Abstract. The Magneto-Hydro-Dynamic (MHD) power facility simulating supersonic hydrogen/oxygen combustion is described. This facility was constructed in the result of modernization TsNIIMash huge shock tube, U-12. It consists of a high-pressure vessel, supersonic nozzle, magnet, MHD generator, diffuser and exhaust system. The magnet, MHD generator and the supersonic diffuser were constructed by IVTAN. Utilization of many existing test equipment is allowed to make minimum production expense. To increase the electron concentration a seed injector system is used. The goal of this study is the physical demonstration of the MHD electrical power generation under conditions simulating those for on-board multi-megawatt power generating system. The measurements included pressure, temperature at different locations of flow-train and electric parameters of MHD generator. The preliminary experimental results are presented and discussed.

Introduction

The generation of high levels of electrical power using Magneto-Hydro-Dynamic (MHD) processes with supersonic hydrogen/air or hydrogen/oxygen combustion sources is of great interest today [1-6]. Significant earlier studies have shown the promise of producing small, multi-megawatt power generating systems using MHD [7,8]. However, the practical demonstration of such systems which take advantage of recent improvements in materials, magnets, modeling, ionization, and power conditioning technology are lacking. Therefore, fundamental research and development are needed to assess the potentiality of MHD for advanced high power, compact, lightweight electrical generation technology and its application to a range of commercial products. As the first step solving this problem it is necessary to design and construct the facility to conduct relevant MHD power generation demonstration tests.

In this paper the Magneto-Hydro-Dynamic power facility, simulating supersonic hydrogen/oxygen combustion, is described along with the discussion of preliminary experimental results.

Magneto-Hydro-Dynamic power facility

The MHD power facility was constructed in the result of modernization TsNIIMash huge shock tube U-12 [9], and using IVTAN MHD generator and magnet system. It allowed to minimize production expenses, because many existing test equipment could be used. In Figure 1 the MHD power facility is shown schematically.
nozzle geometry gives Mach number about 1.8 at the MHD generator enter. The non-cooled nozzle inlays made of cooper and can be replaced for another Mach number receiving. The flat sidewalls of the Laval nozzle made of cooper also.

The gasholder 7 is 3.2m in diameter and 180m³ by volume. It is equipped with power-full vacuum pumps. The vacuum pressure up to ~1Pa can be reached there in ~ 20 minutes.

During the tests the pressure is measured at three points of the HPV (8,9,13), at the enter and exit section of the Laval nozzle (14,15) and at the stagnation point after normal shock wave at the exit of the diffuser section (16).

For the temperature value evaluation a thermoelectric couple and calorimeter are used. The Tungsten-Renium thermoelectric couple (18) is installed near the Laval nozzle on the side surface of the HPV, and the calorimeter 17 is installed near the diffuser of the exit section.

**Seed injector and Ignition**

To inject seed and ignite the hydrogen/oxygen mixture the ignition device shown schematically in Fig.2 was used in first runs. The device was placed at opening 12 as it is shown in Fig.1. Six slits 3 were dialed in the fool sheet 1. Before run through the slits 3 the powder of K₂CO₃ is charged in to the chamber and then is kept by paper diaphragms.

![Fig.2. The scheme of the seed injector and setting fire.](image)

Inside the body shell a gunpowder device is installed. It consists of a barrel 4 and a polythene bottom 5, through which the wires 6 come inside. The wires 6 are equipped with Nickel spiral 7 at their ends. The charge of the gun is about three grams of gunpowder 8. Between diafragmes 9 a polythene piston or portion of K₂CO₃ powder about 30 grams (10) is fed. It promotes more full gunpowder combustion and, as result, more high pressure of combustion products realizes at the device exit.

The ignition of the gunpowder is resulted of the nickel wire explosion by the discharge of capacitor battery 11 controlled by the key 12. The high temperature of the gunpowder combustion products initiates the ignition of the hydrogen/oxygen mixture. The gunpowder combustion products high pressure drives the injection of the K₂CO₃ powder through slits 3. The total mass of the K₂CO₃ powder is about 25-30 grams and together with the powder 10 it is about 60 grams.

![Fig.3. The spray cloud evolution in result of “wet seed injecting”](image)
Apart from the above “dry seed injector” using the powdery potassium carbon oxide, the so-called “wet seed injector” system was designed, fabricated and tested. This system works with 50% water solution of potassium carbon oxide. The advantage of the “wet seed injector” is defined by capability of thinner spraying of fluid that advances to the much more difficult powder dispersion and with the considerably more uniform distribution of solution in the HPV before the ignition. It is expected also that wet seed injection could provide the considerably more acceptable allocation of the seed in the working gas mixture and, accordingly, more uniform distribution of the electric conductivity there. The uniformity of the conductivity distribution is a key characteristic of the MHD generator working media especially, at the high Hall parameter values. For spraying of the wet seed the pulse air-operated injector actuated by air high-pressure is used. The injector is set on the side wall of the HPV near to the outlet flange. The operation of the injector was tested in series of autonomous start-up in the open atmosphere. The spray quality obtained in one of those tests is illustrated by high-speed visualization of the wet seed cloud evolution shown in Fig.3.

**Physical Processes inside HPV**

In Fig.4 the time dependences of pressure for probes D1, D2, D3, D4 (marked as 8, 9, 13, 14 in Fig.1) are presented. Analysis of this dependences helps to understand the physical processes inside HPV during experiments.

The experiments are carried out at the initial pressure about 1atm for the near stoichiometric hydrogen/oxygen mixture. After the gunpowder ignition the hot combustion products initiate the hydrogen/oxygen detonation. The initial shock waves propagate in the radial direction to contact with the wall of HPV (look at Probe D3 oscillation in Fig.4). Probe D4 shows that the detonation waves in the axis direction form later, about 10mks. The detonation wave comes to Probe 1 and 2 as fully formed. Then one can see the shock wave moving as reflected from HPV back ends. Such a process decays significantly in 12-14 turns. The pressure peak could be reduced if the ignition would be realized at many locations of HPV at the same time.

The powder spraying occurs during about 100ms, because the signal modulation from the powder particles blows on place of nearest Probe D3 shows on that. In result of such blows the signal thickness become thicker.

In Fig.5 the time dependence of temperature \(T_{\text{Wb}}\) after decoding of Tungsten-Renium thermoelectric couple recording and pressure for Probe D3 are presented. In Fig.5 one can see that during ~35 ms after hydrogen/oxygen combustion the thermoelectric couple heats up its temperature becomes about 3500°C. After every run the wire of
the thermoelectric couple became thinner and after forth run it is totally burned out.

**MHD Generator**

As intermediate MHD generator model in the first series of experimental runs the MHD generator channel, designed and made in IVTAN more than 20 years ago was used. Geometry of the channel is rectangular cross section linearly expanding on electrode walls from the channel inlet of $25 \times 40 \text{mm}^2$ to the exit of $25 \times 80 \text{mm}^2$. The length of the channel is of 485 mm. The channel was designed for long-duration continuous operation (about 30 mines) and for this reason was to be intensively cooled.

![Fig.6. The channel #1 after repairing](image)

The channel is the Faraday type segmented with the peg-type insulation walls. There are 16 electrodes on each electrode wall. The electrodes are the copper cups filled in with a high thermal ceramic stuff on the basis of zirconium oxide or of lanthanum chromate, which ones have enough high electric conductivity at temperatures above than several hundreds of degrees for lanthanum chromate and above 2000K for zirconium oxide. The size of the electrodes in stream-wise direction is about 20mm, and in the transversal direction is equal to the distance between the insulator walls (25mm). The electrodes are equipped with the individual cooling system, with an effective galvanic insulation, that is an indispensable condition for an effective work of the MHD generator. The interelectrode insulators of the electrode wall are made of the insulation high thermal ceramics such as magnesia or alumina. The thermal operation mode of insulators id determined by conductive thermo exchange with adjacent cooled electrodes. Metal modules of an insulation wall of dimension on a hot surface approximately $20 \times 30 \text{mm}^2$ are also water-cooled.

In this series of experimental researches with rather short time of flow of a high temperature working media - combustion products of hydrogen in oxygen, the need for cooling the channel is missed, and the channel is used in a heat sink mode. Unfortunately, the inspection of the channel conditions after 20-year idle has shown that it should be heavily repaired. The channel after the repairing is shown in Fig.6. This channel referred as #1 in this experiments was used in the first stage of the experiments as a flowtrain-closing element to provide the integrated facility tests and tuning.

![Fig.7. The channel # 2 in the assemblage.](image)

For the main research of the MHD energy conversion under rated conditions the new high temperature ‘hot’ channel of the heat sink type has been designed and fabricated. The basic high temperature material used for this channel (referred as channel #2) is alumina formed in bricks of several different shape. The electrodes of the channel #2 (16 at each electrode wall) are made of high temperature metals (niobium and molybdenum). As an inter-electrode insulation the alumina is also used. The geometry of the channel #2 corresponds exactly to geometry of the channel #1. The channel #2 in the assemblage stage is
shown in Fig. 7. The insulator wall of the channel #2 is pictured in Fig. 8.

**Loading**

Under experimental conditions rather high values of the Hall parameter are expected (from 2 up to 5). For this reason the original idea for the loading scheme was to use a single load diagonally connected. An specially designed and fabricated inverter was installed. To provide the experimental flexibility the remote switchboard was also developed. The schematic diagram of the loading is presented in Fig. 9. The general view of the remote switchboard is shown in Fig. 10. The mentioned flexibility was effectively utilized when the standard loading scheme for a segmented Faraday channel was introduced in the last series of the experiments.

![Fig. 9. The diagonal scheme of loading.](image)

**Magnetic system**

As a magnet system the electromagnet with an iron magnetic circuit is used. The magnetic induction in interpolar space is uniform enough. The rating value of magnetic induction is about 1.6 Teslas. The general view of the magnet system is shown in Fig. 11.

![Fig. 11. The magnet system.](image)

**Supersonic Diffuser**

For maintenance of nominal flow in the MHD generator channel especially at its nominal loading the supersonic diffuser was designed and fabricated. The geometry of the diffuser is elected as linearly expending, that on evaluations could guarantee the conservation of a supersonic flow regime on over the whole flow-train length from the nozzle throat section up to the exhaust in the vacuum gasholder. The important feature of the diffuser is the electrical insulation of external surface for an avoidance of a breakdown between the diffuser and grounded elements of the vacuum gasholder. Besides with the purpose of current leakages avoidance on grounded circuit elements the sealing contains an insulator in a place of diffuser coupling with the vacuum gasholder.

![Fig. 12. The supersonic diffuser.](image)
The flange in the diffuser mid-range is intended for joint with the vacuum gasholder. On this flange the insulation is installed.

**Experimental Research**

During the first series of experiments being discussed in this paper 17 MHD runs have been carried out. The summary information is listed in Table 1.

First runs were conducted with the restored water-cooled channel in the heat sink mode (channel #1 in Table 1). The channel has demonstrated quite satisfactory qualities as a gas dynamic device. The supersonic flow regime with a Mach number on an entrance 1.8 and on an exit 2.4 is confirmed by open circuit voltage and, qualitatively, by static pressure measurements in the channel.

The channel #1 has demonstrated the much worse performance as an electric machine. The poor results obtained with the diagonal loading scheme have caused the change of the loading scheme to the much simpler Faraday type with the active resistance individually connected to each electrode pair. The same loading was used later with the channel #2 as well. The important intermediate result obtained with the channel #1 is that the dry seed injection system operates probably in a non-desirable mode with non-regular seed distribution in the working media. The wet seed injection system resulted in the obvious improvements of the MHD generator performance. The main result obtained with the channel #1 is the confirmation of the gasdynamic operation mode by the open circuit voltage measurements exemplified in the Fig.13. The correlation of the experimental data with the computational results is quite satisfactory. The open circuit voltage is \( V_{oc} = UBd \), where \( U \) stands for flow velocity, \( B \) – for magnetic induction, and \( d \) – for interelectrode gap.

At the same time the measurements of the short circuit electrode current revealed a big difference from the expected values of about 10 Amps/electrode.

The channel #2 was implemented starting from run #8. As anticipated the channel #2 made of high temperature ceramics material should provide higher performance. Generally speaking such expectations are confirmed during the experiments, however, the electrode currents reached with this channel are still much lower as compared with the computational predictions. After 10 runs the channel was opened for inspection. The

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<th>Loading mode</th>
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<th>Average current, A</th>
<th>Max voltage, V</th>
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Table 1
conditions of the main elements: electrode and insulator walls are estimated as very satisfactory. No significant damages due to both high thermal and mechanical stresses and/or electrical erosion have been recognized. The molybdenum electrodes are quite good, except the 11th cathode with some appearance of electrical erosion – this electrode collected the maximal current above 3 Amps. The general view of the channel #2 after 10 runs is presented in Fig.14. The long crack in the upper insulator wall is caused during unsafe disassembling, that is confirmed by the original color in contrast to any surfaces exposed to the hot flow.

Numerical Simulation

Several different numerical models are used for the prediction and post-experiment analysis and interpretation. Generally the approach is based on the 2D-time dependent full Navier-Stokes equations coupled with 2D electrodynamics in MHD approximation optionally included the finite rate kinetics with reduced reaction/species scheme. The basic model is described in detailed elsewhere [10,11]. In these particular efforts the main results are obtained with the quasi-1D version of the basic model. The reduction is motivated by the physical feature of the phenomena studied (the long narrow flow-train) and by the intention to decrease significantly the computational time to the level acceptable for the PCs capability. The gasdynamics is described on the grid with only 4 mesh cells in the transversal direction, but with approximately 600 cells along the whole flow train including the high pressure vessel, the subsonic/supersonic nozzle, the MHD channel, and the diffuser. Due to the very fast processes the standard reduced chemical finite rate kinetics for hydrogen/oxygen mixture is utilized. The electrodynamics of the MHD generator channel is described with the properly averaged generalized Ohm’s law including semi-empirical treatment of the imperfectness of the insulation elements, the finite segmentation, the arcing discharge on the electrodes and others ‘real’ effects as it was earlier developed for the large- and middle-scale MHD generator description [12].

Discussion

The gasdynamics characteristics of the flow are defined by the features of the working media generator. The latter operates in significantly non-steady state mode that corresponds to the detonation waves propagating along the 10m-long high pressure vessel after ignition. As it can be seen from Fig.4, the pressure (and, correspondingly) temperature at the outlet of HPV fluctuates significantly with the main frequency about several hundreds Hertz. The pressure measured in subsonic part of the nozzle reveals clearly the non-steady state behavior. An example of the pressure measurement is presented in Fig.15. The significant difference in the experimental and calculated curves are caused by the rather rough discretization used in HPV, from one hand, and by poor time resolution of the pressure transducers, from the other hand. The simulation with the finer grid (several hundreds mesh points) provides much better resolution even in higher harmonics. Another important conclusion is that the average pressure drops obviously in hundreds milliseconds time scale. This is explained by the working media cooling due to radiation losses to HPV walls that results in a rather short time available for MHD generator operation. The pressure and temperature fluctuations are good correlated with the fluctuations of electrodynamics parameters of the

Fig.13. The open circuit voltage as measured with the channel #1. Crosses are for the high pressure mode, Circles – for low pressure mode. Curves – 1D calculation.

Fig.14. The channel #2 after 10 runs.
MHD generator. In Fig.13 the open circuit voltage measured in the channel #1 at different time of the same run. The upper curve corresponds to the pressure pick, and the lower – to the pressure next minimum. The sensitivity of the open circuit voltage to the pressure level depends strongly on the electro-physical imperfectness of the channel elements and on the Hall parameter value. The decreasing of the pressure and temperature results in increasing of the Hall parameter under experimental conditions in several times. The similar data for the channel #2 presented in Fig.16 confirm indirectly the better quality of the channel #2.

Fig.15. Evolution of the pressure at the nozzle (experiment) and in the MHD channel (simulation).

Fig.16. The open circuit voltage measured in the channel #2 for high pressure (crosses) and for low pressure (circles) operation.

The short circuit current distribution along the channel#2 is presented in Fig.17 along with the calculation results. In this case the correlation of the experimental and calculated data is rather poor, only the average values are in some agreement, but the character of the distributions are qualitatively different. There is no satisfactory explanation of this fact and one can assume that the electrodes reveal very irregular characteristics, probably, due to off-design thermal regime and the arcing mode of the electrode discharge.

Fig.17. Confrontation of experimental and computational short circuit current distributions lengthwise of the MHD generator channel.

Fig.18. Electrode current distribution along the channel #2 in power extraction run #15. The upper curve corresponds to high pressure operation mode, the lower – to the low pressure operation mode. Curves represent the calculation results under conditions of Fig.16.
The power generation mode was estimated from the data on open circuit voltage and short circuit current. The load resistance for each electrode pair was chosen the same. Two different values were used, \( R_{\text{load}} = 30 \text{Ohm} \), and \( R_{\text{load}} = 12 \text{Ohm} \). With lower value the maximal integral electrical power was reached – about 300 Wts that corresponds to less than 0.1% of enthalpy extraction instead of the expected level of about 1%. The Fig.18 presents the current distributions along the channel in the power extraction experiment #15. The big difference between the high and low pressure modes could be considered again as an indirect confirmation of the strong Hall effect appearance under conditions of the channel imperfectness. The Hall potential (the voltage between the first and last electrode pairs of the channel) measured at the level of several tens of volts instead of several hundreds volts predicted in simulation proves probably such a hypothesis.

The dramatically reduced Hall field is defined probably by the imperfectness of the insulation, the finite (and very rough in this case) electrode segmentation, by the high electrical resistivity of the cold boundary layers, and other real effects.

**Conclusion**

The first series of experimental study of the model of on-board MHD generator working with the exhaust of scramjet has been carried out at the newly constructed MHD experimental facility. The facility is based on the huge shock wind tunnel of TSNIImash and a small scale MHD generator of IVTAN. The facility operates in blow-down mode with hydrogen/oxygen combustion products seeded by dry or water solved potassium oxide.

Two MHD generator channels are tested in this experimental series. The channel #1 is the old originally designed for long-duration operation water-cooled channel of Faraday segmented type. The channel was strongly repaired and adopted to the short duration operation in heat sink mode.

The second newly designed and fabricated channel #2 is basically made of high temperature material such as ceramics for insulation elements and high temperature metal (molybdenum and/or niobium) for electrodes. The condition of the channel after 10 runs is quite well.

The supersonic flow from Mach 1.8 at the channel inlet till Mach 2.4 at the channel exit is provided by supersonic nozzle and supersonic diffuser. The static pressure in the channel varies between about 1 atm at inlet and .3 atm at the exit, the stagnation temperature is about 3500K. The mass flow rate is about .1 kg/sec.

The open circuit voltage under the Faraday segmented loading conditions is in satisfactory agreement with predicted values. The short circuit current reveals a rather irregular behavior and differs significantly from the predictions. The main reason for such a discrepancy is preliminary assumed as strong imperfectness of insulation, off-design wall temperature and the finite rough segmentation ratio under the strong Hall effect conditions (the Hall parameter estimated for high pressure mode as high as 2-3, and up to 10 for the low pressure operation mode).

The maximum power extracted in this series is about 0.3kW for the Faraday segmented loading scheme. The diagonal connection was operated in far from on-design condition that resulted in none recorded power. The main reason is probably the same as mentioned above – the dramatically reduced Hall field.

The non-steady state operation nature of the working media generation could be responsible for the over predicted performance of the MHD generator. The significant improvement of the facility operation mode can be provided by modification of the ignition of the hydrogen/oxygen mixture, by father improvement and controllability of the seed injection, by compensation of the radiative heat losses to the HPV wall with additional fuel injection. introduced in Fig.11. So, the real calculated curve is received at the same values of non ideal arguments, which one have supplied as average the coordination of the short circuit current distributions.

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