Cogeneration via Magneto-Hydro-Dynamic (MHD) Power Generator

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ABSTRACT

By passing the combustion gases through magnetic field, magneto generator converts heat directly to electricity power without moving parts. The inherent characteristic of high efficiency and low emission makes Coal fired electric power generation technology attractive to be a potential alternative power generation method in the future. This article presents the working principle of MHD generator and describes the coal fired MHD power plant systems and the key components in these systems. It also reviews the batch research of Department of Energy on coal fired MHD electric power generation—Proof of Concept Program from 1987 to 1993 and states some challenges remained on the way to commercial use.

INTRODUCTION

With intensifying attention worldwide to green effect and increasing restriction of emission of SO_X, and NO_X, high efficiency and low emission coal burning technology developed quickly in the past twenty years. Magnetohydrodynamics (MHD) power generation is among these new technologies and served this purpose very well. By passing the ionized combustion gases through a magnetic field to directly convert heat to electricity, the MHD power generator requires no rotation machinery or moving parts. Its specific structure makes it possible to reduce all kinds of mechanical loss and operate at very high temperature to achieve a high efficiency. The efficiency of a coal burning MHD power station can reach as high as 50-60 percent range [1].

Low emission is another attractive characteristics of MHD power plant. According to Attig et al [2], coal-fired MHD system is able to meet the current contaminant emission limits and even tighter pollution standards in the future. Attig et al [2] reported the emission of sulfur dioxide can easily reach well under 0.1 lb/10^6 Btu (<43ng/J) (0.6 lb/10^6 Btu) and Nitrogen oxide (NO_x) level can achieve less than 0.1 lb/10^6 Btu, when operating the primary combustor with a stoichiometry of about 0.85 and completing combustion at a temperature of 2500°F or lower. The effective control of pollutant is inherent in the operation of MHD generator. The seed material (potassium salt) is added to coal in the combustor to ionize the high temperature flue gas. The seed material combines with the sulfur dioxide in the combustion process and is removed by precipitator. After regeneration, the seed material is feed back to the combustor for reuse. Because of high efficiency, the MHD power plant can greatly reduce the emission of carbon dioxide per kWh electricity generation. Thus, use of MHD for power generation will significantly reduce the environment impact. The environment benefit and high efficiency of MHD technology make it prospective as an alternative coal fired power generation technology as well as fuel cell and IGCC.

The research of MHD for coal firing power plant began at 1960s. In the 1960s and 1970s much effect was focused on developing and testing individual MHD components at laboratory size test facilities. In the early 1980s, DOE began developing and testing MHD components at two large test facilities that were constructed in the late 1970s: CDIF and CFFF. CDIF, the Component Development and Integration Facility, is located in Butte, Montana and CFFF, the Coal Fired Flow Facility, is located in Tullahoma, Tennessee. In 1987, the plan of proof-of-concept (POC) of coal fired MHD electric power plants was carried out by DOE, which was ended in September 1993. The POC program's objectives are to test and demonstrate the proof-of-concept of 1. the topping cycle system; 2. the bottoming cycle system; 3. the potassium seed regeneration system; 4. the feasibility of retrofitting MHD power system to an existing power plant. In these years, the topping cycle was tested at CDIF, Montana facility, the bottoming cycle at CFFF, Tennessee facility, and the seed regeneration system at a TRW plant in California. Two retrofit studies were done on two commercial power plants in Florida and Montana respectively. Valuable data were obtained from these test, however, the reliability and stability are still remain unsolved. The cost effective is another important question.

This article will introduce the principle of MHD power generator; review the development of MHD technology, the system of coal fired MHD power plant and the challenges remained.

PRINCIPLE OF MHD GENERATOR

The phenomena of MHD electrical power generation was first recognized as early as the nineteenth century, when Michael Faraday (1791-1867) experimented with the generation of electricity by moving a fluid electrical conductor through a stationary magnetic field. It appeared in the patent literature from the early 1900s [3]. Theoretical work on cosmic problems and projects for thermonuclear generation of energy initiated interest in MHD in 1920-1950. Approximate calculations in the late fifties and early sixties indicated early success. Interest in MHD continued to increase since 1960s. It has special application in U.S. space program, power generation and defense. The research on coal fired MHD electric power generation started from 1960s.

The coal fired MHD power station exploits two fundamental principles: the Faraday effect and Carnot principle. The MHD generator uses flowing ionized flue gases as working fluid in magnetic field. However, the flue gases coming from the combustor do not become sufficiently ionized until they have attained temperature of the order of 80000K. Although, according to Carnot principle, the higher source temperature, the higher thermal efficiency of the system, the temperature resistance of material of combustor must be considered. To increase the conductivity of flue gases and reduce the temperature of combustion products, seed materials are added with coal in the combustion process. The alkali salts such as potassium and sodium salts satisfy the requirement of this task and usually be used as seed materials. The ionized flue gases leave the combustor at the temperature of 4600-4800°F (2538-2648°C) and are funneled through a channel containing electrodes and surrounded by a magnet that creates a magnetic field which is at right angles to the gas velocity. Faraday electric field is at right angles to both the flow velocity and magnetic fields (Figure 1). The interaction of gases and the magnetic field generates electric current which is extracted through the electrodes. If electrodes are placed on the two sides of the channel aligned with the electric field and connected through a load or resistance, current flows through gases, electrodes, and load. The exhaust gases leaves the MHD at a relatively high temperature (normally 3500°F). The heat of the exhaust gases can be recovered in the heat recovery area, which produces steam to power the steam turbine.

The principle of MHD generator is as shown in Figure 1. Ionized combustion gases flow with velocity U along X direction through a magnetic field B in Z direction. The electrical connection is in the y direction. The flow proceeding in a single direction can be modeled by a steady, one dimensional flow through a duct of cross section area A. On the basis of large characteristic dimension (i.e. small surface to volume ratio), the effects of friction and heat transfer can be neglected. According to Decher [4], the channel flow equations of the working gases are:

Mass Conservation: $$\frac{d}{dx}(\rho u A) = 0 \tag{1}$$

X Momentum: $$\rho u \frac{du}{dx} + \frac{dp}{dx} = j_y B \tag{2}$$

Y Momentum: $$\frac{dp}{dy} = \pm j_x B \tag{3}$$

Enthalpy: $$\rho u \left[\frac{d\left(h + \frac{1}{2}u^2\right)}{dx} \right] = j_y E_y + j_x E_x \tag{4}$$

j, Current density, is defined by the ratio of current per unit area; E, electric field density, is defined as a voltage applying over a distance $E = \pm \frac{\phi}{d}$;

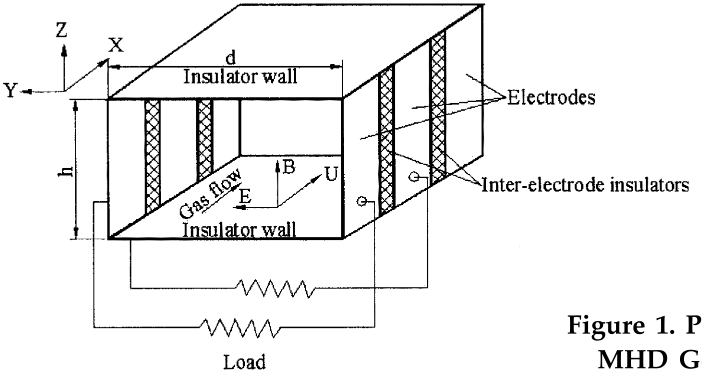

Figure 1. Principle of MHD Generator

B, magnetic field density; u, velocity of gas flow; P, pressure of the gas flow; h, height of the electrodes.

In the channel generator as shown in Figure 1, the current flow through y-z, electrodes and load. This device is termed as Faraday device. The group of governing equations is applied to a simplified situation where the gas is ideal, inviscid, and one-dimensional. The electric current flows uniformly from one electrode to another across uniform plasma.

The current density an be defined as:

$$j_x = \frac{\sigma}{1+\beta^2}\left[E_x \pm \beta E_y^{'}\right] \tag{5}$$

$$j_y = \frac{\sigma}{1+\beta^2}\left[E_y^{'} + \beta E_{xy}\right] \tag{6}$$

Where σ is the scalar conductivity defined as $\sigma = \frac{e^2 n_e}{m_e v_c}$ and β is the Hall parameter defined as $\beta = \frac{eB}{m_e v_c}$. v_c is collision frequency. The electric field E_y' is the field measured in the frame of the moving fluid and defined as $E_y' = E_y - uB$. E_y is the field measures in the stationary laboratory frame.

Inducing load factor K, $k = \frac{E_y}{uB}$, $E_y = kuB$, $K = 0$, at short circuit, $k = 1$ at open circuit. For the segmented electrode, the axial current j_x equals to zero. The equation (5) becomes $j_x = 0 = \frac{\sigma}{1+\beta^2}\left[E_x \pm \beta E_y^{'}\right]$

so, $$E_x = \beta E_y^{'} \tag{7}$$

The equation (6) becomes

$$\begin{aligned} j_y &= \frac{\sigma}{1+\beta^2}\left[E_y^{'} + \beta E_x\right] \\ &= \frac{\sigma}{1+\beta^2} E_y^{'}\left(1+B^2\right) \\ &= \sigma E_y^{'} = \sigma\left(E_y \pm uB\right) = \sigma uB(k \pm 1) \end{aligned} \tag{8}$$

Enthalpy equation (4) for segmented electrode generator becomes

$$\rho u\left[\frac{d\left(h + \frac{1}{2}u^2\right)}{dx}\right] = j_y E_y + j_x E_x$$

$$= j_y E_y = \sigma u B(k-1)\ E_y$$

$$= \sigma u^2\ B^2\ (k-1) \tag{9}$$

Equation (9) shows that the rate of energy removal (k<1) is proportional to the power density in the generator, $\sigma u^2 B^2$. The load resistance, through k, controls the rate of power removed from the steam with a maximum rate at $k = 0.5$

Equation (9) can be rearranged as (assuming removal of energy is positive)

$$\begin{aligned} &\pm \frac{j_y}{\sigma u B} \Sigma \frac{E_y}{uB} = \pm k(k \pm 1) \\ &\Rightarrow \pm \frac{j_y}{\sigma u B} = \pm(k \pm 1) = 1 \pm k \end{aligned} \tag{10}$$

$$\pm \frac{j_y E_y}{\sigma u^2 B^2} = \pm k(k \pm 1) = \pm \left(k \pm \frac{1}{2}\right)^2 + \frac{1}{4} \tag{11}$$

Basing on equation (10) and (11), the relationship between the voltage and current, and power output of segmented MHD generator can be obtained as shown in Figure 2 and Figure 3. The V-I characteristic is linear, while the power output is quadratic with a maximum at K=0.5.

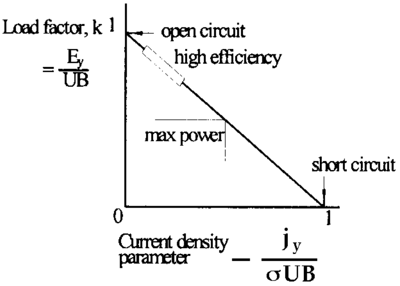

Figure 2. Voltage-current characteristic of a segment of a Faraday MHD generator (actually nondimensional E field and current density, source: literature [4] chapter 4)

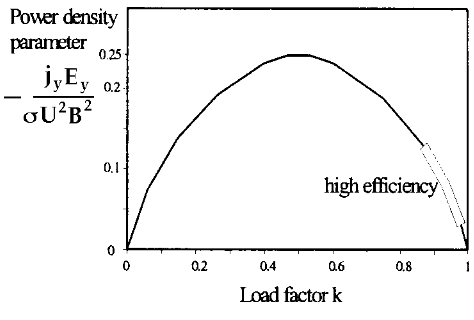

Figure 3. Power density parameter for a segmented electrode Faraday generator (source: literature [4] chapter 4)

COMBINED CYCLE COAL FIRED MHD POWER PLANT

In application to power generation, MHD generator can combine with various kinds of power conversion device to form different cycles. According to the end of the working fluid, MHD cycles can be divided as closed cycle and open cycle. In open cycle system, the working fluid is used on the once-through basis, while, in the close cycle system, the working fluid is recycled to the heat source. In the coal fired MHD power station, combustion gases are used as working fluid and the open cycle is an obvious choice. MHD generator can combine with gas turbine and steam system, air turbine and steam system, and conventional way—boiler and steam turbine system. The practical commercial application for coal fueled power plant is MHD generator combining with steam boiler and turbine system.

Because of the limitation of material temperature resistance and pressure, the performance development of steam boiler and turbine systems has reached its upper limits. It is hard for thermal efficiency of conventional steam power plant to excess of 40%. The MHD generator combining with the steam turbine system can improve thermal efficiency of power plant significantly. Cycle analysis has shown that the MHD combined cycles can achieve efficiencies in the range of 48 to 52% with preheat air temperature around 2700°F [3]. With the development of superconductor technology and other improvement in all aspects of MHD, the combined circle can raise this overall efficiency to beyond 60%. The electricity generated by MHD generator accounts for half of the total output of the unit in the first stage of this technology. The other half is balanced by the steam part of the cycle. The higher the share of the MHD generator, the higher the overall efficiency.

Typically, the MHD combining binary cycle has the system as shown in Figure 4. It consists of a topping cycle that is centered by the MHD generator and a bottoming cycle that is centered by a turbine generator. The diffuser connects the toping and bottoming cycle. In the topping cycle, coal and potassium seed material are fed to combustor and burned under the pressure of 5-10 atmosphere and temperature about 4600°F, which produce a product of high electric conductivity. The combustion gases can easily be ionized at the temperature above 4500°F when potassium salts are added. When the high temperature and relative high-pressure gases flow through the nozzle between the combustor and the channel, they are accelerated to a very high speed. The velocity of working gases can reach the range of 0.8 to 1.3 in Mach number. When the high speed ionized fluid flow through the magnetic field in the channel, the channel converts the thermal and kinetic energy of the combustion products directly into electricity. The electrodes at two sides of the channel extract the electricity. The gas flow is expended in the channel to overcome the decelerating effects from interaction with magnetic field. The gas flow expansion and energy extraction cause the temperature to drop. The diffuser is integrated with the channel to increase the energy extraction. Energy extraction is continued until the temperature becomes too low to have a useful electric conductivity. The temperature at the outlet of the diffuser is in the range of 3500°F to 4000°F[1], when the flue gases reach the radiant boiler. The exhaust gases have high heat energy content. This energy is extracted in the bottoming cycle by produce steam to drive the steam turbine, which is on the same shaft with a generator and compressor, to generate additional electricity and compress the air and oxygen needed to the required pressure for the combustion.

In the bottoming cycle, the initial heat extraction from the combustion gases is accomplished in the radiant boiler. Then the combustion gases go through the secondary combustor where the combustion process is completed. In the secondary combustor, the sulfur compounds derived with coal are converted to SO_X which reacts with potassium ion to produce K_2SO_4. This reaction reduces the content of SO_X in the combustion gases below the allowable level. The K_2SO_4 depositing in the combustor is collected and transmitted to seed regeneration plant. Coming out of the secondary combustor, the combustion gases flow through the steam super heater, reheater, air preheater and economizer. By preheating the air and oxygen to temperature of 2500°F-3000°F [5], the required high combustion temperature can be achieved. However, the air preheater must be high temperature refractory heat exchanger. The high combustion temperature can also be attained by enriching the combustion air with oxygen and preheating the oxygen enriched air to a moderate temperature. Low temperature gases flow through electrostatic precipitator or bag house where the particulates are removed. Seeds are separated with ash and regenerated.

As shown in Figure 4, the main components in topping cycle are combustor, nozzle, MHD channel, Superconducting Magnet, diffuser, power conditioning equipment (inverter) and feed system, while radiant furnace, secondary combustor, steam superheater, reheater, air preheater, economizer, ESP or Baghouse, steam turbine, generator and compressor

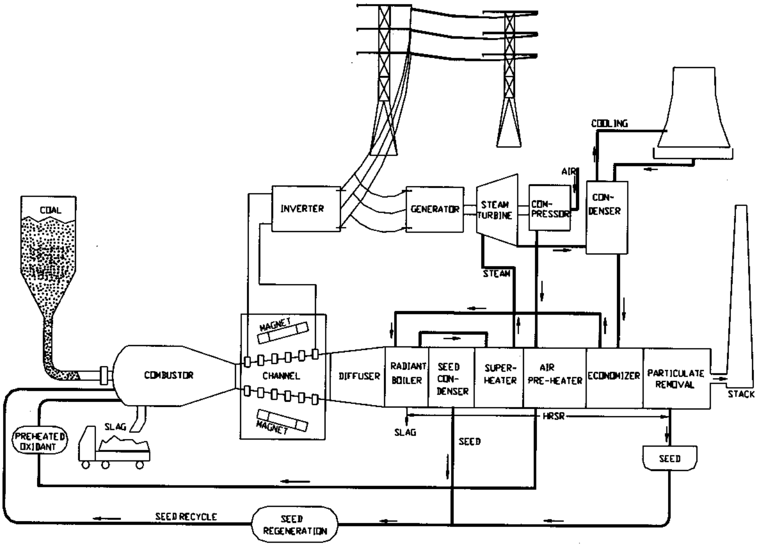

Figure 4. MHD Steam Power Plant System

make up of the bottoming cycle. The combined MHD power plant contains four chief systems: the topping cycle, the bottoming cycle, the seed regeneration plant, and the oxygen plant. The key components in MHD power and their function are listed as following:

Combustor

The function of the combustor is burning coal with oxidants and potassium salts efficiently and covert the mixture into uniform high temperature plasma with adequate electrical conductivity (6-10 siemens/meter). The combustor is operated in the temperature range of 4600°F to 4800°F under the pressure of 5-10 atmosphere. Because of contacting with MHD channel and high temperature, the combustor must withstand a environment of molten slag and high voltage of 20kv-40kv below ground potential. The ash rejected by the combustor must account for a large fraction (70%). Small fraction of ash rejection at the stage of combustor will make seed separation process less efficient and difficult.

Channel

The function of MHD channel is converting the thermal and kinetic energy of combustion products directly into electricity. The MHD channel is the most important component in the whole plant. The overall

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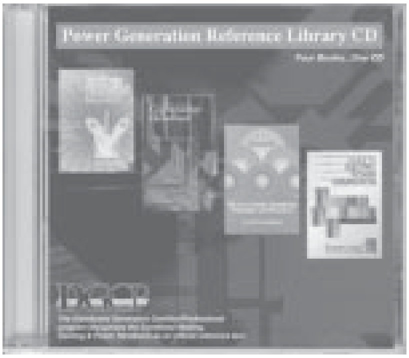

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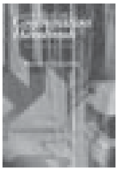

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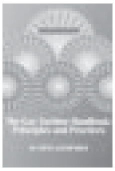

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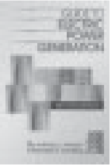

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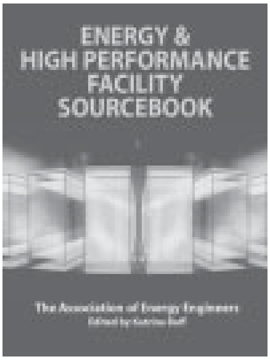
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efficiency of MHD power plant depends strongly on the level of the MHD channel performance. MHD channel is linear and can be configured in either segmented or diagonal mode. Lots work has been put into the research of MHD channel since 1970s. Many types of MHD channel have been tested and designed. The theoretic research is still on the way in the world.

Superconducting Magnet

Strong magnetic field is preferred, when an ionized combustion gas flow through a magnetic field to generate the electricity. Intense magnetic fields over large volumes are the primary condition to improve the MHD plant performance. The magnetic field required in a commercial plant is 4.5-6.0 tesla. A conventional magnet would require too much electric power to generate such tense magnetic field to be operated efficiently. To be economical, in the commercial MHD power plant, the use of Superconducting Magnet is necessary, although most MHD channels have been tested with conventional magnets. The structure of Magnet used in MHD power plant is huge. External dimension is more than 15 meters in diameter and 20 meters in length depending on the capacity of the topping cycle, reported by Kessler and Hals [5]. In order to maintain the superconductivity of the wire, the internal temperature must be kept as low as 40k. The device must withstand the extremely temperature difference between inside of the diffuser (4600°F-3700°F) and super conductive wire (40k) without excessive heat loss and can sustain mechanical loads imposed by magnetic fields. Engineering design of such structure is difficult.

Diffuser

The functions of diffuser are increasing the power extraction from the working gases and reducing the pressure at the exit of the channel. The working gases expand in the diffuser. The velocity of the working gases is reduced by diffuser and the momentum is converted into static pressure. The diffuser works under the condition of high temperature and both supersonic and subsonic flows inside. The design of the diffuser is often integrated into the part of the channel.

Inverter

Inverter is a power-conditioning device which is necessary between the channel and the transmission grid. The direct current output of an MHD generator must be converted to high quality AC efficiently before put into commercial power grid. Usually, a large MHD channel includes hundreds of pair of electrodes. Each pair of electrodes has two terminal and different potential voltage output. The power conditioning system collects and consolidates the direct currents from all terminal pairs of electrodes and transmits them to main load inverter. The output of the inverter must be stable under the condition of fluctuation of MHD generator and change of grid load.

Radiant Boiler

The radiant boiler is the beginning of steam bottoming cycle. The radiant boiler has two functions. The first is recovering the heat from the exhaust gases from the channel to produce steam. The second is providing sufficient residence time of at least 2 seconds for NO_x to decompose into element nitrogen at a temperature of 2800°F. The temperature at the exit of the channel is between 3500°F and 4000°F. High temperature resistive material is required for the tube in such boiler. High radiant heat transfer rates are also required to achieve a high efficiency.

Secondary Combustor

In order to control the generation of NO_x, coal is burned in a fuel rich environment in the combustor. The combustion processes is finished in the secondary combustor where the air is refilled. The sulfur compounds deriving from coal are burned in this stage and converted to SO_X which reacts with potassium to produce K_2SO_4 which deposits and is collected and delivered to seed generation plant. The secondary combustor must withstand high temperature and provide enough residence time for sulfide conversion.

The Other Heat Recovery Device

Besides radiant boiler and secondary combustor, the heat recovery system in MHD power plant also includes steam super heater, steam reheater, air preheater, economizer et al. The steam super heater is a key device in the HR system. Because of interaction with corrosive potassium compounds, the tubes of steam superheater and reheater must be corrosive resistive steel and can withstand metal temperature of 800°F to 1300°F and fire-side temperature of 2900°F. Appropriate material with high heat transfer coefficients and thermal resistive are required to design such heat exchanger.

Seed Regeneration System

Seed regeneration system collects seed materials under secondary combustor and ESP or baghouse, regenerates these material then feed them into combustor again. Seed material must be reused in order to make MHD generator operate cost effectively. Seed regeneration plant can operate separately or integrate into the power plant system. Studies have shown that integration seed regeneration system is more cost effective. Cost of seed generation system is also a barrier which impedes putting MHD power plant into commercial use.

Air preheater

Air preheater preheat air or oxygen-enriched air for the oxidant need in combustor and secondary combustor. In the past experiment project, the temperature of the tube is in the range of 1300°F to 1200°F. High oxidant temperature (2500°F-3000°F) is preferred to achieve high efficiency of the mature technology of MHD. The exhaust gas directly from the MHD generator will be used to heat the refractory heat exchanger in advanced design of MHD power plant. Although lots of research work has been done and progress has been made, there is still a long way to go before this high temperature air heat exchange is put into practice.

MHD process can achieve the control of SO_X very well. One expected goal of commercial MHD power plant is that this type of power plant can burn a wide range of coals especially those with high sulfur levels. According to Attig, et al [2], the emission of particulate and SO_X can be controlled to levels well below New Source Performance Standards (NSPS) for utility boilers. Because of a strong chemical affinity, the potassium seed material can easily combine with sulfur to form potassium sulfate, part of which condenses in the secondary combustor, the rest of which is collected by particulate removal equipment such as ESP or baghouse. The mixture of ash and potassium sulfate is sent to seed regeneration plant where the ash and sulfur are removed. Potassium in the form of formate or carbonate is recycled to combustor.

Control of NO_x is a challenge for MHD power plant, but this problem is solved by a two-stage combustion process. The first stage combustion happens in the MHD combustor in a fuel-rich environment. The temperature in this stage can be as high as 4600°F. The uncontrolled combustion can result in equilibrium NO_x levels of up to

10,000ppm by volume [2]. Operating the MHD combustor with a stoichiometry of about 0.85 can greatly reduce the level of NO_x. The secondary combustion takes place in the radiant boiler which provides enough residence time at a temperature above 2800°F to allow NO_x to decompose into N2 and O2. The cooling rate of exhaust gases in the radiant boiler is an important factor in the decomposition processes, which can be achieved by appropriate design of radiant boiler.

PROOF OF CONCEPT PROJECTS OF DEPARTMENT OF ENERGY

The research on the components of MHD was initiated in 1960's. The efforts of research in United States began to focus on coal fired, open, combined cycle power generation apparatus since 1973. In 1984, tests with coal at the Component Development and Integration Facility (CDIF) were started when the first stage of a 50MWt two-stage combustor developed by TRW, Inc. was installed. In August 1985, the integrated topping cycle achieved 1.5 MWe power generation. In September 1986, the integrated topping cycle was operated successfully for 8.5-hour continuous test and the power was transmitted to the grid via an inverter supplied by Electric Power Research Institute [EPRI]. The Proof Of Concept [POC] or reliability program [5] was implemented by the U.S. Department of Energy (DOE) in 1987, which was ended in September 1993. Hardware development and extensive research needed to complete the POC program were initiated at the beginning of 1988. The purpose of this program was to establish an engineering database which could be used for private sector to evaluate the risks and benefits of the technology before making decision to pursue developing and using MHD technology at new or existing commercial power plants. The Proof-Of-Concept program focused on performance and lifetime of major components and subsystem. Extensive tests were carried out and knowledge about coal fired MHD was enhanced by this program. There are four chief elements in POC program as shown in Figure 5 [6].

1. The integrated topping cycle program—Develop technical and environment data for the integrated MHD topping cycle system through long duration (1000 hours) testing at CDIF.
2. The integrated bottoming cycle program— Develop technical and environment data for the integrated MHD bottoming cycle system

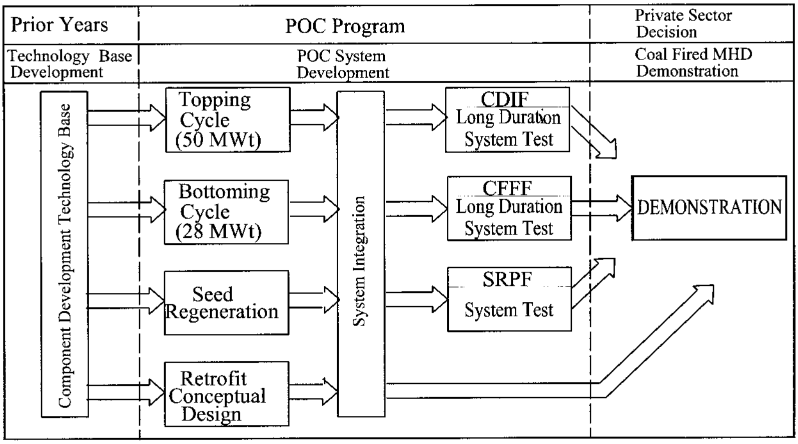

Figure 5. MHD Proof of Concept Program Structure

through long duration (4000 hours) testing at DOE's Coal Fired Flow Facility (CFFF).

3. The seed regeneration system—Design, construct, and operate a seed regeneration POC facility (SRPF) capable of processing spent seed materials from the MHD bottoming cycle.
4. The conceptual design program—Prepare a conceptual design for retrofitting MHD to an existing coal fired plant.

The major tests were done at DOE's two test facilities: Component Development and Integration Facility (CDIF) in Butte, Montana, which is responsible for testing integrated topping cycle at 50 MW (thermal); Coal Fired Flow Facility (CFFF), in Tullahoma, Tennessee, which is responsible for testing integrated bottoming cycle at 28 MW (thermal). The CDIF has a complete coal fired power train including a 3 tesla iron core magnet and an inverter. The CFFF has a complete HRSR system fired by coal fired flow train without magnet [5].

The Integrated Topping Cycle Program

The objective of the integrated topping cycle program is to accumulate technical and environment data by testing full-scale, ready for commercial use hardware such as combustor, nozzle, channel, magnet, diffuser and power conditional device for 1000 hours. MHD topping cycle components installed at Montana facility were designed to operate for 2000 hours. The output of the complete power train is 50 thermal megawatts.

In 1987, the contract of integrated topping cycle was awarded to a team headed by TRW, Inc., Redondo Beach, California, which was responsible for the coal-fired combustor and integration of overall effort. Textron Defense Systems (TDS), formerly Avco Research Laboratory was in charge of development of the nozzle, channel, diffuser and the power conditioning equipment. Westinghouse Electric Corporation supplied current consolidation equipment for the channel. These two companies are subcontractors to TRW. The combustor and channel were tested respectively at test sites of TRW and TDS before they were delivered to CDIF site.

The prototypical devices for the topping cycle system were installed at CDIF in June 1992 and the duration testing of the device and system were initiated in October 1992 and ended in September 1993. In this year, 600-hour [7] tests were conducted and valuable data were collected. Because of delays in the development and procurement of hardware, the experiment hours were 400 hours shorter than planned. The topping cycle successfully generated 1.5 megawatts of electrical power as expected. 200 hours of originally planed high sulfur coal tests were not carried out because of postpone of the schedule. The data obtained in 600 hours of testing the integrated topping cycle may not be sufficient to demonstrate the durability of the MHD generator and other critical components.

The Integrated Bottoming Cycle Program

The integrated bottoming cycle program is aimed at providing data on durability and performance of components of heat recovery and seed recovery systems, the HRSR in the bottoming cycle. The functions of bottoming cycle are heat recovery, which is steam generation and air preheat, removal of spent seed, ash and slag, cleaning and treatment of the flue gas. This program was conducted at Coal-Fired Flow Facility in Tullahoma, Tennessee. The University of Tennessee Space Institute was the contractor of the integrated bottoming cycle and was responsible for operating the CFFF for the Department of Energy. Babcock and Wilcox Corporation was a consultant for this program. Supplemental material test data were provided by Argonne National Laboratory.

The CFFF was fired by a coal fired flow train rated at 28 thermal Megawatts. The CFFF became operational long before the beginning of POC program in 1982. The efforts were focus on assembling and testing the subsystem components such as radiant boiler, steam superheater, and air preheater over the next several years. Preliminary data on NO_x and

SO_X control, interaction of seed with coal ash and slag products were also obtained in this period. By 1985, all major system including a baghouse and electrostatic precipitator had been installed and preliminary tested, according to Wright [6].

The goal of POC program was duration tests on two types of coal for 4000 hours. 2000 hour tests were scheduled on Montana Rosebud, which is a representative low sulfur western coal, and 2000 hour tests on Illinois No. 6, a representative high sulfur Eastern coal. The data of operational characteristics, reliability, maintainability and materials performance applicable to commercial MHD bottoming cycle system were expected to establish. This facility had completed the 2000 hours of testing Illinois No. 6 coal but completed only 1400-hour tests of Montana coal, 600 hours shorter than planed, because of a shortage of funds. According to Attig et al [5], the technology of open cycle, coal-fired MHD system demonstrated the ability to meet current contaminant emission limits and ever tighter pollution standards. The tests that have been done have provided extensive data on heat transfer characteristics of materials to be used in an MHD bottoming cycle facility and also provided useful data on the mechanisms for removing ash deposits and effective ways to control particulate emissions. However, the data obtained from 1400 test hours on Montana coal may not be sufficient enough to direct the design of future MHD equipment [7].

The Seed Regeneration System

The objective of seed regeneration system in POC program was trying to find an effective and economic way to regenerate seed material by experiment verification. The regeneration process can be used for the first commercial MHD power plant. This program was developed in two phases. In phase one, three participants, Babcock and Wilcox, the UTSI, and TRW, Inc. carried out batch scale research respectively and assessment of the cost of their specific procedure. The optimum procedure based on cost, schedule and performance estimates for POC program and 300 MWt scale MHD plant was selected to access to the Phase two which includes the design, construction, and operation of a POC plant to confirm the viability and feasibility of this procedure. TRW, Inc.'s Econoseed process, which was based on the conversion of the recovered potassium sulfate seed to potassium formate by reaction with calcium formate, was selected to the second phase in 1989. TRW completed detailed design and construction in 1991. During 1991 and 1992, TRW used this system to process 17.5 tons spent seed collected by CFFF during bottoming cycle testing Illinois high sulfur coal. About 12 tons of regeneration seed were shipped to CDIF for use in some topping cycle tests. According to literature [7], the TRW seed regeneration system performed adequately for a first-of-its-kind system, but the cost effectiveness is a major problem when this procedure is put into practice in commercial projects.

The Retrofit Conceptual Designs

Study has shown that using MHD technology in retrofitting the existing power plants is the most economic way in the first step towards commercialization of this technology. Retrofit conceptual design of two existing commercial power plants is one part of the POC program. Retrofitting an existing power plant by MHD can make use of many existing equipment and systems including steam turbine, generator, parts of cooling system, cooling water system, waste handling system and electrical transmission system and the site etc., which are considerate cost if new plant is built from the ground up.

The MHD retrofit conceptual designs included designs of two projects. One was based on Montana Power Company's Corette plant in Billings, Montana, which was under the design of the MHD Development Corporation, Butte, Montana. The other is Gulf Power's Scholz plant located in Sneads, Florida, which was designed by Westinghouse. While neither of these conceptual design of retrofit projects were put into actually construction, the design study gave valuable guidance in designing components for the future scale-up commercial size. Both the conceptual designs were done in 1989 and updated with the progress of the other part of POC program.

The Corette plant has a net electrical power output of 150MWe and burns Montana Rosebud Coal. Design of Retrofit project aimed at increasing the net electricity generation to 188MWe. The MHD channel added 28MWe, and the steam bottoming cycle added 78MWe. The steam generated by the bottoming cycle is sent to the existing turbine to generate electricity. The existing steam plant produced 107MWe, while 25MWe power is consumed by the whole plant itself. The electricity generated by MHD is transmitted to existing transformer station. The design parameters are shown in Table 1 [6]. The retrofit projects represent five-time scale up and is about half the size of the expected commercial MHD plant. Walter and Labrie [8] reported the design of Corette plant retrofit in detail.

Table 1. Corette Plant MHD Retrofit [6]

Location	Billings, Montana
Owner	Montana Power Company
Coal	Montana Rosebud
Coal Thermal Input In MW	556
Combustor Operating Pressure in bars	5.1
Oxygen Enrichment in mole %	38
Oxidant Preheat Temperature in °K	922
Power Generation in MWe	213
MHD Generator in MWe	28
Heat Recovery (MHD) in MWe	78
Turbine-Generator in MWe	107
Power Consumed in MWe	25
Retrofit Power Plant output in MWe	188
Existing System Power Output in MWe	166
Retrofit Plant Thermal Efficiency	34
Existing Plant Thermal Efficiency	31

The 50 MWe Scholz plant would produce net electricity of 60 MWe after the retrofit according to Westinghouse's study, reported by Lance et al [9]. MHD will add 24 MWe of gross electrical power while 14MWe power is consumed by the whole power plant itself. The plant efficiency will increase from 28% to 31% by the retrofit. The retrofit design parameter is shown in table 2. The retrofit Scholz plant will meet all environmental requirements.

Table 2. Scholz plant MHD retrofit [6]

Location	Sneads, Florida
Owner	Gulf Power Company
Coal	Illinois No. 6
Coal Thermal Input In MW	192
Combustor Operating Pressure in bars	6.1
Oxygen Enrichment in mole %	40
Oxidant Preheat Temperature in °K	1061
Power Generation in MWe	74
MHD Generator in MWe	24
Turbine-Generator in MWe	50
Power Consumed in MWe	14
Retrofit Power Plant output in MWe	60
Existing System Power Output in MWe	49
Retrofit Plant Thermal Efficiency	31
Existing Plant Thermal Efficiency	28

The Proof of Concept Program lasted for six years, which was ended at September 30, 1993. Department of Energy had spent $223 million in appropriated funds under the POC program. While most of the test goals were reached, the long-term high-temperature component reliability and durability required for commercial application are still in question. A demonstration MHD project proposed by a consortium of private companies was not selected as one of five demonstration projects in 21 other project proposal by the Department of Energy in May 1993, because some high competitive coal based technologies which showed better commercial perspective accounted for all founds available. In 1994, Department of Energy began the shutdown and wrap-up of the POC program.

INTERNATIONAL RESEARCH ABOUT MHD TECHNOLOGY

Since 1970s, many countries have been active in MHD technology development with varying scope and depth. These countries offer their comments in international liaison meetings which are regularly hold around the world. These countries which made major efforts include U.S., Russia, Japan, Italy, China, and India. Most of the countries put their efforts on open cycle combustion gas systems. Among these countries, Russia and India carried out their research and development on gas fueled topping cycle. China emphasized on coal fired topping cycle. Japan has broad, basic studies in a wide spectrum of MHD technologies.

The research projects in U.S. and former U.S.S.R had received significant funding support. These projects in both countries have been closed down. U-25 in former U.S.S.R was the largest MHD test facility in the world, which was fueled by nature gas. This facility, the thermal input of which is 150 MWt, included a topping cycle and a bottoming cycle. U-25 provided 25MW electricity to Moscow power grid for several years.

Japan own several test facilities for the purpose of experimental research work, including Mark □ through Mark VII, Fuji- □, Fuji-II and other facilities. The study and technology development is still going on in Japan, but the emphasis is on the research of MHD generator and basic plasma theories.

TECHNICAL RISKS AND OPPORTUNITIES

The inherent characteristics of high efficiency and environmental benefit of coal fired MHD technology make it attractive as a power generation method. Although Proof of Concept projects and experience in other counties showed that there is no major technical barrier in developing MHD technology for commercial use, the technology requirements of coal fired MHD are rigorous because most of the components in topping and bottoming cycle operate in an environment of very high temperature. The achievement of high efficiency still depends on the development of other advanced technologies such as normal temperature superconductive material, high temperature heat exchanger and ultrasupercritical steam generator. According to Kesseler and Hals [5], the first stage commercial MHD plants scaled at 212-492MWe would be expected to obtain 40%-42% efficiency by using oxygen enriched air with moderate (1200°F) preheat temperature as the oxidant. To achieve 55-60 percent efficiencies, there is still a long way to go. The technical issues remained in coal fired MHD technology need to be solved as following:

1. Development of high temperature heat exchanger to preheat the combustion air to over 2500°F (1370°C). Although lots of research work has been done, there is still a long way to go before it can be put into practice.

2. Cost effectiveness of seed regeneration process is an important factor, which will affect the commercialization of coal fired MHD technology. TRW, the contractor of seed regeneration system in POC program, estimated that the cost of seed regeneration in an MHD power system using high sulfur coal would be more than 20 percent of the average sales price of the electricity generated by the system. Low cost integrated seed regeneration system is necessary in the commercial plants, but only preliminary research has been done in this area.

3. Long time operation of high temperature channel has never been demonstrated. Developing and using high temperature resistive electrodes in the MHD channel are essential for durability of channel in commercial MHD plants.

4. Although the topping and bottoming cycle has been operated and tested in the POC program, the integrated plant has never been operated. Unanticipated problems may occur when two system are integrated together.

5. Control of slag removal in the MHD combustor is also a problem in the POC program. At least 50-70 percent slag need to be removed from the combustor in order to keep the stability of power generation of the channel afterward. The slag that leaves the combustor and goes through the channel absorbs part of the seed material. The conductivity of the combustion gases will be decreased by losing the seed material, which will reduce the output of electricity power of the channel.

6. Certain problems are likely to arise when the size and output of the components in the integrated system are scaled up. Demonstration projects are needed at each stage to minimize the risks.

Reference

U.S. Department of Energy, "MHD Program Plan FY 1990," DOE, October 1991, Washington, DC.

Attig, R.C., Crawford, L.W., Lynch, T.P., and Sheth, A.C., "Pollution Control and Environmental Monitoring Efforts at DOE's Coal-Fired Flow Facility," *Magnetohydroaynamic(MHD) Power Generation*, 1991. American Society of Mechanical Engineers. Winter Meeting (1991 : Atlanta, Ga.). AES-Vol. 23 P41-51.

Grundy, Robert F, *Magnetohydrodynamic Energy for Electric Power Generation* Noyes Data Corporation. 1978

Decher, Reiner, *Direct Energy Conversion, chapter 4*, Oxford University Press, 1996

Kessler, R. and Hals, F. "Coal-Burning Open Cycle Magnetohydrodynamic Power Generation," *Magnetohydroaynamic(MHD) Power Generation*, 1991. American Society of Mechanical Engineers. Winter Meeting (1991 : Atlanta, Ga.). AES-Vol.23 P29-39.

Wright, Robert J., The U.S. Department of Energy's Magnetohydrodynamics Proof-of-Concept Program, *Magnetohydrodynamics(MHD) Power Plant Retrofit Program*. American Society of Mechanical Engineers. Winter Meeting (1990 : Dallas, TX.). AES-Vol.17 P1-6.

U.S. General Accounting Office, "Fossil Fuels, The Department of Energy's Magnetohydrodynamics Development Program" Report to the Chairman, Subcommittee on Energy, Committee on Science, Space and Technology, House of Representative. July 1993

Walter, Fred E and Labrie, Robert J., "The J.E. Corette Magnetohydrodynamics (MHD) Report—A Conceptual Design," *Magnetohydrodynamics(MHD) Power Plant Retrofit Program*. American Society of Mechanical Engineers. Winter Meeting (1990 : Dallas, TX.). AES-Vol.17 P19-25.

Lance, J.R., Bibber, L.E. Van, Bernard, F.E., Holman, R.R., and J. Cuchens "Scholz MHD Retrofit—Gulf Power Company," *Magnetohydrodynamics (MHD) Power Plant Retrofit Program*. American Society of Mechanical Engineers. Winter Meeting (1990 : Dallas, TX.). AES-Vol.17 P13-17.