SPECIALISTS MEETING ON COAL FIRED MHD POWER GENERATION 1981

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SPECIALISTS MEETING ON COAL FIRED MHD POWER GENERATION 1981

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Preface

Magneto hydro dynamic electric power generation is establishing itself as a process for the production of electrical energy which offers a greatly enhanced utilization of the world's fossil fuel resources. As a generation process for bulk power it should break through the efficiency barrier imposed by the Rankine steam cycle used in conventional power plant. If applied to co-generation processes, MHD offers combined electrical and thermal energy outputs which can lead to substantial saving in fuel in chemical processes requiring both forms of energy.

Large-scale national programmes to develop MHD power generation plant have been established in major industrial countries like the USSR, USA, Japan and China. Other facilities have been set up in the Netherlands, Poland, India and Australia and other countries have shown interest in the potential of MHD. Substantial progress has been made and a 500 MW natural gas fired MHD power station is under construction in the USSR. Coal fired MHD still needs basic development and demonstration effort applied before it becomes economically accepted. An extensive effort to establish the economic feasibility of coal fired MHD has developed specifically in the USA as well as other countries. Extensive studies indicate that overall power station efficiencies can be raised from today's 35 percent to at least 45 percent in early MHD power stations with a promise of 55 percent for second-generation developments.

MHD must be judged not only as a potential power generation process. It is important to evaluate also additional benefits and fall out. High efficiency is not in itself the most important factor in determining power station economics. In the present economic climate we find that capital costs are even more critical. However high efficiency implies

(i) an improvement on environmental impact
(ii) a recovery of efficiency downturn in recent times
(iii) an extension of site use
(iv) a development of lower quality coal resources.

There are other developments competing against MHD and they involve new technologies and changes in the social environment. In recent years gas turbines in a combined cycle have shown great promise in economy and efficiency, however gas turbines require a clean fuel and direct coal firing is not feasible as yet. Fuel cells offer very high conversion efficiencies but costs are still high for an overall electrochemical process starting with coal as basic fuel. More challenging might be nuclear energy and its revival with slackening opposition from environmental forces. However, considering the very long time scales involved, even a crash programme in nuclear power will fall far short in providing for the full demand for electricity during the early part of the next century.

The potential impact of MHD on power system development must be considered as real and should be taken into account by power system planners.

The proceedings of this specialist meeting is a collection of papers from leading MHD experts from most countries involved in MHD research and development. The meeting is sponsored internationally by the UNESCO International Liaison Group on MHD Electrical Power Generation. Australian co-sponsors are the Australian Academy of Science and the Australian Institute of Energy. The Conference is organized by The University of Sydney and The Institution of Engineers, Australia. The help offered by all these organizations is gratefully acknowledged.

The meeting is intended to be less formal than the major international MHD conferences and the subject chosen is more specific. Two types of papers are presented. The first kind are invited papers which generally describe completed work and general concept areas. Other papers have been submitted and are mostly shorter and will deal with work currently in progress. Authors have been asked to submit a manuscript rather than a summary and a majority of authors have taken advantage of this opportunity. It is hoped that this volume of collected papers will prove useful and serve as a basis for discussion and information exchange at the meeting.

H.K. Messerle
Chairmar

SESSION 1:

COAL FIRED MHD PROGRAMMES

Papers

SESSION 1: COAL FIRED MHD PROGRAMMES

SESSION 2: MAGNETS, DIAGNOSTICS AND OTHER TOPICS

SESSION 3: COAL CHARACTERISTICS AND COMBUSTOR DESIGN

SESSION 4: COMBUSTION AND INTEGRATION WITH CHEMICAL PROCESSES, OPEN CYCLE

SESSION 5: CLOSED CYCLE MHD

SESSION 6: MHD GENERATOR DESIGN

SESSION 7: POWER SYSTEM INTEGRATION

Specialists Meeting on
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Power Generation 1981
Sydney, 4-6 November 1981

Principle Directions of Investigations and Development Works on Elaboration of a Coal-Fired MHD Power Plant in the USSR

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The Soviet national program of research and development in the field of MHD conversion of energy provides for a phased commercialization of MHD power plants, starting with simpler, natural gas-fired plants to be followed, after adequate research and accumulation of operating experience, by solid fuel-fired plants. The construction of the first clean fuel-fired MHD-generating unit having an electrical capacity of 500 MW has already begun at the site of the Ryazan central-station power plant. It is planned to commission this unit in mid-eighties. The development of this unit will help to solve a number of vital problems associated with further utilization of the MHD method of power generation. However, in view of the overall fuel-and-energy resource situation, the most promising way of commercializing MHD power plants is through the use of coal fuel. It is expected that solid fuel-fired MHD will be rather economical and will help considerably to reduce heat discharges to the atmosphere, and provide a potent means of fighting the chemical pollution of the atmosphere.

As early as at the start of the 1990s, it isplanned to build in the USSR the first solid fuel-fired commercial power-generating MHD unit having a capacity of 500-1,000 MW to be followed over the subsequent years with a series of suoh units. The realization of these plans calls for the development of new and remodeling of a series of existing large MHD facilities and stands for carrying out comprehensive studies into the specific conditions of operation of basic components and systems of commercial solid fuel-fired MHD power plants. This work is to be preceded by a series of basic and technical-and-economic studies aimed at defining both the optimum MHD scheme and the type of coals used, as well as the rational location of MHD power plants.

At present, three major trends in the development of coal-fired MHD are under consideration, namely:
- MHD power plants with the direct combustion of coal in special combustors and maximum slag removal. This work is carried out in the Institute of High Temperatures (IVTAN), at the U-02-500 Facility, in the Kazakh Institute of Power-Engineering Research and in a number of other organizations;
- MHD power plants with direct combustion of coal without slag removal in the combustor (Krzhizhanovsky Institute of Power Engineering Research - ENIN);
- MHD power plants utilizing the products of coal gasification and processing. In view of the increasing deficit of liquid fuel and rising recovery costs per ton of oil, the interest grows towards the various process schemes for comprehensive utilization of coal characterized by the maximum yield of liquid fractions as by-products. The incorporation of MHD facilities in such complexes for cogeneration of energy and various by-products offers additional economic advantages owing both to a rational utilization of pyrolysis products in a MHD facility and to facilitating the solution of ecological problems. Such studies are being carried out at IVTAN, Institute of Electrodynamics of the Ukrainian Academy of Sciences and in other institutions.

For commercializing the coal-fired MHD, a whole series of scientific and design problems are to be solved, the major of those problems including:
- designing the scheme of pulverized coal preparation and feed to the combustor operating under pressure, and organizing high-voltage potential decoupling between the elements of this scheme and the combustor;
- developing a combustor with a service life of about 10,000 hours under conditions of intensely aggressive media, as well as solving the scientific-and-technical and engineering problems of slag removal from the combustor working under pressure of about 10 atm and under conditions of high electric potential;
- studying and perfecting an MHD-channel structure characterized by the presence of slag film on the electrode and insulating elements;
- perfecting a highly efficient diffusor structure operating under conditions of slag flow;
- developing a steam generator equipped with an efficient system of cleaning the heating surfaces from slag and seed deposits;
- developing a system for seed injection, recovery and regeneration;
- studying the ecological problems associated with the operation of commercial, solid fuel-fired MHD power plants;
- developing a system for the purification of discharge gases;
- developing high-temperature air preheaters for operation at a refractory mate-

rial temperature of 1,700-2,000°C using ash-containing combustion products;
- determining the electrophysical and thermophysical properties of combustion products of solid fuel seeded with alkali metals, as well as the properties of ash and slags;
- developing methods and means of diagnostics and control of the parameters of plasma and combustion products containing seed, ash and slags, over a wide range of parameters.

It is expected that the principal problems associated with solid fuel-fired MHD facilities will be solved over the next few years.

Let us consider briefly the major results of research-and-development work related to the development of MHD power plants with direct coal combustion and maximum slag removal in the combustor.

In accordance with the existing research program, coal MHD studies have been carried out in the U-02-500 (Kirillin and Sheindlin, 1968) Facility over the last few years. At the first stage of this work (ca. 1976-1977), the main loop of the Facility was partly remodeled to provide for the possibility of simulating the solid fuel combustion by way of introducing an appropriate amount of ash in the combustor and, more recently, for studying the operation of MHD facilities under conditions of direct combustion of coal.

The basic non-standard components subjected in the course of this work to profound changes or built anew included the systems for the delivery, batching and control over the flow rate of ash or pulverized coal, combustor designed for liquid slag removal, MHD-channel and the system for cooling the combustion products and for recovering slags and seed compounds.

At the initial stage involving the simulation of solid fuel combustion, materials and structures of the combustor lining have been developed which provide for a continuous combustor operation under conditions of contact of its lining with slag films which form over the combustor walls a solid coat of lining slag. There has been recently developed (now being successfully tested) a combustor designed for high-temperature combustion of pulverized coal under conditions of air preheat and oxygen enrichment of up to 50%.

The combustor is of a cyclone type, single stage, with the seed injected in the form of a 50% aqueous solution of K_2CO_3 and with liquid slag removal. The combustor has demonstrated successful operation at plasma temperature and conductivity close to the rated values (Burenkov et al., 1980). The operation of this combustor is noted for high stability and reliability, 80-85% slag removal and a practical absence of seed losses with removed slag.

It is planned to study the combustor operation under conditions of high-temperature combustion (both direct and two-stage) of the various promising coals with different degrees of slag recovery.

The investigations into the MHD-channel operation have been mainly directed towards studying the formation and behavior of slag films on the channel walls and their effect upon the electrode processes and upon the operation of various electrode systems and MHD-channel (Burenkov et al., 1978; Burenkov et al., 1978). It was during the U-02-500 experiments that attention was first paid to the ripple motion of film on the surface of the channel walls.

One of the new and important phenomena revealed in the course of the afore-mentioned studies was the pronounced (up to complete) destruction of slag film continuity under the effect of current spots (especially anode ones) and Joule heating. Current densities in this case were close to those expected in commercial MHD-generators.

It has been found that at a low temperature of electrode surface (metal electrodes), apart from intensely heated spots on the film surface, breakdowns may occur between the liquid slag film and electrode surface which "explode" the film from within. This destruction of the film causes doubts as to the seemingly evident simplicity of obtaining a stable slag coating on the electrode walls of the channel of MHD-generator.

At the U-02-500 Facility studies were made into both high-temperature ceramic and metal electrodes.

These studies have shown the optimum range of the surface temperature of ceramic electrode lies within 1,300 to 1,500 K, i.e., somewhat below the slag softenting temperature.

Duration tests of electrodes have shown that the optimum metal electrode material for cathodes is represented by low-alloyed copper alloys and for anodes - by nickel-coated copper (Zalkind et al., 1980), the adequate stability of nickel coatings under conditions of using promising domestic coals being, in our opinion, due to the practical absence of sulfur from these coals.

Silicon carbide and chromites of rare-earth metals (Zalkind et al., 1980) proved to be the best material for use in ceramic electrodes. However, their strength is still inadequate for use in power MHD-generators.

One of the major stages in the Soviet program aimed at the development of MHD power plants with direct coal combustion and maximum slag removal in the combustor is the development of the integrated coal-fired U-25G Facility on the basis of the U-25 (Kirillin et al., 1968) and U-25B (Kirillin et al., 1978) Facilities, which is to be commissioned by 1982.

This projected U-25G Facility is rated for the following parameters:

Working fluid	- coal combustion products
Oxidizer	- air enriched with oxygen of 40% (continuous mode of ope ration) and up to 60% (short-term mode of operation)
Seed	- 50% aqueous solution of potassium carbonate or dry potassium carbonate
Flow rate of combustion products	- up to 5 kg/s
Flow rate of coal	- up to 0.8 kg/s under continuous operation mode and up to 1.2 kg/s under short-term operation mode
Oxidizer preheat temperature	- 900°C
Pressure in the combustor	- 3.5 abs.atm
Time of operation	- continuous

The schematic of the U-25G Facility, together with the pulverized coal preparation and delivery system, is shown in Fig. 1. Coal will be charged in a 15-ton bin (1). At the initial stage of investigations, it is possible to charge and use pre-pulverized coal of desired composition supplied by motor transport.

From the feed bin, coal is delivered by a feeder (2) to a mill dryer (4). Drying is done by nitrogen (or air) supplied from the oxygen plant of the U-25 Facility. Nitrogen is heated in a heat exchanger (3). Nitrogen has the following characteristics at the outlet from the heat exchanger:

temperature	- up to 250°C
flow rate	- 10^4 nm^3/h
pressure	- up to 2 atm

This same gas serves for conveying pulverized coal to a cyclone (5). The bulk of pulverized coal gets separated in the cyclone and then delivered to one of two storage bins (9). Each of these bins has a capacity of about 3 tons. Nitrogen is cleaned of pulverized coal particles in cyclones or filters (6). Cleaned nitrogen is returned to the loop or discharged to the atmosphere while the pulverized coal is fed by a pump (7) to the storage bin (9). The storage bin is rated for a working pressure of 6 atm. After one of the storage bins is filled with coal dust, it is cut off from the low (atmospheric) pressure main with the aid of quick-closing valves (8) and pressure-charged with nitrogen. When the pressure of 6 atm is reached, the storage bin is communicated via high-pressure line to a service bin (10) for filling the latter with pulverized coal. Upon draining one of the storage bins, the other one comes under charging. The service bin (10) has a capacity of about 10 tons and is rated from 3 to 4-hour operation without topping-up under conditions of rated coal flow rate. From the service bin (10), pulverized coal is fed via batcher (11) to an ejector (12) and then conveyed in a flow of nitrogen to a combustor (13) of the U-25G Facility.

The currently developed system for pulverized coal preparation and delivery will facilitate future investigations and perfection of basic loop components in the pilot U-25 Facility under conditions simulating the operation of a number of principal components and systems of a commercial MHD power plant.

The choice of the combustor scheme depends upon contradictory factors: on the one hand, the slag film serves to protect the combustor and channel walls against direct plasma effect and to reduce heat losses while, on the other hand, slag compounds actively bind the seed thereby hampering its regeneration.

At the first stage of development of the coal-fired U-25G Facility, it is planned to utilize single-stage coal combustion with a possibility of future transition to two-stage combustion.

Under conditions of single-stage combustion, coal and oxidizer are supplied in a close-to-stoichiometric ratio to the bottom portion of the combustor where slag removal is effected in an amount of up to 80-90%. The seed is injected to the top portion of the combustor such that its losses with slag being removed should be minimum while the residence time in the combustor sufficient for its full ionization. Under conditions of two-stage combustion, about two-thirds of the pulverized coal will be burned at the bottom of the combustor at the air excess coefficient of 1.6. The temperature of combustion products at this stage (ca. 2,000°C) is lower than the initial evaporation temperature of the mineral fraction of fuel, which helps to recover 80-90% of slag.

In the second chamber, the after-burning of the remaining coal takes place in an atmosphere of oxidizer unused at the first stage. The temperature of combustion products at the outlet from the second chamber is about 2,800-3,000 K.

At the first stage, slag removal is effected to a special bin (14) rated for 10-hour continuous operation of the combustor. It is planned to develop later a continuously acting system for slag collection and removal.

An aeuqous seed solution will be used at the initial stage of investigations. Later on, it is planned to inject "dry" seed into the combustor for increasing the electric conductivity of the combustion products. The agglomeration of powder is precluded by pre-mixing it with special additives.

From the combustor, the combustion products are delivered via nozzle (15) to the MHD-channel (16). The flow portion of the channel is of subsonic type with the Mach number at the channel inlet of 0.8-0.85

and at the outlet - of 0.9-0.95. The total length of the channel is about 2.8 m and the active length - 1.5 m. The MHD-channel structure is made such as to be readily dismantled for carrying out studies related to the perfection of the optimum structure of components.

For carrying out studies into the electrophysical properties of plasma and for determining the parameters at the inlet to the MHD generator, a diagnostic spacer (17) is positioned before the channel, having a length of about 3000 mm and designed for optical and probe measurements (including laser diagnostics).

The magnetic field of up to 4 T will be created by a conventional magnet supplied from standard d.c. sources available at the U-25 Facility. The magnet will have an active length of about 1.5 m and the total length of up to 2.8 m.

A diffusor (19) having a length of about 2 m is placed after the MHS channel.

The critically important unit of the U-25G Facility is the steam generator. It is designed for cooling the combustion products, removing seed and slags and for carrying out investigations under conditions of operation of a commercial MHD power plant.

The steam generator is one of the most sophisticated and costly components of the auxiliary equipment. The specifics of the steam generator operation reside in its multifunctional nature, namely, it serves for utilizing the heat of combustion products leaving the channel, for cleaning the gas from impurities and for removing the ionizing seed. The most complicated scientific and technical problem associated with the development of a steam generator for a coal-fired MHD power plant is that of precluding the active clogging of the boiler heat surfaces with ash deposits and seed compounds. Considerable experience has been gained at the IVTAN U-02 and U-25 Facilities of operating steam generators in continuous modes; along with the optimization of the temperature conditions of combustion products and steam-water path, the various techniques of cleaning the heating surfaces were perfected such as air-blast cleaning, ball cleaning and acoustic cleaning. Although "clean" fuel combustion products were used, the investigation results can be in part extended to cover ash-bearing fuels as well. It is planned to make the model steam generator of the U-25G Facility a multisectional one. The head portion of the steam generator accomodates a radiation chamber (20) shielded with water-cooled tubes, wherein the most intensive slag removal (up to 90-95%) and decomposition of nitrogen oxides take place.

Positioned after the radiation portion is a convective one (21) where the most of the seed will be extracted. For studying the problems associated with the decomposition of nitrogen oxides, as well as the possibility of varying the temperature conditions at the inlet to the convective portion, additional burner devices will be additionally envisaged.

For the collection and removal of slag, ash and seed, provision is made for placing each section bins equipped with means for unloading them during the operation of the facility. From the steam generator, combustion products are delivered to the existing electrostatic precipitator (22) of the U-25 Facility, which serves to clean the flue gases from flying ash and seed.

The temperature of gases before the electrostatic precipitator should be maintained at a level above 180-200°C at which no moistening and carbonization of the seed to $KHCO_3$ takes place.

After the electrostatic precipitator, the combustion products are discharged by flue gas exhausters to the stack.

For accelerating the commission of the U-25G Facility to operation, it is planned to use at the first stage of coal-firing operation, instead of the steam generator and electrostatic precipitator, a simplified scheme for cooling and cleaning of outgoing gases which comprises a radiation chamber, a cooling system with water injection, a scrubber and a settling tank with a slag collecting bin. The bin capacity should be such as to provide for the removal of slag and seed for a period of about 10 hours. The cooled combustion products are then fed to the stack.

The coal-fired U-25G Facility will be equipped with a complete set of instrumentation enabling one to register all of the requisite operating parameters of the principal systems of the facility, carry out comprehensive investigations and perform the monitoring and control over the operating modes, as well as the emergency protection of the facility.

The modernized U-25G Facility should help to solve the entire set of scientific, technical and engineering problems associated with the development studies into the component structures and units under conditions close to the operating conditions of coal-fired commercial MHD power plants. The most essential of these problems include: a study into the operation of basic units and systems of the loop under conditions of continuous operation and high electric potentials for coal-firing conditions; a study and development of the optimum structures of MHD-generator components under conditions of MHD interaction, high electric fields (up to 2.0 kV/m) and marked influence of Hall effect, and a study of coal-fired MHD operation in the optimum and transient modes.

A sizable part of the Soviet R&D program for coal-fired MHD power plants is associated with research and development of fuel delivery systems and with the organization of fuel combustion. In addition to the work involving the complete-cycle U-25G and U-02-500 Facilities, it is planned to carry out a series of experiments using special flow trains of the Krzhizhanovsky Institute of Power Engineering at its experimental base in Kokhtla-Yarve (Estonia). Under development at IVTAN is a coal-firing facilities designed for studying the systems of fuel delivery, seed injection, as well as for development studies into coal-fired combustors, diagnostics of heterogeneous plasma, studies into the slag-seed interaction and purification of combustion products.

The Institute of High Temperatures of the USSR Academy of Sciences is carrying out extensive research into the development of solid fuel-fired MHD power plants in cooperation with the Kazakh Scientific-Research Institute of Power Engineering (KazNIIE). In 1980, design and manufacturing work was completed in KazNIIE on components of an experimental facilities designed for studying the processes of high-temperature coal combustion and development of combustor structures. Under construction in the experimental complex of the institute, including a coal dust preparation system and requisite auxiliary equipment, is a new facility rated for high-temperature combustion of about 500 kg of coal per hour. The facility will be used for studying the coal combustion modes, the various methods of injecting the ionizing seed into the combustor and the problems associated with slag removal from the combustor, as well as for developing the various combustor structures and elements.

It is also planned to use this KazNIIE facility for studying deposition on the heating surfaces, as well as for developing methods of cleaning the latter and for studying the corrosion and erosion processes occuring on metal heating surfaces. In addition, laboratory installations have been set up at KazNIIE for studying the aerodynamics of cold combustor models, laboratory studies are under way into the seed interaction with slag melts, work is going on aimed at developing a theoretical model of the working process in the combustor.

As already pointed out, the work aimed at developing MHD power plants characterized by direct coal combustion without slag removal is carried out in the Krzhizhanovsky Institute of Power Engineering (ENIN). The absence of slag removal from the combustor simplifies the solution to the problem of isolating the combustor from high electric potential, although such MHD power plants are less efficient from the viewpoint of thermodynamics.

Extensive R&D work is currently under way at ENIN, related to direct combustion of different coals; studies are conducted into the problems of heat- and mass transfer, slag formation on the heating and cooling surfaces, behavior of slag films in MHD channels. Some of the investigation results have been described in (Proceedings ..., 1980).

In parallel with the experimental research and development work, the overall program provides for theoretical studies into the various problems related to the development of coal-fired MHD power plants. These include studies into the thermodynamic, thermophysical and electrophysical properties of combustion products of the various grades of domestic coals, determination of the transport properties of slags and emissivity characteristics of surfaces coated with slag film, theoretical calculation studies of coal-fired MHD components, developing the methods of gas-dynamic calculations of flow trains as well as a technical and economic analysis of solid fuel-fired MHD power plants, including the schemes utilizing direct combustion, gasified solid fuel combustion and schemes involving the processing of fuel.

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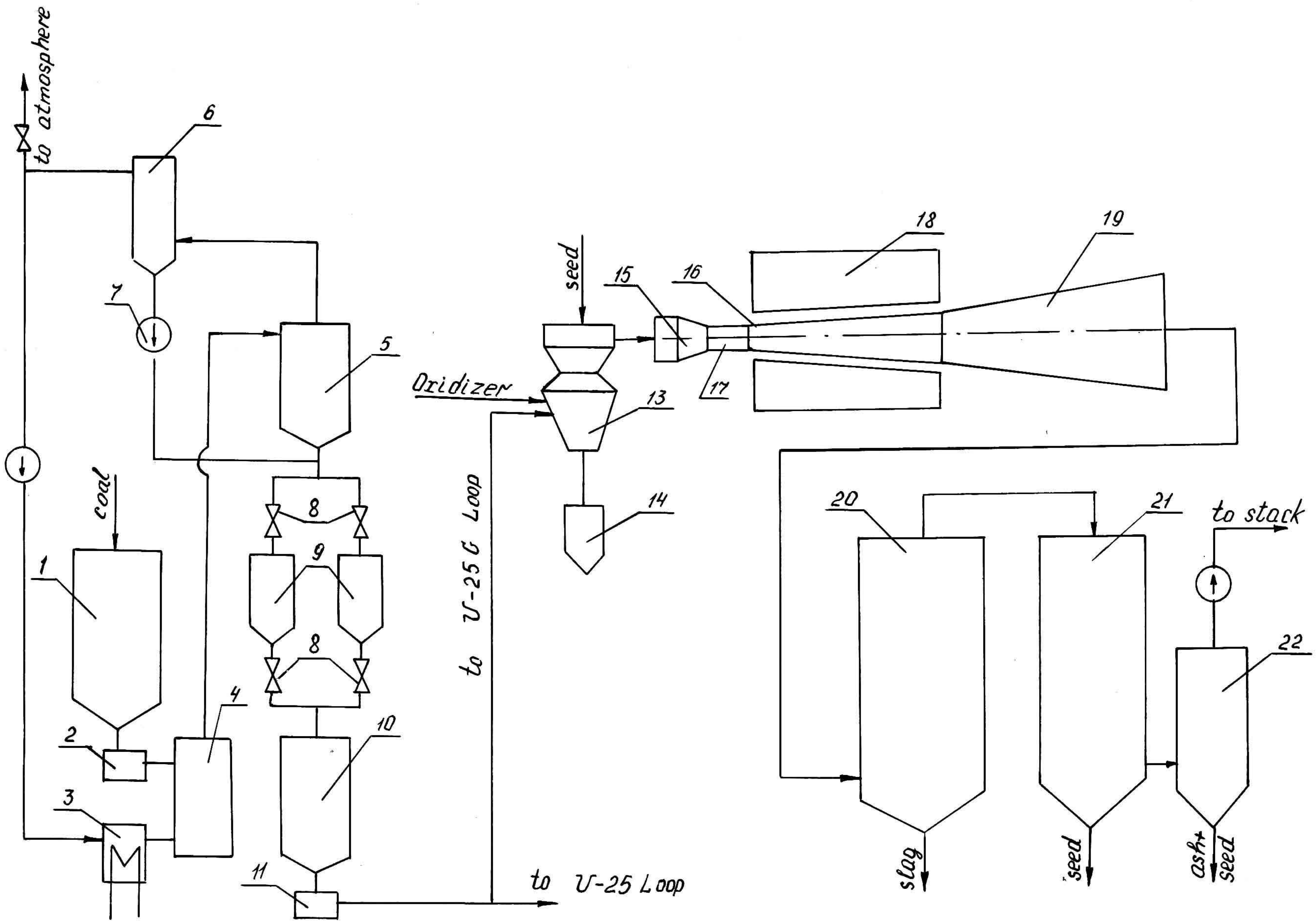

Fig. 1 A Schematic of the U-25G MHD Facility with the Pulverized Coal Preparation and Delivery System. Components are defined and discussed on page 3.

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Conceptual Design of 2,000 MWt Coal-Fired MHD Plant

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SUMMARY A conceptual design of the 2,000 MWt coal-fired MHD-steam combined power plant is presented. This design is based on the assumed matured technologies of the components and subsystems of the plant. Construction costs of the components and subsystems and cost of electricity are estimated for this plant and compared with those of a typical conventional coal-fired steam plant.

1 INTRODUCTION

The object of MHD national project in Japan is commercialization of base-load MHD-steam power plants. The R&D works for the oil-fired MHD plants had been conducted since 1966. Nowadays it becomes difficult to construct new oil-fired power plants because of the tense and unstable energy resources situation. A turning point in the MHD development strategy has come in our project. Now we are discussing a new program for the development of the coal-fired MHD power plant. As a part of the work, a conceptual design of 2,000 MWt coal-fired MHD plant has been carried out in order to evaluate the plant in the electric power system of Japan. This is the first detailed conceptual design of the coal-fired MHD plant in Japan, even through the detailed design work for oil-fired MHD plants had been conducted in our country[1) 2)]. The design is based on the assumed matured technologies of the components and subsystems of MHD-steam combined plant. The study aims to specify a advanced coal-fired MHD-steam combined plant and it will provide a guidance for the overall program.

The results of the conceptual design are discribed in this paper. In chapter 2, the component design and the system configuration are discussed, especially detailed discussions are given for slag rejection, seed recovery and NO_x control. The system performance is described in chapter 3, and the outlines which give bases of cost estimation for each components are described in chapter 4. In chapter 5, the results of cost estimation are shown and compared with a typical convensional coal-fired steam power plant.

2 SYSTEM CONFIGURATION AND DESIGN PARAMETERS

The system configuration which has been obtained as a results of this conceptual design are shown in Figure 1.

2.1 Coal

Japan has some reserves of coal but a little economically recoverable. Most coal used in Japan has been imported from foreign countries such as Australia, China, Soviet Russia and others. Most of the imported coal is now of fairly good quality because for convenience of ash disposal and transportation. Datong coal mined in China will be one of the most imported coal in future after about 10 years. Therefore, Datong coal is selected as a typical coal for the MHD-steam power plant.

The proximate and ultimate analyses of Datong coal with ash composition are given in TABLE I. The heat value of the coal is rather high and ash and sulfur contents are low. For the other coal of poor quality, ash and sulfur may be partially removed befor the combustion by a coal cleanning process like a oil agglomeration process. The oil agglomeration process combined transportation is attractive for Japan.

Datong coal as received contains about 10 % of moisture. The moisture reduces the electrial conductivity of the combustion gas due to the decrease of the gas temperature and the relatively large electron collision cross section of water vapor. So that the coal is dried to 2 % moisture content in pulverizing and drying processes, where the exaust gas of 310 °C branched from the waste heat boiler is utilized.

2.2 Air Heating System

The choice of air heating system is the most sensitive to the thermal efficiency of the open cycle

TABLE I
PROPERTIES OF DATONG COAL

Proximate Analysis (as received)			
Moisture	9.9 %		
Volatile	25.9 %		
Fixed Carbon	55.1 %		
Ash	8.1 %		
Heating value (as dry base)	7,450 Kcal/Kg		
Ultimate Analysis			
C	77.9 %	N	0.9 %
H	4.5 %	S	0.7 %
O	7.0 %		
Ash Composition			
SiO_2	47.61 %	SO_3	3.99 %
Al_2O_3	17.91 %	NaO_2	0.3 %
Fe_2O_3	19.41 %	Cl	< 0.02 %
CaO	5.48 %	F	< 0.01 %
MgO	2.05 %		

MHD-steam combined cycle. The direct regenerative air heating system is chosen for the advanced MHD plant because of its highest thermal efficiency, although the direct regenerative air heater is one of the components which need much development. The separately oil-fired regenerative air heater could be made in the state of the art, but the efficiency of the plant with this indirect air heating system is 3 or 5 % lower than the direct air heating system. The MHD power plant which uses the oxygen enrichment of the combustion air instead of the high temperature air heater can be a early realized power plant, but also with low thermal efficiency. The higher preheated air temperature, the higher thermal efficiency. The maximum preheated air temperature is assumed to be 1,500 °C considering the feasibility and the material development state of the air heater. Because of the reason related with slag rejection in a primary two-stage cyclone combustor (PCC), the temperature of the air is kept low 1,233 °C for the first stage of the cyclone combustor. The inlet air temperature of the high temperature air heater is chosen to be 700 °C in order to reduce the deposition of slag and seed in the heating matrix and to flow them out of the air heater. The great part of the compressed air which is heated to 700 °C through a low temperature metal tube air heater (MAH), is reheated to 1,500 °C through a high temperature regenerative air heater (HTAH). The air of 1,233 °C for the first stage of the cyclone combustor is made by mixing the air of 700 °C from MAH and the air of 1,500 °C from HTAM.

2.3 Slag Rejection and Seed Recovery

The seed absorbed chemically in slag may be a great part of losses in seed recovery process, because potassium extraction from the chemically bonded slag and seed is expected to be difficult. The seed should be put into the combustor after the slag is rejected out of the combustor as much as possible to supress to the seed loss. The slag rejection through the combustor depends upon the type of combustor and operating conditions. A two-stage cyclone combustor was selected for its high slag rejection ratio, and the rejection ratio has be assumed 80 ∿ 90 %.

In seed recovery and regeneration processes, consumptions of water, thermal and electrical energy and coal are relatively large, which may be a very important component that reduces the total efficiency of MHD-steam power plants. So that potassium carbonate, which is very soluble in water, is used as a seeding material to minimize consumptions of water and energy in the seed recovery process. The potassium carbonate is injected into the combustor as dry powder which is better than aqueous solution for the high temperature and the high conductivity of combustion gas. Seeding ratio was chosen as K = 1 wt % of the combustion gas in MHD channel. And also steam bleeding from high and intermediate turbines is utilized in the seed recovery and regeneration processes in order to minimize the reduction of thermal efficiency due to thermal energy consuming in the processes. Seed

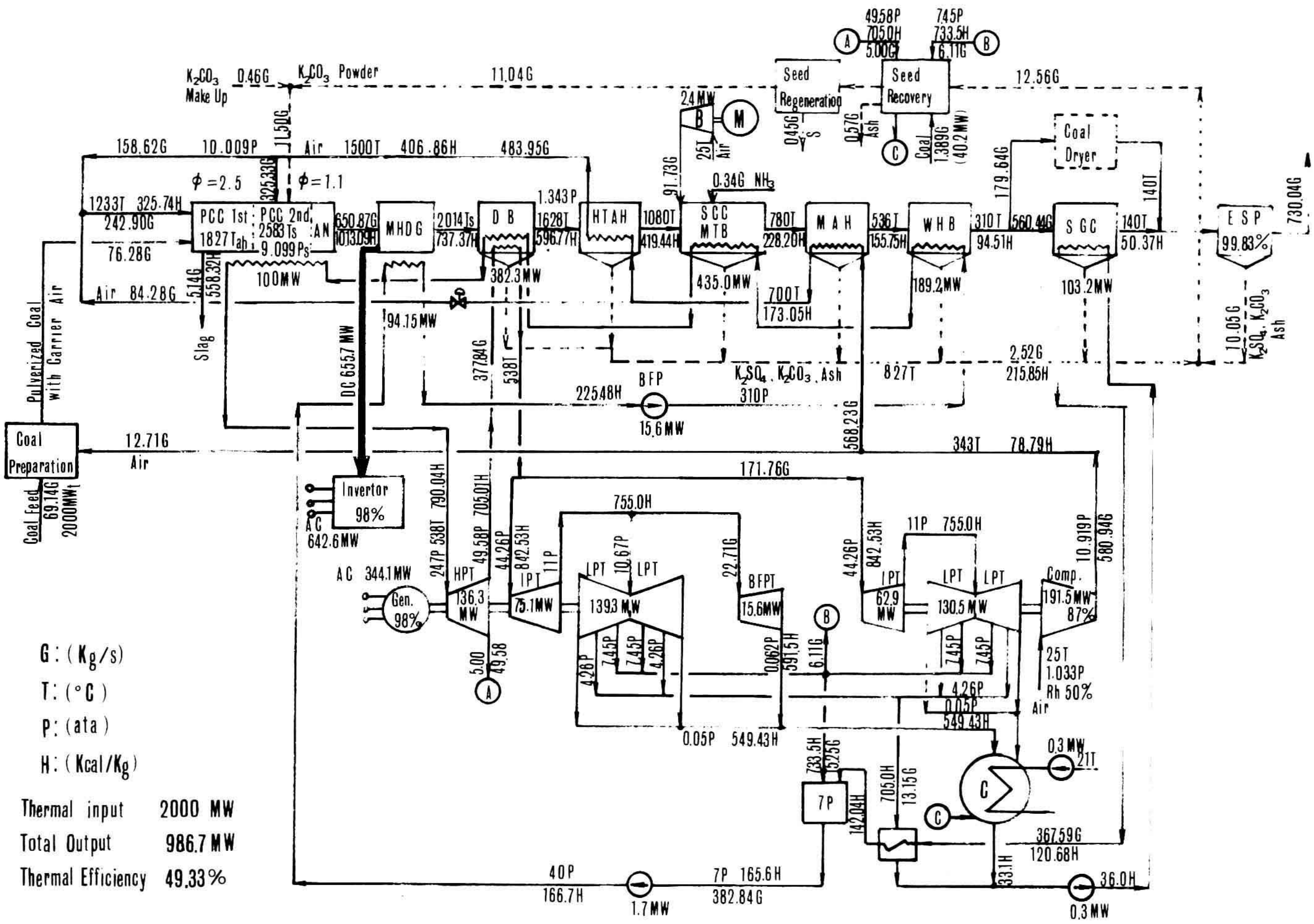

Figure 1 Schematic Diagram of the Optimized MHD-Steam Coal-Fired Power Plant.

losses in the combustion gas flow train and in the seed recovery and regeneration system must be restricted to economically and environmentally allowable limits. Seed recovery from stack gas is done by electrostatic precipitators (ESP). The seed recovery efficiency of the precipitators is 99.83 %, which has been determined by the environmentally acceptable dusts emission level of 30 mg/Nm^3 in stack gas. It is assumed that total 20 % of seed and slag contained in the combustion gas are removed through every kinds of boilers and air heaters.

We attempted to design conceptually a high temperature seed recovery device where the slag and seed contained in the combustion gas would be removed by cyclones at gas temperature between 850 °C and 1,200 °C. But high efficiency of the seed recovery was not attainable within acceptable numbers of the cyclones. Therefore it was given up to integrate the high temperature seed recovery device in the system.

2.4 Combustion System

In two-stage cyclone combustor it is important to know how much the coal slag vaporizes in the first stage of the cyclone. Vaporizing slag ratio to total slag in coal is shown against combustion temperature and equivalence ratio ($\phi_{F/O}$) in Figure 2. This is calculated for the combustion gas of Datong coal and air at combustion pressure of 10 atm by assuming phase and gas equilibriums[3]. And it is assumed that the components of solid phase and liquid phase of slag and seed cannot be soluble in each other. Coal slag becomes to vaporize with temperature rising beyond 1,800 ~ 2,000 K and almost slag vaporizes above 2,300 ~ 2,800 K, depending on combustion condition. To minimize slag evaporation, it is necessary to decrease combustion gas temperature. The equivalence ratio of the first stage of the cyclone combustor has been chosen as $\phi_{F/O}$ = 2.5 in order to decrease the combustion gas temperature without solid carbon formation. The adiabatic gas temperature in the first stage of the cyclone combustor is about 2,100 K where the slag vapor ratio is about 25 % in the equilibrium state. Actual evaporation of slag will be smaller than that of thermal equilibrium due to microscopic vaporization processes and lower gas temperature by heat loss. So that it will be reasonable to expect that the vaporizing ratio of slag is reduced to 10 ~ 20 %.

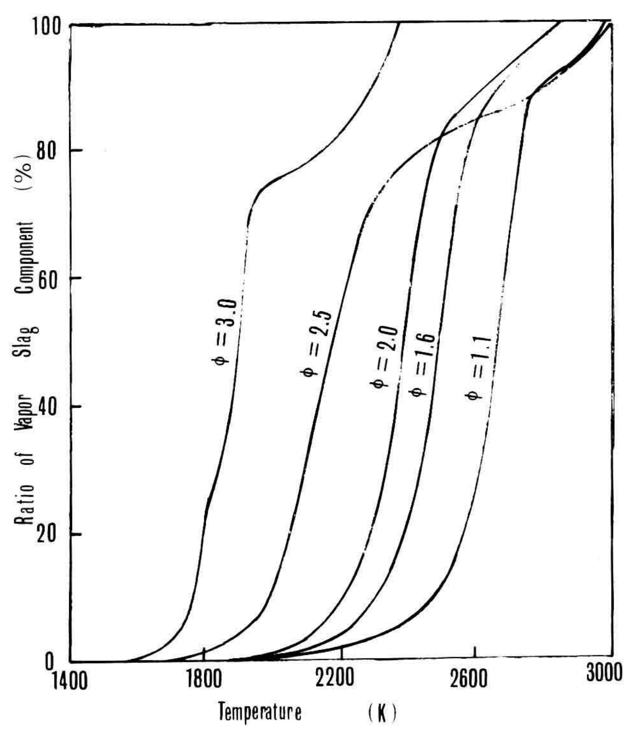

Figure 2 Variations of Ratio of Vapor Slag Component to Total Slag Content Against Temperature and Equivalence Ratio.

Seeding material is injected in the second stage of the cyclone combustor where secondary preheated air of 1,500 °C is introduced. The equivalence ratio of the second stage is chosen as $\phi_{F/O}$ = 1.1 in order to minimize NO formation and to increase dissociation rate of NO in a diffuser boiler. The total combustion reaction efficiency of the primary combustor is assumed to be 99 %. Unreleased heat of coal due to fuel rich combustion is recovered in a final secondary combustor (SCC) where secondary air is injected until $\phi_{F/O}$ = 0.95. The combustion efficiency at this stage is assumed 100 %. The secondary combustor is located in the temperature region in the flow train where complete combustion can be achieved without NO regeneration. Total heat loss in the primary combustor and the accelerating nozzle is sensitive parameter for MHD conversion efficiency. The total heat loss has be assumed to be 5 % of thermal heat input from coal according to estimation based on the conceptual design of the combustor and nozzle.

2.5 MHD Generator

Magnetic field generated by a superconducting magnet, is assumed to have a nearly flat distribution of average 6 Tesla. A segmented Faraday MHD generator with the magnet is considered in this design. The conditions of constant Mach number flow (M = 0.9) and constant load factor (K = 0.8) are assumed. The characteristics of the MHD generator are calculated using quasi-one-dimensional analysis taking into account of convective and radiative heat losses and friction loss[2]. Electrical losses due to gas boundary layer and slag layer on the generator wall and the losses related to inhomogeneous gas flow and segmented electrodes are taken into account in the calculation as decreasing of the effective conductivity of the combustion gas. Diffuser efficiency is assumed to be 80 %. The diffuser outlet pressure is a summation of pressure losses in downstream components. The pressure loss through the high temperature air heater may be large due to the deposition of slag and seed in the air heater. So that the diffuser outlet pressure is assumed to be rather large value of 1.3 atm. The experimental results by ETL Mark VI[4] and ref 5) support this assumption. Inverter efficiency is assumed to be 98 %, where power losses of auxiliary equipments such as control system and cooling system are taken into account.

2.6 Emission Control

Almost power plants recently under construction in Japan have to clear up much severer levels of the emission than the EPA standerds of Japan because of the strong social requests for the environmental protection. Therefore considerably low emission levels as shown in TABLE II are assumed in this report, which accord with the levels of a typical coal-fired power plant which has been constructed. Sulfur in the combustion gas will be completely recovered by the reaction with potassium which is injected about 6 times of stoichiometry.

TABLE II

EMISSION LEVELS FOR ENVIRONMENTAL PROTECTION

NO_x	<	60 ppm
SO_x	<	100 ppm
Dusts	<	30 mg/Nm^3

NO emission is controlled by the two stage combustion and the ammonia gas injection. Kinetic analysis of NO_x behavior in the system predicts that NO is reduced to 373 ppm by the gas phase reactions along the diffuser boiler (DB). After the diffuser boiler, decomposition of NO by the gas phase reactions is very slow in the downstream components without any countermeasure. It is known that ammonia injection is effective to decomposition of NO in combustion gas at adequate temperature[6). In order to decrease NO emission below acceptable level of 60 ppm, ammonia injection at 1,050 °C in mid temperature boiler (MTB) is planned. The ammonia is injected twice mol amount of NO flow. The temperature and the amount of injection were chosen according to the results of the basic experiment[6).
Dust emission is controlled by the electrostatic precipitators as described in 2.3.

2.7 Bottoming Cycle and Compressor

Bottoming steam cycle is a supercritical steam turbine system of 247 ata / 538 °C / 538 °C. The heat loss from the MHD generator wall is recovered with the boiler feed water which is pumped up to 310 ata after cooling the MHD generator wall. The heat loss from the main combustion chamber is used for the steam generation. An air compressor is driven by intermediate and low pressure turbines. The efficiency of the compressor is 87 %. The pressure losses of air heaters and the primary cyclone combustor are taken into account to decide the output pressure of the compressor.

Above-mentioned pricipal design parameters are summarized in TABLE III.

3 THE SYSTEM PERFORMANCE

The combustion gas properties, which are necessary for calculation of the performances of MHD generator and the other components, have been calculated by assuming thermal equilibrium of combustion components which consist of electron, 7 kinds of ions (K^+, OH^-, AlO_2^-, etc.), 45 kinds of neutral gas phase molecules (CO_2, H_2O, CO, etc.), and 20 kinds of solid or liquid phase molecules (C (s), K_2CO_3 (s, l), Al_2O_3 (s, l), etc.). Heat balance of the system has been obtained based on the calculation of MHD generator performance and the efficiencies of the other components taking into account of heat losses of the components. MHD channel design parameters such as channel length were optimized to maximize the thermal efficiency within acceptable costs of superconducting magnet and inverter taking into account of the engineering restrictions such as Hall field limitation. The efficiencies of a turbogenerator, steam turbines and feed water pumps were assumed to be normal values of conventional machines for the calculation of heat balance in the steam cycle.

The energy and mass balance of the optimized system is shown in Figure 1 and the principal performance data are shown in TABLE IV. D.C. power output of MHD generator is 655.7 MW, and inverted to 642.6 MW A.C.. The stagnation pressure at the outlet of main combustor is 8.81 atm and the driving power of compressor is 191.5 MW. MHD enthalpy extraction efficiency is 76.3 %. Total output from steam turbines including the compressor driving power is 531.8 MW and net turbo-generator output is 344.1 MW. Total output of the system is 986.7 MW and thermal

TABLE III

SYSTEM DESIGN PARAMETERS

Fuel	Datong Coal
Thermal Input	2,000 MW
Oxidizer	Preheated Air
Air Preheat Temperature	1,233 °C/1,500 °C
Fuel/Air Equiv. Ratio	
Main Combustor 1st	2.5
2nd	1.1
Secondary combustor	0.95
Slag Rejection Ratio	80 % to 90 %
Seed Material	K_2CO_3 Powder
Seeding Ratio	K = 1.0 wt %
Combustion Efficiency Main Combustor	99 %
Secondary Combustor	100 %
Mass Flow Rate	650.9 Kg/s
Magnetic Field	6 Tesla (average)
Diffuser Exit Pressure	1.3 atm
Diffuser Efficiency	80 %
Compressor Efficiency	87 %
Inverter Efficiency	98 %
MHD Channel Length	20 m
Stack Gas Temperature	140 °C
Bottoming Cycle	Supercritical Steam Cycle
Ambient Air Temperature	25 °C
Humidity	RH 50 %

TABLE IV

PRINCIPAL PERFORMANCE DATA

Thermal Input	2,000 MW
MHD Generator Output D.C.	655.7 MW
A.C.	642.6 MW
MHD Extraction Efficiency	25.52 %
MHD Isentropic Efficiency	76.3 %
Combustor Exit Total Pressure	8.81 atm
Compressor Driving Power	191.5 MW
Turbo-generator Output	344.1 MW
Total Generation Output	986.7 MW
Thermal Efficiency	49.33 %
Auxiliaries Power	18.9 MW
Net Plant Output	967.8 MW
Net Plant Efficiency	48.39 %