of various sections. We hope that this does not detract too much from the complete and coherent account of our research work which we wish to achieve.

Similarly, as the work progressed it became necessary to modify some of the initial assumptions, and whilst every effort was made to avoid divergence, some minor differences in the boundary conditions occur for some of the studies, dependent on the stage at which the studies were carried out.

In most of the engineering studies Imperial units were used, whilst the duct studies used S.I. units. For consistency all units have been converted to S.I., but in some cases where it is useful to the reader, or where integer parameters were studied, the equivalent Imperial unit is given in parentheses.

The reported studies involve contributions by many workers over and above the authors of the main sections and their responsibility for much of the work is acknowledged. Finally, the Editors would like to record their appreciation of the efforts of the main contributors, the painstaking secretarial assistance of Miss Janice Cullum, Miss Daphne Gray and Miss Jennifer Gulliver in the preparation of the manuscript, and the excellent work of the Central Electricity Research Laboratories Illustrative Drawing Office in preparing the diagrams.

J. B. HEYWOOD
G. J. WOMACK

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CHAPTER 1

INTRODUCTION*

Nomenclature

B magnetic field strength.
e electronic charge.
k Boltzmann's constant.
T temperature.
v fluid velocity.
V_i ionization potential.
σ electrical conductivity.
η_0 combined plant efficiency.
η_1 $\dfrac{\text{MHD electrical power output}}{\text{fuel thermal input}}$.

1.1 General Principles of MHD Power Generation

Magnetohydrodynamics (MHD) is the science underlying the interaction between an electrically conducting fluid and a magnetic field. It is not a new subject, and dates back to Michael Faraday in the early nineteenth century. In his pioneer work on electromagnetic induction in fluids he attempted to use the earth's magnetic field to measure the flow in the River Thames; he also postulated that the motion of the oceans influenced the earth's magnetic field, an idea which still has support today. In the last 10 years or so, work on MHD has expanded enormously because several applications of the subject have become practicable. It is one of these applications—power generation—which is the subject of this book.

MHD power generation† uses the interaction of an electrically conducting fluid with a magnetic field to convert part of the energy of the fluid directly into electricity. For an incompressible fluid this energy is kinetic; for a compressible fluid it may be both kinetic and thermal. When

* This chapter was written by G. J. Womack, C.E.G.B., Marchwood Engineering Laboratories, and J. B. Heywood, C.E.G.B., Central Electricity Research Laboratories.

† Sometimes called magnetoplasmadynamic (MPD), magnetogasdynamic (MGD) or magnetofluiddynamic (MFD) power generation.

a conducting fluid flows through a magnetic field an electric field is induced in the fluid normal to both the flow and magnetic field directions.* If the flow is in a duct, and an external load is electrically connected to the fluid, this induced field can drive electric currents in a closed path through the fluid and the load. These currents interact with the magnetic field and exert a braking force on the fluid. The flow does work against this force, and energy is transferred from the fluid to the external load; energy is converted directly to electricity.

The simplest MHD generating duct is shown diagrammatically in Fig. 1.1. It consists of a channel of rectangular cross-section with one pair of walls electrically insulating and one pair electrically conducting electrodes in contact with the fluid. The magnetic field is perpendicular to the insulating walls; the load is connected between the electrodes. The fluid may be

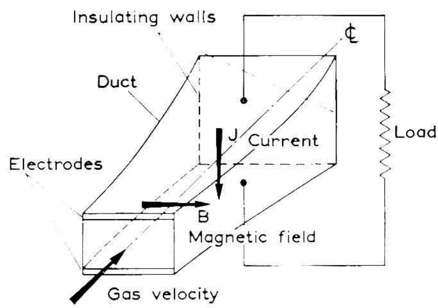

FIG. 1.1. Schematic arrangement of an MHD duct.

either compressible or incompressible. The energy is added to the fluid from either a fossil fuel or nuclear heat source upstream of the duct, the flow is accelerated in a nozzle and enters the duct. Obviously the power density in the duct is important since a smaller duct reduces heat loss and is of lower capital cost. The power density in the duct has a maximum value of $\frac{1}{4}\sigma v^2 B^2$, where σ is the electrical conductivity, v the fluid velocity, and B the magnetic field; obviously a high fluid velocity and conductivity are required for a given magnetic field.

Appropriate working fluids are liquid metals and ionized gases. Liquid metals have a high conductivity ($\sim 10^7$ mho m^{-1}), but it is difficult to convert the thermal energy in the heat source to the kinetic energy of the fluid. With gases, at the highest temperatures attainable with fossil-fuel combustion products or with the noble gases and a nuclear heat source, the difficulty is that the electrical conductivity is too low. The electrical

* In vector notation, this field is $\mathbf{v} \times \mathbf{B}$, $\mathbf{v}$ and $\mathbf{B}$ being the flow velocity and magnetic field. A fuller explanation of the basic principles of MHD can be found in Shercliff (1965).

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 the electronic charge and k is Boltzmann's constant. Hence, to obtain an acceptable electrical conductivity it is necessary to add a more easily ionizable substance (called seed) to the gas. The best substances are caesium (V_i = 3·89 V) and potassium (V_i = 4·34 V),* and these are added to give concentrations in the working gas of about 1 mol %. There are alternatives to thermal ionization and also methods of increasing the electron density. These include low- and radio-frequency induction, photoionization, electron-beam ionization, chemi-ionization, the use of radioactivity and thermionic emission and magnetically induced ionization. Only magnetically induced ionization shows promise of enhancing the electrical conductivity above the thermal equilibrium value, and then only in noble-gas systems. This book describes researches on the fossil-fuel-fired, open-cycle MHD power generator, and is therefore concerned exclusively with thermal ionization of the seed material to render the working fluid, combustion products, electrically conducting.

So far we have described only the MHD part of the system. In the successful exploitation of MHD for commercial power generation, the MHD generator must be incorporated into a complete cycle, and the other plant items in the cycle are of equal importance. In the fossil-fired system which is our subject here, the temperature of the gas at the MHD duct inlet, which determines the conductivity and hence power density at that point, depends on the performance of the combustion chamber. High power densities require high magnetic fields and the magnet design is therefore important. In the MHD duct the electrical conductivity falls rapidly with decreasing gas temperature along the duct, and it becomes uneconomic to extract electrical power directly from the gas by the MHD process below gas temperatures of 1800–2000°C. The remaining heat in the combustion gas stream must be extracted by some other process, and a regenerative air heater and a steam-raising plant are included in the system. The seed material must be recovered from the gas stream for economic and amenity reasons. As the cycle is described in more detail in the next section, the importance of all these plant items will become apparent.

1.2. Possible MHD Cycles

For large-scale generation there are basically three types of MHD cycle: (i) open, (ii) closed and (iii) liquid metal.

* Rubidium (4·18 V) lies between but is too costly to be of interest.

1.2.1. Open-cycle System

In the open cycle the working fluid is finally rejected to the atmosphere and it must therefore be cheap. The only practical example is the fossil-fuel-fired cycle where the fluid is seeded combustion products. This combustion-fired system, sometimes called the "classical open cycle", produces a high-temperature seeded gas by burning the fossil fuel (either coal, oil or gas) with highly preheated air, possibly enriched with oxygen, at high pressure. Seed is usually introduced into the combustion chamber in the form of a fine powder of a salt of the seed material. The gas is then accelerated in a nozzle before it enters the MHD generator. Obviously a high flame temperature is important in obtaining a high conversion efficiency in the cycle and in obtaining the highest possible electrical conductivity in the MHD duct. As electrical power is extracted from the flow in the duct the temperature falls, the conductivity falls more rapidly, and below 1800–2000°C the Joule dissipation in the gas becomes too large and MHD power generation is uneconomic. This limit is reached when the gas is still extremely hot by conventional steam-generating plant standards and the remaining heat must still be extracted. The gases are then diffused to a relatively low velocity and pass on to the heat and seed recovery plant.

One can show the importance of the air regenerator and the steam plant which make up the heat recovery plant by a simple heat balance. The specific heat and mass flow rate of combustion products are greater than for the air, and this makes complete regeneration of heat impossible. In a typical design of a plant with a fuel thermal input of 2000 MW,* the heat loss to combustion chamber, nozzle and duct walls is about 180 MW and the MHD power output is 550 MW with an MHD duct exit temperature of about 2000°C. The enthalpy of the gas stream is still slightly less than 2000 MW, whereas if it is exhausted to the atmosphere at 150°C, as in conventional plant, its enthalpy would be 104 MW. Even if the air preheat temperature could be brought up to the duct exhaust gas temperature of 2000°C only 1160 MW† could be regenerated. A practical limit on air preheat temperature is 1200–1500°C (see Chapter 2) which corresponds to regeneration of between 630 and 830 MW. The remaining energy in the flow is recovered with a Rankine steam cycle. Even this plant item must depart from the conventional design (see Chapter 10) since it must absorb the low-grade heat in the MHD combustion chamber and duct-wall cooling water; and since seed condensation takes place as the gas temperature

* For a 2000 MW (T) fuel input with air preheated to 1200°C the total enthalpy input to the gases is 2630 MW (T). (Air mass flow 663 kg s^{-1}; specific heat 10^3 J kg^{-1} $°K^{-1}$; air temperature rise 950°C.)

† Air mass flow 663 kg s^{-1}; specific heat 10^3 J kg^{-1} $°K^{-1}$; temperature rise 1750°C.