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Session Name: Status Reports on International Program

SEAM: 28 (1990)

SEAM EDX URL: https://edx.netl.doe.gov/dataset/seam-28

EDX Paper ID: 1379

RESEARCH ACTIVITIES OF MHD POWER GENERATION IN JAPAN

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Abstract

This paper describes the research activities of MHD power generation in Japan. Major facility for the closed-cycle MHD power generation is Fuji-I facility located at Tokyo Institute of Technology, where the enthalpy extraction ratio of 16 % is achieved in the blow-down facility with the disk and SCM (4.7 T) while 27 % is demonstrated in the shock tube experiment. A variety of activities of open-cycle MHD are carried out at universities and national research laboratories. A new facility of open-cycle is under construction at Hokkaido University, of which thermal input is 5 MW with the magnetic field of 2.9 T. The main source of funding on MHD power generation now comes from the Ministry of Education, Science and Culture. In addition, are introduced in the present paper, feasibility studies, fundamental experiments, generator designs, numerical simulations, mechanisms of arcing phenomena, power conditionings, control circuits, coal combustor, diagnostics, liquid metal MHD power generation and fusion applications.

I. INTRODUCTION

Studies of MHD power generation in Japan have been carried out for more than twenty years[1,2]. The MITI's National Project was the major activity, which was carried out mainly by Electrotechnical Laboratory (ETL) with the Mark I through Mark VII facilities. The project was terminated in FY 1988 after the objective of the project was attained with accumulation of test time of 430 hrs in oil burning and with some coal burning. On the other hand, a variety of activities carried out at universities under the Ministry of Education, Science and Culture have shown wide and active researches in the open-cycle, closed-cycle, liquid metal MHD generation, and fusion applications, resulting in new concepts of MHD generation.

The largest project grown from such efforts is the closed cycle Fuji-I project carried out at Tokyo Institute of Technology (TIT) which is sponsored by the same Ministry and electric power utility companies as well. They are proposing Fuji-II closed cycle system where continuous closed-loop and larger blow-down facility will be operated. The other example is the Advanced MHD Research Institute at Hokkaido University where a new 5 MWth facility is now under construction and planned to carry out the research of open cycle MHD generator with high performance. In addition many important but more fundamental researches have been made at universities such as Tsukuba, Toyohashi, Kyoto and Kyushu and also at national research laboratories such as ETL, Mechanical Engineering Lab. and Chemical Lab., including feasibility studies, fundamental experiments, generator designs, numerical simulations, mechanisms of arcing phenomena, power conditionings, control circuits, coal combustor, diagnostics, liquid metal MHD power generation and fusion applications.

II. CLOSED CYCLE MHD POWER GENERATION

2.1 Fuji-I Facilities

The Fuji-I blow-down facility located at Tokyo Institute of Technology is one of the most active facilities in the closed-cycle MHD power generation. Pebble bed heat exchanger of about 6 MWth supplies thermal energy to the MHD generator, which is Ar-Cs or Ar-K driven disk. The maximum magnetic field of 4.67 T is maintained by superconducting magnet. The experiments are financially supported mainly by the Ministry of Education, Science and Culture and partly by electric power utility companies.

The power output of 500 kW was obtained with the enthalpy extraction ratio of 15.6 %. The operation condition at this experiment was as follows:

Thermal Input	3.3	MW
Stagnation Temperature	1900	K
Stangation Pressure	0.64	MPa
Cesium Seed Fraction	$2.0\text{-}2.3 \times 10^{-4}$	
Magnetic Flux Density	4.3-2.7	T (1)

New experiments have recently been initiated, where helium is used instead of argon and over 25 % of enthalpy extraction is expected.

Shock tube experiments are also carried out both in disks and in linear Faraday channel to challenge the limitation of enthalpy extraction ratio. A recent run on He-Cs driven disk could demonstrate over 27 % enthalpy extraction and they are challenging 35 % with newly fabricated disk channel of only 2.7 T. A small Faraday channel driven with He-Cs has achieved about 18 % of enthalpy extraction, showing capability of the linear channel.

They also propose the second generation project of Fuji-II facility which will consist of larger blow-down facility and smaller full closed loop system. The former will be 100 MWth input, 1 minute blow-down generator with over 25 % enthalpy extraction ratio and 60 % isentropic efficiency, while the latter will be designed as the continuous operation loop with several MWth input. Disk generators are planned to be installed together with superconducting magnet.

2.2 Theoretical Works and Feasibility Studies

Computer simulations for disk generators are made by using time-dependent one-dimensional calculations at Kyoto university and TIT. Full interaction between gasdynamics and electrodynamics is taken into account together with relaxation effect without any modeling of plasma instability. Comparison with experimental results shows that even one-dimensional calculation can predict the generator performance when the interaction between gasdynamics and electrodynamics is taken into account, although agreement tends to degrade for higher load resistance, where the shock seems to be induced. A full time-dependent two-dimensional code is developed at Kyoto University, showing the shock behavior at high load resistance and the plasma instability at low load resistance.

A computer code which analyzes linear generators is developed at Kyoto University, where two-dimensional electrodynamics and time-dependent one-dimensional gasdynamics with assumed boundary layer are calculated with the relaxation effect. Comparison with the experiments made with shock tube He-Cs Faraday channel demonstrates good agreement, showing understanding of behavior of closed cycle linear channel. The calculation shows that discharge experiences the ionization instability and the fluctuation level is higher in the core region than the region near electrodes, which phenomena suggest that the uniform discharge is difficult to be realized in linear generators.

A coal-fired triple cycle with inert-gas MHD is studied under cooperation between TIT and Electric Power Development Company (Tokyo). Sulfur compounds and particulate are extracted from a combustion gas by using a clean up system located between a regenerative heat exchanger and a gas turbine. The cycle efficiency is expected to exceed 50 %. Another new system of MHD-gasturbine Brayton cycle for natural gas fuel is proposed at TIT, where the steam turbine is totally eliminated. A He turbine drives a He compressor and electric power is supplied from the MHD generator and the gas turbine driven by combustion gas coming from the regenerative heat exchanger. Studies show that the efficiency of the Brayton combined cycle exceeds 50 % and becomes higher than that of the triple cycle when enthalpy extraction ratio of MHD generator is higher than about 35 %.

Some study of power conditioning of closed-cycle has been carried out theoretically at Kyoto University and TIT. Line commutated inversion system is assumed and interaction between disk generator and inverter is investigated with time-dependent one-dimensional calculations.

III. OPEN CYCLE MHD POWER GENERATION

3.1 Advanced MHD Research Institute

New facilities are under construction at the Advanced MHD Research Institute of Hokkaido University. Cyclone type combustor will be operated with kerosene, oxygen and KOH (48 % aq.). A subsonic Faraday channel is fabricated, which consists of 32 electrode -pairs of 25 mm pitch. Cathodes are made of W-Cu, while anodes are SUS 304 with Sic Peg insulators. The main parameters are:

Thermal Input	5	MW
Mass Flow Rate	0.637	kg/s
Inlet Mach Number	0.8	
Total Length	120	cm
Active Length	80	cm
Magnetic Flux Density :		
Uniform B	2.5	T
Shaped B	2.9	T (2)

Besides this system, a 1.5 MWth splash-type plasma stand driven by ethanol and COM fuels and a 1 MWth ethanol comustion facility are operated mainly for material testing and diagnostics studies.

(1) Plasma and flow optimization study

The generator power density varies substantially with the combustion gas properties and the Mach number under a given combustor power. Equilibrium analyses for various fuels with possible additives and heat transfer analyses in the combustor and the channel are thus carried out, taking the radiation from solid particles into accounts.

(2) Magnetic field and channel optimization

Experimental and analytical investigations are carried out to demonstrate improvement of the performance by means of a two-dimensional, two-component B-field (the SFC-design), where the field strength near electrodes is reduced as low as possible. A shock driven SFC-type Faraday channel has been designed and tested, showing a significant increase of generated power. Further experimental investigation is planned on the new facility.

(3) Plasma fluctuation study

They investigate analytically and experimentally the influence of various correlations such as $<\sigma' E'>$ and $<\sigma' E'>$ between the fluid- and electrodynamical fields. The light polarization line reversal method is used for the measurement of temperature fluctuation.

3.2 Feasibility Studies and System Analyses

Preliminary but wide research of pilot plant of open-cycle MHD-steam combined system has been carried out at Kyoto University. The thermal input is about 100 MW, while the power output from the MHD channel is about 10 MW with 30 MW power output from the steam-driven synchronous generator. Preliminary designs of the Faraday and diagonal channels with subsonic or supersonic flow have been made. Study of dynamical behavior of the MHD-steam combined cycle is also carried out together with a variety of studies such as dynamical response of generators to the temperature fluctuation at entrance; interaction between MHD channel, synchronous generator and power grid through line-commutated or forced-commutated inverters; effect of short-fault at a single electrode pair of supersonic Faraday type channel; and three-dimensional interaction between gasdynamics and electrodynamics. Feasibility study of larger system is also carried out.

3.3 Coal Combustion

The Agency of Industrial Science and Technology (AIST), MITI, has promoted research and development of the coal fired open-cycle MHD power generation within a frame work of a comprehensive R&D programs for energy conservation which is called 'Moonlight Project'. This MHD project, initiated in FY 1984, came to an end successfully in FY 1988 with establishment of key component engineering technologies. The scope of the program includes coal combustor, generator channel and high temperature heat exchanger. Under the Program, a series of cold model experiments and coal firing tests for a candidate design of a two-stage combustor have been carried out jointly by Mechanical Engineering Lab. and ETL.

The two-stage combustor system consists of a slag tap cyclone combustion chamber which constitutes the first stage and of a high temperature combustion chamber of the second stage. The major feature of cyclone combustor is that three types of gas inlet nozzles are installed; i.e., swirl nozzle, cyclone nozzle, and coal nozzle. The high temperature combustor of the second stage has two secondary oxygen nozzles.

The cold model experiment provided some important results such as the conditions to form a stable recirculation flow in the cyclone chamber, the optimum design of pulverized coal nozzle, and the development of effective technique for the elimination of strong swirl entering the high temperature combustor from the first stage.

A two-stage combustor with rated thermal input of 1 MWth was designed and fabricated based on the cold model tests. During six runs of coal firing test, stable combustion was achieved from fuel lean to highly fuel rich conditions. The amount of unburnt carbon in the recovered slag was less than 1 %, and the slag recovery efficiency was estimated to exceed 80 %.

3.4 Coal Slag Studies and Arcing Phenomena

Arcing phenomena have been studied in Toyohasi University of Technology. One of their efforts has been focused on the effect of slagging layer on the arcing phenomena. Recently they have studied the effect of B-field on the movement of arc spots on the electrode with and without coal slagging layer. The experimental study clearly showed that the Lorentz force acting on the arc spots braked their movements. It was clarified that the B-field applied in the direction of accelerator mode could move the arc spots to the downstream faster than in the case of B-field applied as the generator mode. This suggests that if the magnetic field near the electrode surface can be reversed by some special magnet system, then the duration time of arc spots on the electrode is shortened and the electrode life time becomes longer. This results are compared with the theoretical values, resulting in reasonable coincidence.

Another effort has been focused on the transition mechanism of discharge modes. Recently, they have found very interesting phenomena by a sophisticated experimental system that the generation frequency spectrum of arc pulses has been clearly separated two modes at about 1 A/arc (micro-arcs) and 100 A/arc (big-arcs) and that no current pulse appears between them. The bifurcation mechanism between micro- and big-arcs is now intensively investigated experimentally and theoretically in order to find the way to suppress the formation of big-arcs in the MHD channel.

Numerical simulations of arcing and interelectrode breakdown are carried out at Kyoto University in cooperation with Yatsushiro National College of Technology. Time-dependent two-dimensional simulation codes are developed; one is for longer computation, which does not take the interaction between gasdynamics and electrodynamics into account, while another is for details, which includes the interaction. The calculation results done by the simplified model agree with the observed experimental data, showing periodic movement of arc spots on electrode surface. The detailed model can simulate the interelectrode breakdown. The intercathode breakdown is induced by the convection of hot gas over the insulator between adjacent cathodes, and the process is faster than the interanode breakdown which is induced by the extension of the load current over the insulator between anodes, which current is concentrated at the upstream edge of anode.

3.5 MHD Gas Flow

Two- and three-dimensional codes for the electrodynamics using finite element method(FEM), finite difference method(FDM), and equivalent circuit method have been developed at Kyoto University. The two-dimensional weak shock is calculated in the supersonic Faraday channel, which shock is induced by load shorting, where time-dependent, two-dimensional, compressible Navier-Stokes equations are solved together with the Maxwell equations. Three-dimensional gasdynamics codes have been developed with the parabolic assumption at Kyoto and Hokkaido University. The eddy-like secondary flow is induced in MHD channels by the three-dimensional MHD interaction.

Shock tube experiments have been carried out as well as numerical simulations at Kyushu University. The objective is to study gasdynamic characteristics in supersonic MHD generator, especially such as transient flow, effect of Lorentz force on plasma and shock wave formation in MHD channel. The color schlieren photographic method has been developed.

3.6 Power Conditioning

Many kinds of external circuits have been examined at Kyoto University for local control of MHD channel, including master/slave current control circuit, where transformers and GTO's are used and the switching frequency of GTO's is 1 kHz. In addition, electrical nonuniformities in the diagonal type generator are simulated with the equivalent circuit method, showing agreement between the calculation and the experiment in both wave length and magnitude of nonuniformities. It is demonstrated that the master/slave control circuit can suppress the electrical nonuniformities. Consolidation and shuffler circuits are also proposed and examined.

Interactions between MHD generator and power grid system have been studied at Kyoto University in cooperation with Kobe Technical College, including inverter, transmission line, synchronous generator, and infinite bus. Both line- and forced-commutation are analyzed, while many kinds of faults are investigated. Some faults result in that the MHD generator fluctuates violently and a large influence is given both on the synchronous generator and on the power transmission line in the case of line-commutation, whereas the disturbance becomes much smaller in the case of forced-commutation.

3.7 Measurement

Laser-aided diagnostics to measure the plasma parameters in the MHD field are developed at Kyushu University.

(1) Boundary layer phenomena

Potassium density profile around electrodes is studied using a line-absorption method and a computer simulation. It is found that nonequilibrium phenomena become important due to transport of potassium compounds and their boundary condition. Potassium density is enhanced in the neighborhood of electrodes in the presence of diffusive current.

An interferometer method for temperature measurement of a small arc has been developed. This system is provided with two lasers, two CCD cameras and a personal computer to detect fringe shifts. A preliminary experiment shows that this method is applicable to an arc of the order of millimeters in diameter.

(2) Fluctuation measurements

A method was established, which can measure simultaneously the electron density and conductivity by using a far-infrared laser. The Michelson interferometer was modified to give simultaneously the fringe shift and the laser beam absorption, while the performance of this interferometer system was proved by the experiments.

The above method was applied to fluctuation measurements. To obtain high temporal resolution, the detectors of the far-infrared laser interferometer were replaced by the Schottky barrier diode. This diode was tested with the Michelson interferometer, and the fluctuation of electron density was measured. This system is currently being extended to the simultaneous measurement of the electron density and conductivity.

IV. OTHER MHD ACTIVITIES

4.1 Liquid Metal MHD Studies

Fundamental research of the two phase liquid metal MHD power generation is carried out at Kyoto University and Tsukuba University. Numerical study of liquid metal MHD flow has been initiated at Kyoto University.

4.2 Pulsed MHD Generator

The explosive MHD generator is studied in National Chemical Laboratory For Industry, Tsukuba as a part of project of Explosive-Driven Pulsed Electric Generators. High explosives have an available energy of 4 – 8 kj/kg and can liberate the energy in a time of $10^{-5}-10^{-6}$ sec through a rapid reaction (detonation). Explosives are very useful for pulsed power energy source. The laboratory conducts basic research on explosive generators which convert the explosive energy to electric energy. Two types of generators have been developed in this project; i.e., magnetic cumulation explosive generator and MHD-explosive generator. These explosive generators are used as a power source in their electro-magnetic launcher system, ultra high magnetic field generators, and high density plasma devices.

4.3 Fusion Applications

(1) Power source for large test facilities

Designs of large test facilities of nuclear fusion research succeeding the current large Tokamaks show that huge pulsed power is required to operate the new test facilities; i.e, 700 MW for 10 s to excite poloidal coils. Application of MHD power generation to fusion to provide such large pulsed power is proposed at Kyoto University. A design of a hydrogen oxygen fired MHD generation system has shown that the maximum magnetic field becomes 3.5 T with the load current of about 100 kA for the large 800 MWe generator.

(2) Power generation in fusion reactors

The feasibility of high enthalpy extraction from the in-situ radiation -catalyzed MHD generator is numerically studied at Kyoto University as a part of the compact fusion advanced Rankin (CFAR) cycle for fusion reactor. The cesium seeded mercury is selected as the working medium, which is superheated by synchrotron radiation from the fusion plasma. The enthalpy extraction ratio reaches about 59.4 %, while the obtained cycle efficiency becomes about 41.7 % with amorphous thermoelectric conversion system.

V. CONCLUDING REMARKS

Research activities of MHD power generation in Japan have been briefly introduced.

(1) Major facility for the closed-cycle MHD power generation is Fuji-I facility located at Tokyo Institute of Technology. The enthalpy extraction ratio of 16 % is achieved in the blow-down facility with the disk and SCM(4.7 T), while 27 % is demonstrated in the shock tube experiment.

(2) A variety of activities of open-cycle MHD are carried out at universities and national research laboratories: feasibility studies, fundamental experiments, generator designs, numerical simulations, mechanisms of arcing phenomena, power conditionings, control circuits, coal combustor and diagnostics. A new facility is under construction at Hokkaido University, of which thermal input is 5 MW with the magnetic field of 2.9 T.

(3) The main source of funding on MHD power generation now comes from the Ministry of Education, Science and Culture.

Details of some studies are reported in the recent International Conference on MHD power generation and the present SEAM.

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