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Viertes Arbeitsseminar über Fragen

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ПРИКЛАДНОЙ МАГНИТОГИДРОДИНАМИКЕ И ГАЗОДИНАМИКЕ ВЫСОКИХ ТЕМПЕРАТУР

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ZDZISŁAW CELIŃSKI
Świerk *

Open-Cycle MHD Generators

1. Introduction

The present growth of electrical power production in the industrialized countries is about doubled within every ten years. The coverage of such a high demand for power in the near future will not only strain the natural and economic resources but it will also constitute a threat against the human environment by huge rising in thermal and air pollution.

Better utilization of the fuel resources and reduction of the cost of electricity and of pollution per unit power produced strongly suggest the urgent necessity to increase the thermal efficiency of future large power plants over their present level. Simple considerations of Carnot cycle efficiency indicate that this goal can be reached by increasing the top temperature of power cycles.

Cycle top temperature in present steam power stations (825°K) is much below the flame temperature of coal or fuel oil. Such plants have almost reached at present their maximum efficiency about 40%, a number which is determined by cycle and economic considerations. There exists no apparent technological limitation to prevent substantial increase in temperature of operation enabling cooperation with MHD generators. MHD generators operating as topping units for the steam power plants can break through this efficiency barrier in large power generation and reduce pollution substantially.

Recent estimates indicate that the MHD plants (MHD-steam) of the first generation promise a quantum jump in efficiency up to about 50 percent. Efficiency of the second generation MHD plants based on advanced technology is expected to be about 60 percent.

During past decade the extensive research has been performed in MHD generators which have been developed from the small, experimental devices, through larger laboratory units, to the first MHD pilot plant being now in the stage of starting up. The MHD generator research provided quite a good understanding of the plasma physics and the fluid mechanics in these machines.

The main MHD activities are directed towards the open cycle generators due to the possibility to use them in near future in coal- or oil-fired base-load power stations. But in the last years some new concepts have arisen aimed to utilize large MHD units for cover-

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age of peak load and/or for emergency operation. Low capital costs of this kind of MHD plants in spite of their low efficiency may be economically preferable to the other kinds of peak load or emergency plants.

2. Status and prospects of MHD generators

2.1. Open-cycle systems

Open-cycle systems are usually of the regenerative Brayton type with an associated steam plant as shown in Fig. 1. The fuel in form of gas, oil or coal is fed with preheated air and seed material to a burner in which temperatures of about 2800°K are achieved.

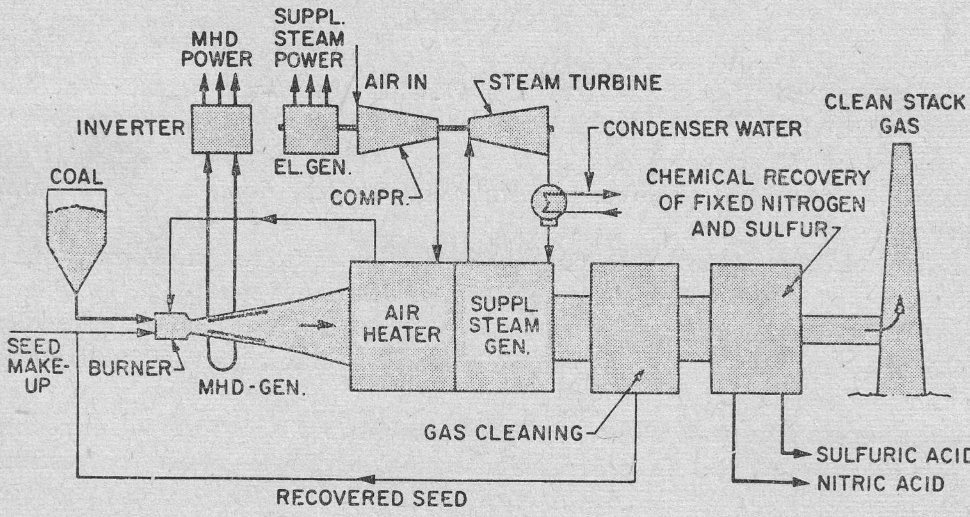

Fig. 1. MHD – steam cycle

After passing through the generator channel, the combustion gases are used to preheat the compressed air and to drive the boiler of the supplementary steam generator. Removal of the seed material is necessary for both economic and environmental reasons. This clean-up stage also enables to remove SO_2 and NO from the exhaust gases. The system is completed by an air compressor and an inverter DC into AC.

2.2. Performance of open-cycle generators

Very substantial progress has been made in improving both the performance and life time of open-cycle generator systems during last several years. This work has gone forward in a number of laboratories, notably in the United States, the Soviet Union, Japan, Federal Republic of Germany and Poland.

In the United States the LORHO generator with an installed thermal capacity of 430 MW has delivered electrical output of 18 MW for a 3-minute run. The Avco MARK V generator achieved, several years ago, an electrical output of 32 MW. Continuous operating times substantially in excess of 50 hr have been reported for the U-02 installation in the Soviet Union, for the long-duration facility constructed by Toshiba in Japan and for the Avco long-duration test facility. The linear dimensions of the biggest generators operating or under construction are in the order of several meters, and thus it is possible to obtain high electrical power outputs. Experiments on a smaller scale, such as those conducted at the University of Tennessee Space Institute or at the Electrotechnical Laboratory in Tokyo (MARK II) have attained high power densities up to 30 MW/m^3.

Different approaches have been taken in the study of open-cycle generators. On the one hand, several small-scale installations which include many of the components required for the complete system have been developed, the most complete example of these is the U-02 installation in Moscow. This has delivered a maximum of 43 kW and the power has been inverted and sent to the Moscow grid. In other installations, the facility consists only of a combustor, nozzle, generator duct, and magnet, and the emphasis is put on generator studies rather than long-duration operation. This concerns the Avco MARK V machine and also the Japanese MARK II generator. Institute of Power Engineering in Moscow has constructed a facility of this type known as the ENIN-2, which has an input thermal power of 250 MW and run times up to 15 minutes.

A rich variety of fuels has been used in the course of these experiments, ranging from liquid and solid rocket fuels at the University of Tennessee, through kerosene in Avco MARK V, to natural gas in U-02 and fuel oil in the MARK II generator.

Various channel configurations have been used. The LORHO generator is of Hall type machine with a circular cross-section whereas in the ENIN-2 and the University of Tennessee diagonal configurations have been used. In other places the segmented Faraday design has been adopted generally.

2.3. Channel constructions

All types of the channel walls tested may be divided into two groups: „hot" and „cold" walls.

„Hot" electrode walls are made from refractories whose thermoemission properties at high emperature provide for a distributed discharge on the surface of the electrode. „Hot" insulating walls are made from ceramic elements or metallic elements with ceramic coatings.

„Cold" electrode walls made from water cooled metallic electrodes operate with an arc discharge on the surface, which may considerably reduce their reliability and operating life owing to erosion. „Cold" insulating walls consist of separate, water cooled, electrically insulated metallic modules („peg wall" construction).

The experiments have shown that the high temperature of electrode surface is of great importance for a sufficient operation of the generator. The formation of the relatively cold gas boundary layer near the electrodes may decrease the generated power by an order of magnitude. Especially large electrode drops ranging from tens to several hundreds volts have been observed in the case of „cold" electrodes. Some decrease of the cold electrode effects may be achieved by extension of the electrodes beyond the boundary layer [9,10]. It seems at the present that the most promising electrode material is zirconia stabilized by the rare earth elements to increase its electronic conductivity. Ceramic materials of this type have been tested under laboratory conditions at a current density of 3.5 A/cm^2 for 250 h without showing any traces of electrolysis or structural changes [10].

The peg type insulating wall is very reliable and proved to be so in numerous experimental devices. It has however two unfavourable features. Heat losses from plasma flow to the water cooling metallic pegs are very large (e.g. 2 ... 3 MW/m^2). The potassium compounds condensed on the cold surface of the pegs deteriorate the electrical wall insulation and decrease the output power. The tests with insulating walls made from MgO with surface temperature up to 1900°C performed in the U-02 installation show good reliability of this construction during long-period operation (up to 500 hours) [10].

2.4. Auxiliary equipment

The successful operation of a complete MHD power plant depends heavily on the development of auxiliary equipment including combustion chambers, heat exchangers, seeding techniques, and seed recovery systems.

Seed injection may be accomplished either in dry powder or dissolved form.

Usually potassium, and in some cases cesium are used as the ionizable seed. Potassium is usually introduced into the combustion chamber in the form of a water solution of K_2CO_3, a water or alcohol solution of KOH or in the form of K_2SO_4 powder.

Bag filters, cyclone separators and electrostatic precipitators are under consideration for effective seed recovery and collection efficiencies in excess of 99% are expected to be obtained.

The predicted performance of an MHD cycle very critically depends on development of a successful high-temperature air heater. Good progress has been made in this direction. Generally, the air preheaters considered have been of the regenerative storage type with either fixed or moving beds. The development of a directly fired heat exchanger is more difficult than the separately fired unit which avoids problems of seed and ash corrosion but decreases the overall cycle efficiency. The separately fired, moving pebble bed heater with continuous preheat temperature up to 1300°C has been developed at Świerk. The separately fired air preheater for the U-02 installation employs a fixed pebble bed and includes two units which are switched by water-cooled gate valves. It has been working till now for over 7000 hours providing a continuous heating of 1.2 kg/sec air up to 1600°C and in short-time operation up to 2000°C. Long-duration tests have proved the reliability of its operation [4].

The requirements for an MHD combustion chamber are that a combustion should take place at high temperature under pressure and in the presence of alkali seed material. A number of tests have now been successfully completed using oil and gas (MARK V, LORHO, U-02, ENIN-2, U-25). The combustion chamber of the U-02 facility was operated during several thousand of hours with natural gas and lined with zirconium oxide. At present the combustion chambers using gaseous or liquid fuel are sufficiently developed to be considered as heat source for full scale MHD plant. It does not concern the combustion chamber using coal – much effort must be undertaken to solve this problem.

2.5. Magnetic systems

Although conventional magnets are being employed in experimental MHD generators being tested currently and also in the pilot plant U-25, it is obvious at present that superconducting magnets offer the best prospects to be used in large scale MHD plants. The provision of a superconducting magnet with a field induction of 4 ... 5 T will reduce by 3 to 4 times the channel length as compared to the channel length of an MHD generator using an conventional iron magnet with an induction of 2 T. The use of superconductors will reduce the power requirements for the magnet system and the system weight by approximately an order of magnitude. Maintenance costs are reduced accordingly. Prospective capital costs of a superconducting magnet system will be approximately equal to those of a conventional system.

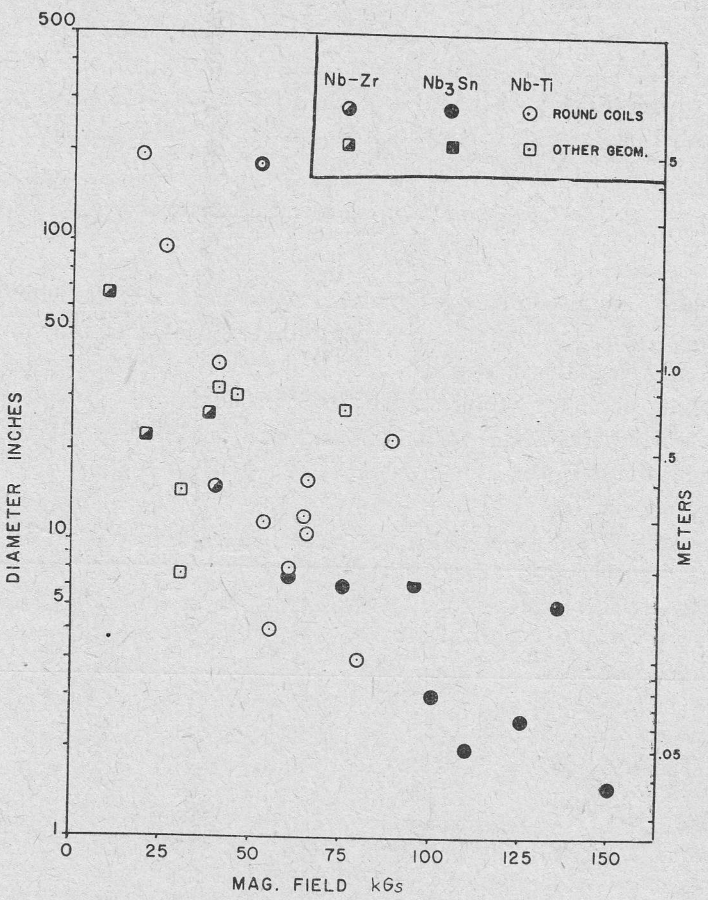

Fig. 2. Diameter vs. magnetic field for several operating superconducting magnets [11]

During last few years a considerable progress in development of superconducting magnetic sytems especially in technology of superconducting materials has been done. Although the number of superconducting materials is very numerous, up to now only the alloy system Nb – Ti – Zr and the compound Nb_3Sn have been used in magnets. The critical temperature of Nb – Ti – Zr is about 10°K and the critical field about 10 T at 4.2°K. Nb_3Sn has a critical temperature of 18°K, and remains superconducting in fields exceeding 20 T at 4.2°K. In spite of the potential of Nb_3Sn, Nb – Ti has become the most widely used superconductor at fields below 10 T due to its good mechanical characteristics and ability to be fabricated into a variety of shapes and sizes. In order to gain an overall view of the state-of-the-art it is best to refer to Fig. 2 which shows a plot of the size of the useful inside dimensions of existing or being tested superconducting magnets versus the magnetic field.

Several sufficiently large magnetic systems with the coils up to 5 m in inner diameter and magnetic field up to 4 T (e.g. for the large bubble chambers in Argonne National Laboratory, USA or in CERN) has already been started-up or are ready to start-up. But magnetic systems for MHD are more difficult to construct due to the much more complicated coil and dewar shapes. In last two years several relatively large superconducting magnetic systems designed for MHD generators have been started up. One of them in Jülich (Federal Republic of Germany) was operated several thousand hours giving a magnetic field of 4 T in 7×7×80 cm MHD generator channel [4]. Another superconducting magnet was tested in Japan in combination with a 1 kW MHD generator [4].

2.6. Power plant concepts and economics

The power cycle most commonly discussed is the binary MHD-steam cycle where the generator exhaust heat is utilized for preheating of the combustion air which may be enriched with oxygen, and for steam generation for supplemental power production (Fig. 1). An alternative to this basic power cycle is to associate the MHD generator with a gas turbine bottoming plant for supplemental power production.

Major data of several MHD-steam power plants presented at Munich Conference, 1971 are summarized in Table 1.

Table 1

Central station MHD-steam power plants

	Paper 569 (Y. Moti)	Paper 615 (S. Way)	Paper 654 (F. Hals, W. Jackson)
Plant design data			
Fuel	oil	char	coal
Thermal input, MW	1995	1490	2000
Oxidizer	air	air	air
Seed	potassium	cesium	potassium
Preheat temp., °C	1500	880	850 - 1650
Burner pressure, Atm.	7.2 - 8.0	5.25	4.5 - 14.0
Magn. field inlet, Tesla	5 - 6	6.6	6 - 8
Magn. field outlet, Tesla	(constant)	2.9	3.6 - 5
Plant power output (AC)			
MHD, MW	686 - 735	377	427 - 965
Steam, MW	354 - 326	383	502 - 229
Total net, MW	1040 - 1061	760	929 - 1194
Net plant eff., %	52.1 - 53.2	51.3	46.5 - 59.7

The projected efficiencies of large binary cycle systems are initially in the range 47 ... 50 % and improvements in technology could later increase this to about 60 %. To attain such efficiency, air preheat temperatures of about 1700°C and magnetic field of 8 T are required.

Estimates of the cost of generating electricity in fossil fuel-fired MHD-steam plants are presented in Fig. 3. The calculations have been performed in the Institute of High Temperature in the Soviet Union [8]. The MHD power plant with efficiency of 50 %, oxygen enrichment up to 50 % and the oxidizer preheat temperature of 850°C were taken into consideration. Approximate specific capital costs of such MHD plant, the oxygen plant including, have been estimated as 135 rubles per kilowatt with the current prices for the materials and equipment, and as 115 rubles/kW with technology progress, compared to 120 rubles/kW for the conventional steam power station. In another, advanced technology MHD power plant with air preheat up to 2000°C and efficiency of 60 percent the capital costs are expected to be of the order of 120 rubles per kW. In nuclear power plants, specific capital costs are estimated at 180 rubles/kW by 1985 ÷ 1990 and 150 rubles/kW in more distant future. The comparison shows that MHD plants are economically advantageous over conventional thermal power plants in those areas where fuel costs exceed 7 ... 8 rubles per ton of coal equivalent. The nuclear power plants are advantageous over the open-cycle MHD-steam plants only in the areas with relatively expensive fossil fuel.

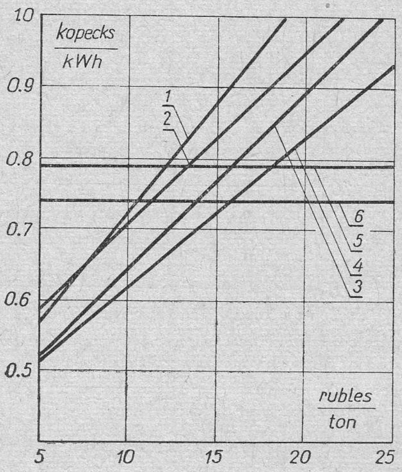

Fig. 3. Electricity costs as a function of fuel costs [8]

1 – Steam Station;	$\eta = 40\%$	$K = 120$ rb/kW;
2 – MHD Power Station;	$\eta = 50\%$	$K = 135$ rb/kW;
3 – MHD Power Station;	$\eta = 50\%$	$K = 115$ rb/kW;
4 – MHD Power Station;	$\eta = 60\%$	$K = 120$ rb/kW;
5 – Atomic Power Station $C_T = 0.2$ kop./kWh		$K = 150$ rb/kW;
6 – Atomic Power Station $C_T = 0.2$ kop./kWh $h = 6{,}500$ h/yr		$K = 135$ rb/kW;

In the discussion of economics, it should be noted that the situation may differ from country to country and also within a country it is depending upon cost and availability of fuel, capital charge rates, sizes and load characteristics, etc.

2.7. Environmental considerations

The environmental effects of MHD must be pointed out since it is a crucial factor in the application of any energy conversion process. The thermal and atmospheric pollution may be expected from an MHD plant.

Thermal pollution will be substantially reduced compared to steam electric power plant due to the higher efficiences. All power plants must reject heat and the amount of heat rejected drops rapidly with increasing efficiency. The amount of thermal pollution Q per unit power produced can be written as $Q=(1-\eta)/\eta$. The rapid decrease in heat rejection with the increasing cycle efficiency is illustrated in Fig. 4.

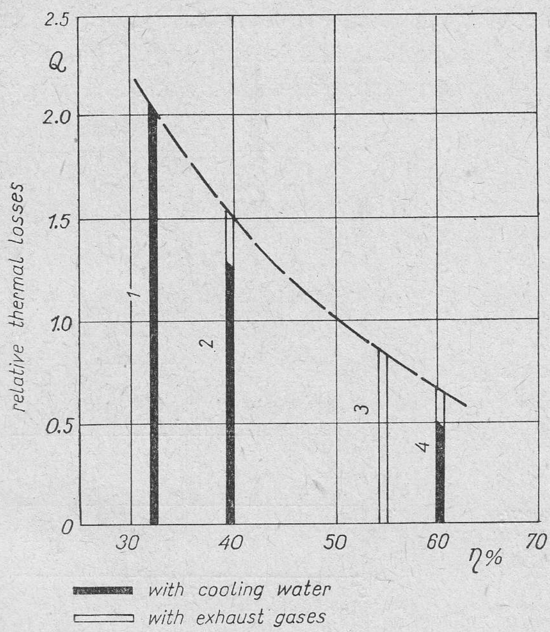

Fig. 4. Comparison of heat rejection from thermal power plants
1 – Atomic Power Station, *2* – Steam Station *3* – MHD Power Station (gas turbine), *4* – MHD Power Station (steam turbine)

Atmospheric pollution is mainly caused by rejection of oxides of nitrogen and sulphur, the major pollutants produced by the combustion of fossil fuel. Two routes for control of nitrogen oxides have been suggested: one is to minimize the nitrogen oxides contents by utilizing special combustion technique and the other is to maximize the nitrogen oxides so that recovery of fixed nitrogen becomes economically attractive. The recovery of fixed nitrogen can be combined with removal of sulphur from the gas by utilizing nitrogen oxides to convert SO_2 in the gas to SO_3 which can be readily removed and utilized to the industrial production of sulphuric acid. The experiments have shown that the SO_2 concentration in stack gas can be reduced in this way to as low as 100 ppm when burning fossil fuel of high sulphur content.

The possibility of utilization of seed for sulphur removal has been indicated. In oil-fired MHD plants potassium is precipitated as K_2SO_4 if the oil contains sulphur. The experiments indicate that if sufficient amount of potassium is used the sulphur contained in the oil is completely eliminated from the exhaust gases. The possibility arises to utilize in MHD plant a cheap high-sulphur oil.

2.8. MHD peaking power systems

The load characteristics of electric utility systems are such that in addition to base load power plants operating with high capacity factors, there is also a need for plants which operate with lower capacity factors. Such plants termed peaking plants will supply power for emergency and for peak load. For such a plant MHD generator offers several attractive features. Such a system would not involve an associated steam plant. It would use a liquid fuel with oxygen and can take advantage of the simplicity, large unit size, and rapid start-up capabilities of the MHD generator.

The simplest MHD peaking power system where fossil fuel is burnt with liquid oxygen supplied under pressure from storage consists of a burner, nozzle, channel, diffuser, superconducting magnet, inversion equipment, fuel and oxygen supply system, exhaust gas system, seed recovery and seed-feeding equipment. The estimate cost of such type of plant of 400 MW unit capacity is 45 rubles per kilowatt including an oxygen plant for supply of oxygen. The overall efficiency of the plant would be about 23%. This simple MHD power plant is considered attractive up to about 500 hours of annual operation [12].

2.9. MHD development programme

The most extensive research in the open cycle MHD generators is being carried out in the Soviet Union. It is concentrated in the three main research centres: in the Institute of High Temperatures of the Soviet Union Academy of Sciences, in the Institute of Power Engineering of the Ministry of Power both in Moscow, and in the Institute of Electrodynamics of the Ukrainian Academy of Sciences in Kiev.

The largest research programme has been worked out in the Institute of High Temperatures where six years ago the U-02 device was completed and put into operation. The construction of U-25 pilot plant, put into operation last year, was based on the physical and engineering experiences gained in U-02. The U-25 plant is based on the existing technology and designed for relatively moderate parameters to ensure adequate reliability. This plant is intended to be the testing ground for all the basic components of a large MHD power plant for commercial use. The thermal power of the plant will be 300 MW, the MHD power output – 25 MW, the steam turbine power output – 75 MW i.e. the overall efficiency will be about 33%. The natural gas is burnt with air preheated up to 1200°C and enriched up to 40% with oxygen. Gas parameters at the channel inlet are: mass flow rate – 50 kg/s, gas temperature – 2900°K, gas velocity – 850 m/s (i.e. $M=0.8$). The generator channel of 5 m in length and with inlet/outlet cross-section of $0.38\times0.77/0.38\times1.88$ m^2 is equipped in 48 electrodes [13].

A preliminary design of a big MHD power station of 2000 MW electrical power, an overall efficiency of 50% and estimated investment costs of about 140 rubles per installed kilowatt is now in preparation [1].

Russian development programme includes also research on large peaking power stations with operation time about 500 hours a year. Such power plants may be built in next future on the basis of experience gained on U-25.

The Institute of Power Engineering, which have built the ENIN-2 device, is concerned mainly with problems arising from coal combustion in MHD installations.

The situation in the United States at the present time is rather favourable for further development in the field of MHD generators. This is due to several factors. One of them is that atomic power generation did not develope as quickly as it had been expected and nuclear power stations turned out to be rather expensive. Another factor is the great emphasis set in the United States on the environmental aspects. The use of MHD plants offers the possibility of a considerable decreasing of the thermal and atmospheric pollution caused by electric power producing industry. The national long-range programme worked out will be financed by Federal Government and private electric utility companies. The programme is oriented towards coal-fired, base-load MHD stations because of enormous coal reserves in the United States. The initial phase of the realization of this programme is construction of two rather big installations: a new MHD generator capable of long-time operation and a peaking pilot plant. So called MARK VI MHD installation being now under construction at the Avco will derive the electric power of 1 MW in the long-duration operation. The construction of the emergency-peaking pilot plant with 50 MW electrical power will be soon started in Boston.

In Japan the open cycle MHD research is concentrated mainly in National Electrotechnical Laboratory (ETL). Up to 1969 the research was concerned with an experimental study of MARK II – ETL generator (output power 1 MW) and with development of plant components such as superconducting magnets and heat exchangers. Since 1970 the project has been divided into three parts: a) the development of a generator of about 1 MW output with a superconducting magnet; b) the development of a testing installation called MARK VI for a long-term experiment including three kinds of air heaters; c) an economic analysis of MHD plants.

The ultimate task of the research is to built in the future a 1000 MW heavy oil-fired plant with heat exchanger heating air up to 1500°C.

Two centres in Federal Republic of Germany are involved in the open cycle MHD research. The first one is the Institute of Plasma Physics in Munich cooperating with MAN to develop pulsed MHD generators for special purposes particularly for emergency and peaking. The second is „Kernforschungsanlage" in Jülich cooperating with „Institut für Bergbauforschung" in Essen on a programme whose aim is to develop MHD plant for long-term operation. The installation called VEGAS II equipped in 30 MW combuster burning coke-oven gas with oxygen and the superconducting magnet providing 5 T in generator channel will be built next year.

In the Institute of Nuclear Research at Świerk, Poland, the research on improving the air heater to increase the air preheat temperature up to 1500°C will be continued. The new investigations started oriented towards studying the problems connected with high temperature coal combustion.

3. MHD research at the Institute of Nuclear Research at Świerk

The investigations on MHD power generation started in Poland in early sixties in several research centres: in the Institute of Nuclear Research at Świerk, in the Department of Nuclear Energy at the Technical University in Warsaw, in the Institute of Fluid-Flow Machinery at Gdańsk and in the Technical University at Poznań.

At present time the research work on MHD open-cycle generators in Poland is being carried out only at Świerk and on a smaller scale at Poznań.

At Poznań University a short time operation combustion generator with thermal power of about 150 kW was investigated several years ago. The larger experimental unit is now under construction.

The investigations of combustion plasma generators have been carried out in the Department of Plasma Physics and Technology at the Institute of Nuclear Research at Świerk since 1961. Experimental facility with 400 kW combustion chamber, hot wall generator and two-stage air preheater up to 800°C was described at Salzburg Conference [15].

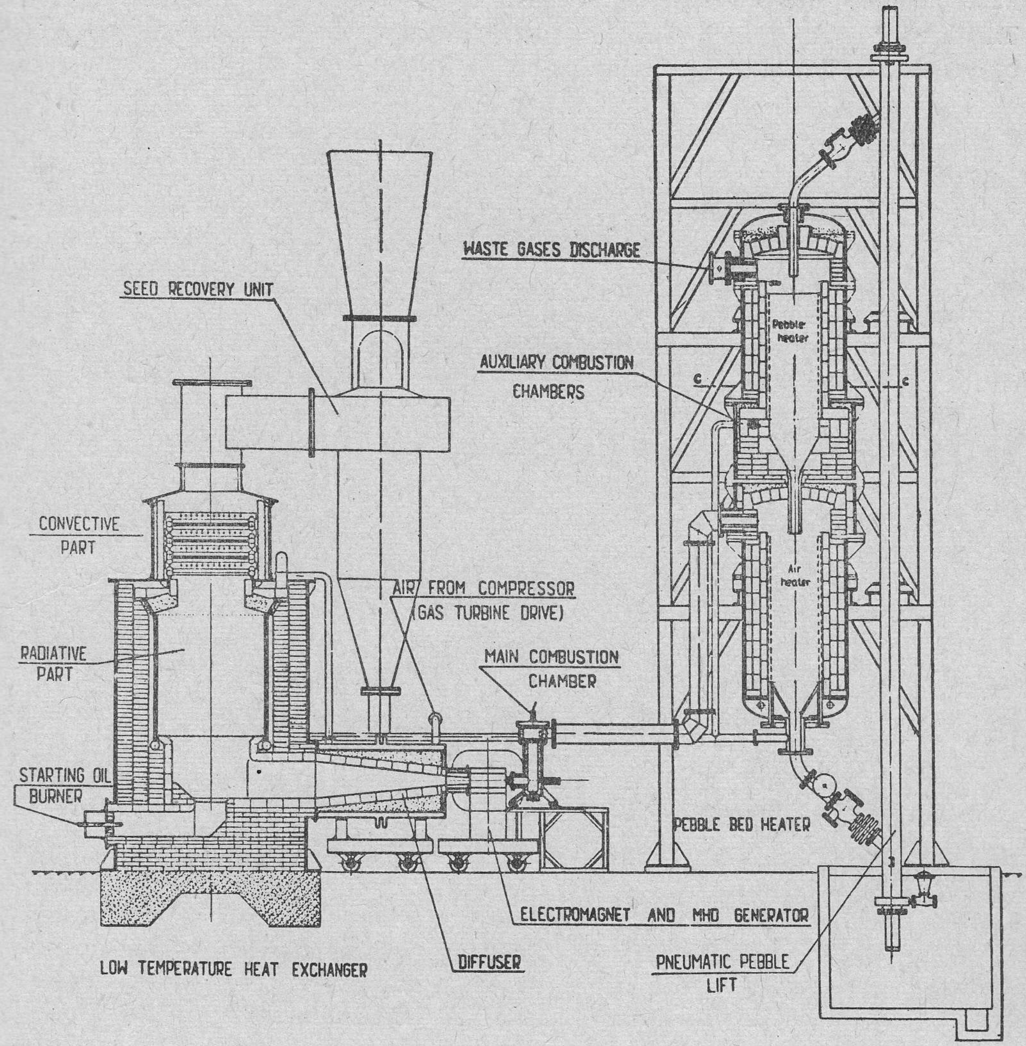

Fig. 5. General arrangement of experimental facility

In 1966 started the research programme carried out in the framework of Franco-Polish Collaboration Agreement. The agreement which concerns with open-cycle MHD was concluded between the "Commisariat à l'energie atomique", Saclay and the Institute of Nuclear Research at Świerk. The complete open cycle rig was constructed and put into operation. It consists of combustion chamber (thermal power 1.5 MW), cold wall MHD generator, magnet, diffuser, radiative-convective heat exchanger (air heated up to 700°C) and high temperature ceramic heat exchanger (air heated up to 1300°C). General arrangement of the rig is shown in Fig. 5.

The most important element of the experimental facility is the high temperature, pebble bed type heat exchanger. It gives the second stage of air preheating from 700°C to 1300°C. The mass flow rate of the air is 0.5 kg/s. The moving bed consists of 5 tons 10 mm in diameter alumina pebbles heated by two auxiliary kerosene fired combustion chambers. The thermal power of both chambers is equal to 1.5 MW. The pebbles are transported by pneumatic elevator.

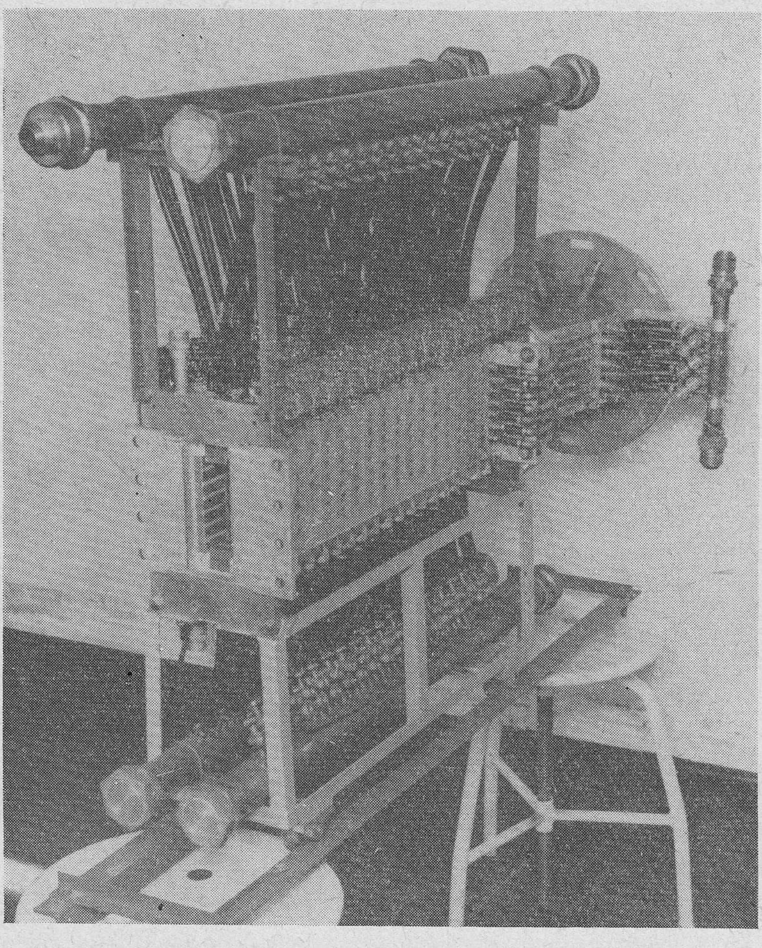

Fig. 6. General view of the cold wall generator channel

The pebble bed heater was put into operation in December 1969 and then tested during next two years. It can be used not only to air preheating in MHD generator installations but also for another numerous industrial applications as for example for heating of reducing gases or water steam to high temperatures in metallurgical or chemical industries.

At the end of 1971 the heat exchanger was put into long period operation for about 700 hours. The experiment ran successfully, the air was heated up to 1300°C without any troubles. In the next stage in the development of the heat exchanger the air heating temperature of 1500°C is to attain. It will be possible with the new charge of more durable pebbles.

Emphasis is set on the development of channel technology to find out the best materials and optimum construction of the channel for long period operation.

Several experiments were carried out with the cold wall generator channel. The constant area channel with water cooled copper walls and 30 pairs of copper electrodes was built and investigated (Fig. 6). The measured electrical, thermal and gasdynamical parameters allowed to gather some experience to be used in next channel construction.

The generator operated with the combustion products of kerosene, enriched air and KOH seed. The active part of the generator test section was 500 mm in length with a constant cross-section of 30×90 mm^2. At normal conditions about 0.042 kg/s of kerosene was burned with 0.154 kg/s of oxygen and 0.176 kg/s of nitrogen resulting in a gas temperature at approximate 2700°K, a total throughput of about 0.4 kg/s and a thermal input of about 1.8 MW. Seed was delivered in form of KOH solved in water. At the entrance to the generator Mach number was about 0.8, gas velocity – 700 m/s, gas pressure – 1.5 atm, and static gas temperature – 2600°K. At these normal operating conditions and with magnetic field equal to 2.4 T the open circuit voltage of about 80 volts and short circuit current of about 2 amperes from each electrode pair were obtained. Short circuit current was strongly decreasing along the channel. A comparison with the calculated values shows large effects of the leakage currents probably through conductive layers on the side walls formed by condensed potassium compounds [16].

The heat loss to the metallic walls was measured and it was found that heat loss was strongly decreasing along the channel especially in the first half of it. At the entrance to the generator heat loss was about 3 MW/m^2, in the middle part of the channel – about 1.5 MW/m^2. The construction of the channel, seven horizontal rows of side wall elements, allowed to measure the distribution of heat loss to the wall between the opposite electrodes. It is found that this distribution is strongly nonuniform: in the middle row heat loss (averaged along the channel) was about 3 MW/m^2, in the top and low rows-less than 1 MW/m^2.

Next generator channel, being now under construction, will have copper or stainless steel water cooled walls protected by the multi-layer ceramic coatings based on alumina. The supersonic channel will have the dimensions: inlet area – 30×40 mm^2, outlet area – 30×90 mm^2 and length of 500 mm. The electrodes will be made from water cooled stainless steel coated with multi-layer coatings based on zirconia.

Coatings will be produced by plasma spraying technique well developed in the Department of Plasma Physics and Technology. The structure of the coatings used for the channel walls is shown in Fig. 7. The ceramic layers are to decrease the thermal losses to the channel walls and to ensure proper electric insulation between plasma and channel casing. The investigations were performed on several samples with various layer thickness with surface temperature up to 2000°C [17]. They have shown that the coatings up to 2 mm thick show excellent thermal and mechanical properties with surface temperatures up to 1600°C. The measured effective thermal conductivity of the ceramic layers was in the range between

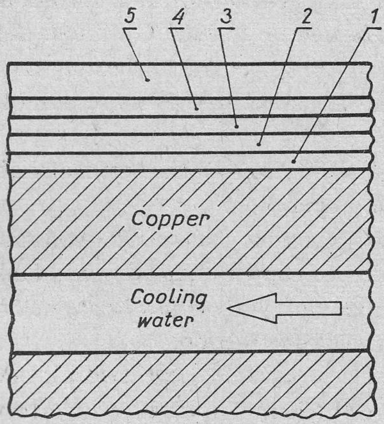

Fig. 7. Structure of the multi-layer ceramic coating [1]

1	– NiCr	0.1 mm
2	– 30% Al_2O_3/70% NiAl	0.2 mm
3	– 50% Al_2O_3/50% NiAl	0.2 mm
4	– 70% Al_2O_3/30% NiAl	0.1 mm
5	– Al_2O_3	0.5 ... 1.8 mm

1.0 and 2.4 W/m °C depending on surface temperature and layer thickness. The thermal flux decreases from 3 MW/m^2 to 1 MW/m^2 when the layer thickness increases from 0.5 to 2 mm in the assumption that surface temperature is constant and equal to 1600°C.

The third generator channel, being also under construction, will have hot electrodes and walls. It will be a supersonic channel too with movable electrode walls allowing to

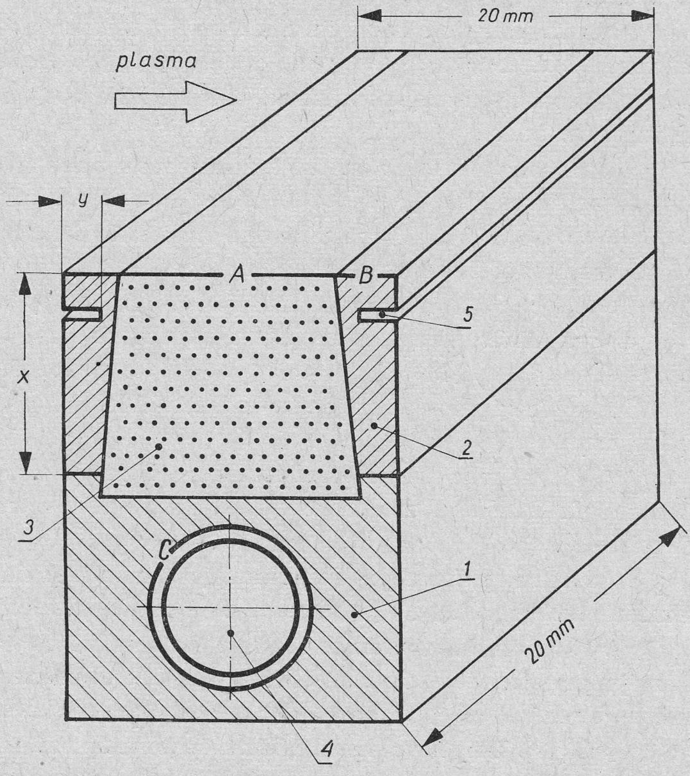

Fig. 8. Side wall element [1]
1 – copper, *2* – Stainless steel, *3* – MgO, *4* – cooling water, *5* – slit

investigate the shock waves in the channel. Several calculations and analog measurements were performed in order to find the optimum geometry of the side wall element consisting of three various materials: copper, stainless steel, and magnesia. It is a very difficult problem to realize because the element surface being in contact with plasma must have a strictly controlled temperature. One of the possible solutions is shown in Fig. 8.

Much work is performed concerning the theoretical analysis of various effects occuring in MHD generator channel. The effects of finite length of electrodes in series-connected generator on its electrical parameters were investigated several years ago. The effects of gas nonuniformity along the channel and in the channel cross-section of the Faraday- and Hall--type generators were investigated in several papers. These effects have been quantitatively determined by the calculations of the coefficients deteriorating the generator performance due to the boundary layers. The electrical effects occuring in the electrode and boundary layer have been analyzed and discussed. Several papers are concerned with the effects of the leakage currents in the MHD generator.

4. Concluding remarks

The successful operation of large experimental generators and the extensive testing of materials for both the generator duct and auxiliary equipment have led to the position where engineering solutions exist for all of the major problems of a typical open-cycle installation. Emphasis is now shifted to the construction of pilot installations in which these solutions can be tested and evaluated during long-period operation although much scope remains for further improvement in the performance of all system components.

As far as the selection of generator type is considered, the linear, *DC* Faraday type generators have been shown to operate satisfactorily and in quite good agreement with predicted performance. Another channel configurations as e.g. disc generator are not yet sufficiently developed. The experiments performed up to now have shown that Hall generators with externally shorted electrodes are unsatisfactory. It is especially true for a generator having combustion gases as the working fluid when the Hall parameter is low. The voltage and power developed in a Hall generator are very sensitive to poor wall insulation. The power generated in experimental MHD channel with electrodes connected in Hall mode are about one order of magnitude smaller than in Faraday mode of connection.

From the electrical point of view the large number of electric load circuits in a Faraday generator is not a particular disadvantage since inverters with silicon thyristors have been developed. Silicon thyristors are available that can handle hundreds of amperes and thousands of volts. It is to be expected that, in the near future, still larger units will be built, and the cost of the thyristors will quickly decrease.

Hot channel structures are most promising from the standpoint of thermodynamic and electrical efficiency. It seems that stabilized zirconium oxide and magnesium oxide will be the basic materials for hot electrode and insulation walls. The problem of channel materials can not be considered as ultimately solved and in the nearest future the emphasis should be set on the improving of the materials and channel construction.

The problem of construction of large superconducting magnets for MHD generators may be considered at the present as solved. It the nearest future further improvements of such magnetic systems are to be expected.

In order to provide a high efficiency in open-cycle MHD plants, it is necessary to utilize the heat of the combustion products leaving the MHD generator for heating the air supplied to the combustion chamber up to 1500...2000°C in a high-temperature heat exchanger. The high temperature air heaters developed up to the present are the units heated by the separate combustion chambers. In the next stage the directly fired heat exchanger must be developed.

While coal is the preferred fuel in many parts of the world because of its abundance and low cost, very little experience has yet been gained in the actual operation on MHD generators with a working fluid obtained from the combustion of coal. An urgent requirement is to show that successful operation is possible in the presence of slag and the corrosive chemistry associated with the impurities contained in coal.

The considerable progress made in last years in understanding of the chemistry of high temperature flue gases and in the problem of seed and slag separation led not only to engineering solutions of the seed recirculations but also to proposals of the quantity production of nitrogen- and sulphur-containing compounds as chemical by-products. This would in effect reduce the cost of the electricity. In addition this ''scrubbing'' of the flue gas results in negligible air pollution. The improved thermal efficiences reduce the thermal pollution of the environment associated with excessive waste-heat discharged in the cooling water.

For emergency and peaking power application, MHD generators have been indicated to offer favorable capital costs, particularly in large unit sizes, coupled with capabilities for fast start-up, rapid response and control. The absence of many auxiliary components, such as the air preheater, from this type of installation with the requirement of relatively short annual running time should enable a plant of this type to be developed in a relatively short time from experience already gained. Peaking or emergency generators have the potential for being the first application of MHD generators to commercial networks.

Open-cycle MHD generators are now in an important transition period and only considerable experience with pilot installations will establish their full potential with respect to large-scale electricity production. Although it must be recognized that the performance and economics of MHD power generation will only become established after considerable operating experience beyond the pilot plant stage, the technological progress to date permits predictions of these to be made. The following development of open-cycle MHD plant may be expected:

– Pilot plant (U-25): initial operation – 1972; output (MHD)-25 MW; output (steam cycle) – 55 MW; fuel – natural gas; oxidizer – air preheated to 1200°C with oxygen enrichment; magnetic field – 2 T; overall plant efficiency – 33%.

– First generation plant (full scale plant based on existing technology): initial operation – 1980...1985; output (MHD) – 500 MW; output (steam cycle) – 500 MW; fuel – natural gas or oil; oxidizer – air preheated to 850°C in metallic heat exchanger with oxygen enrichment or air preheated to 1100°C in ceramic heat exchanger without enrichment; magnetic field – 4 T; overall plant efficiency – 50%.

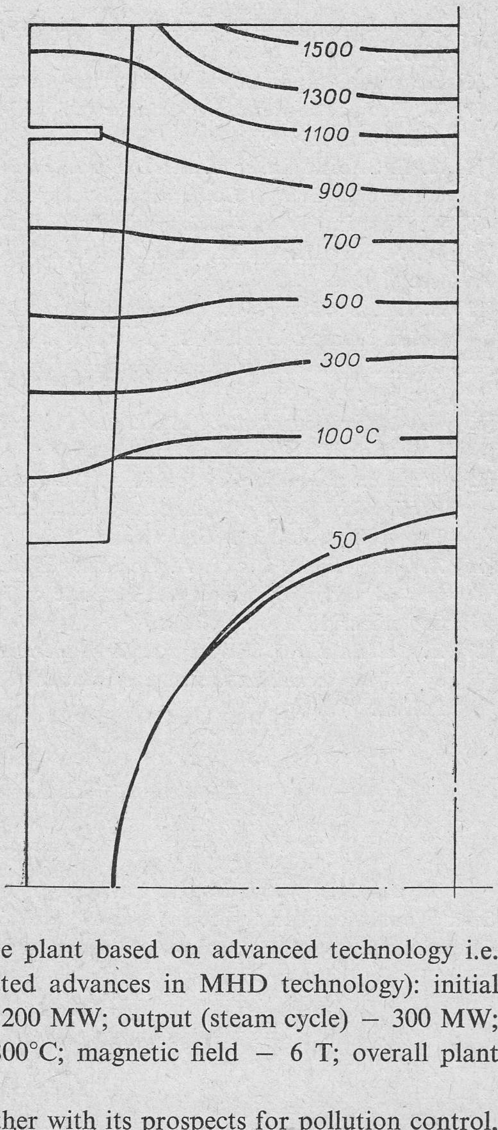

Fig. 9. Temperature distribution in the side wall element [1]

– Second generation plant (full scale plant based on advanced technology i.e. utilizing foreseeable but as yet undemonstrated advances in MHD technology): initial operation – 1995...2000; output (MHD) – 1200 MW; output (steam cycle) – 300 MW; fuel – coal; oxidizer – air preheated to 1800°C; magnetic field – 6 T; overall plant efficiency – 58...60 %.

The realization of these performance together with its prospects for pollution control, would ensure for open-cycle MHD a major role in electrical power production from fossil fuel. On the basis of present experience it must be expected as having a good chance for ultimate success.

Literature

[1] Fifth International Conference on MHD Electrical Power Generation, Munich, April 1971.
[2] Symposium on MHD Electrical Power Generation, Warsaw, July 1968. Proceedings, IAEA, Vienna 1968.
[3] MHD Electrical Power Generation – The 1969 Status Report, IAEA/ENEA 1969.
[4] MHD Electrical Power Generation – The 1971 Status Report, manuscript.

[5] Tenth Symposium on Engineering Aspects of Magnetohydrodynamics, MIT, Mass. Cambridge 1969.
[6] Eleventh Symposium on Engineering Aspects of Magnetohydrodynamics, CIT, Pasadena 1970.
[7] W. D. Jackson *et al.*, *A Critique of MHD Power Generation*. Journal of Engineering for Power, Asme, July 1970.
[8] A. E. Sheindlin *et al. MHD Power Plant—Current Status and Prospects for Commercial Use*. 8th World Energy Conference, Bucharest 1971.
[9] K. Fushimi *et al.*, *Development of a Long Duration MHD Channel*. Munich 1971, Vol. I (see [1]).
[10] W. A. Kirillin *et al.*, *Investigations at U-02 MHD Plant: Some Results*. Munich 1971, Vol. I (see [1]).
[11] Z. I. I. Stekly *et al.*, *Characteristics of MHD Generator Systems Using Superconducting Field Coils*. Munich 1971, Vol. IV (see [1]).
[12] A. E. Sheindlin *et al.*, *Estimation of Efficiency of MHD Peaking Power*. Munich 1971, Vol. I (see [1]).
[13] V. A. Kirillin *et al.*, *A 25 000 kW Pilot MHD-Power Plant*. Energy Conversion, 1970.
[14] I. F. Louis, *High Temperature Power Generation*. MIT, Int. Report, 1970.
[15] W. Brzozowski, Z. Celiński, T. Kozłowski, *Operating Experience with an Open-Cycle MHD Test Facility*. Symposium on MHD Electrical Power Generation, Salzburg, July 1966. Proceedings, Vol. 3, IAEA, Vienna 1966.
[16] Z. Celiński, J. Licki, A. Łopuszyńska, T. Kozłowski, M. Plata, *Results of measurements in cold wall MHD generator*. Institute of Nuclear Research, internal report No. 167/XVIII/71, September 1971 (in Polish).
[17] Z. Celiński, M. Plata, *Results of thermal investigations of ceramic multi-layer coatings sprayed by plasma technique*. Institute of Nuclear Research, internal report No. 159/XVIII/71, 1971 (in Polish).

Generatory MHD w cyklu otwartym

Streszczenie

Artykuł daje przegląd stanu istniejącego w badaniach generatorów MHD w cyklu otwartym. Szerzej omówiono prace prowadzone w tym kierunku w Instytucie Badań Jądrowych w Świerku. Omówiono perspektywy zastosowania generatorów MHD do wytwarzania dużych mocy elektrycznych.

.Verbrennungsgasbetriebene MHD Generatoren

Zusammenfassung

Im Artikel wurden die Resultate der bisherigen Forschungen in dem Gebiet der Verbrennungsgasbetriebenen MHD Generatoren beschrieben und auch die Forschungsprogramme der verschiedenen Laboratorien zusammengestellt. Die im Institut für Kernforschung in Świerk betriebenen Forschungen wurden in der Arbeit ausführlich dargestellt.

МГД генераторы в открытом контуре

Резюме

В статье делается обзор существующего состояния исследований МГД генераторов в открытом контуре. Более широко обсуждаются работы, проводимые в этом направлении в Институте ядерных исследований в Сверке. Обсуждаются перспективы применения МГД генераторов для производства больших электрических мощностей.