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LESSONS LEARNED FROM STUDY OF MHD FLOW/FLIGHT CONTROL IN HIGH SPEED AIRFLOWS

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Abstract. The series of successful experiments with the surface MHD electrical power generation in hypersonic flows is presented and discussed. The preliminary interpretation of the experimental results is given on the base 2D numerical simulation in two cross-section planes. The dominating role of the Hall effects and primary 3D nature of the flow under experimental conditions is recognized as a main factor resulting in complexity of the phenomena. On the other hand the reliable experimental results confirm the prospective such a technique for practical applications.

I. Introduction

Potential applications for the use of MHD interaction in control of external and internal flows on a hypersonic vehicle have been studied by the authors during the last decade (see, for example,[1-16].and references there). Both experimental and theoretical efforts have been undertaken to provide insight into understanding the specific governing phenomena for these MHD aerospace applications as compared with the more familiar terrestrial MHD energy conversion processes.

Several promising areas for MHD in aerospace applications have been hypothesized, including,

- MHD control of external flow to redistribute the pressure and heat fluxes over the vehicle surface;
- MHD control of internal flow to optimise the ramjet/scramjet operation efficiency by redistribution of heat and momentum release/extraction along the engine flow path;
- MHD intensification of mixing in co-flow fuel/air streams to control ignition and enhance combustion in ram/scram jet combustors;
- On-board MHD electrical power generation utilizing the kinetic/thermal energy of oncoming airflow;
- MHD control of boundary layers encompassing separation flow and location of transition points;

The experiments have been performed by the authors in research of these areas at three different experimental facilities:

- MHD Assisted Hypervelocity Wind Tunnel (MHDWT). This facility provides the real hypervelocity flow over models (M ~12-15);

- Subsonic Wind Tunnel Driven by High Frequency Plasmatron (HFP) at TsNIIMash providing high enthalpy typical to hypersonic flights;
- Large Explosive Driven Shock Tunnel (LEDST) used for simulation of scramjet exhaust flow in on-board MHD generation studies.

These experiments have been analytical supported by the computer code family, “PlasmaAero,” which is a 2D, time dependent formulation of the full Navier-Stokes equations coupled with 2D electrodynamics solver and capable of optionally extension to include chemical kinetics solver providing simulation of the finite rate kinetics of seeded airflow and combustion of hydrocarbons. An MHD assisted engine cycle analysis has been carried out with the special flow train model utilizing the air combustion products properties extended with simple simulations of the finite rate kinetics and electron-beam ionization.

The research approach that has been followed in both the experimental and analytical studies by the authors has been to maintain realistic features for on-board MHD systems. These include, for example,

- magnetic field configurations that correspond to on-board implementation constraints, resulting in significantly non-uniformity of the magnetic field distribution,
- electrodes for MHD devices prototyped as required for installation on the surface of the models tested;
- classical model configuration (simple as possible) to separate the MHD interaction effects from the general MHD hypersonic flow phenomena.

A principal lesson learned from the experimental investigations conducted under our study of MHD interaction in hypersonic flows is that segregation of phenomena is extremely difficult to organize. Besides the phenomena/observations that are conventional to hypersonic aerothermodynamics, the additional electrodynamics features present with MHD interaction results in hypersonic “magneto-plasma-aerodynamics - MPA” which becomes an issue for experimentalists. The electrophysical properties of the test section and model surfaces can dramatically affect the phenomena being studied. The actual electrodynamics boundary conditions in experiments are critically important. Typically, hypersonic flow in test sections is created with some kind of energy release into the flow to simulate the high enthalpy conditions of real hypersonic flight. The huge energy release that is needed for this purpose results in a significant change of composition and the electro-physical properties of the working media.

Another class of problems arises from limited model size. First of all, MHD interaction influence on the flow depends on the size of the interaction region over which this occurs. In experiments, this is typically from one to two orders of magnitude less the size of real hypersonic vehicles. A second related problem is that the small size makes the finite rate kinetics important, which is not as critical under real flight conditions.

Due to these stated facets of experiment constraints and others features of ground test MPA hypersonic experiments, the role of the supporting numerical simulation becomes increasingly important in developing of understanding. Numerical modeling has to be adequate to both: properly describe the experiments and to be used to extrapolate the experimental results to real flight conditions.

Three model configurations have been studied in details, i.e.,

- a right circular cylinder with a axial current in cross flow of hypersonic seeded airflow;

- the family of wedges (including a wedge with an opposing cowl) in seeded hypersonic airflow;
- a flat plate under angle of attack in both seeded and unseeded hypersonic airflows.

The actual MHD interaction parameter estimated for the experimental conditions of our studies varied from .01 to 0.5 which is strong enough to reliably derive MHD interaction effects. The numerical model that has been used has provided adequate description of the experimental results over whole range of the experimental conditions. This validation with experiment has allowed us to extrapolate the results to a full-scale hypersonic vehicle and to project phenomena to actual flight conditions, in particular, a strong reduction of the peak heat flux making use of MHD interaction attractive for practical applications.

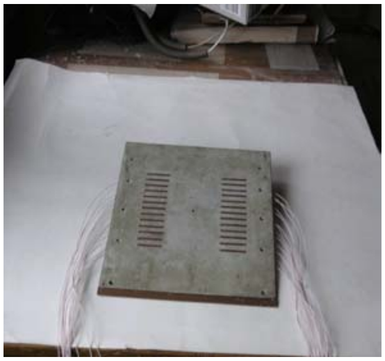

Fig.1. The model assembled.

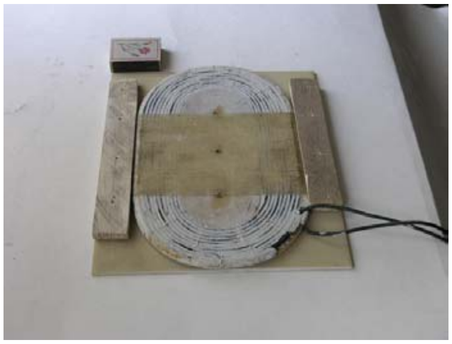

Fig.2. The magnetic system coil.

The importance of the recent experimental studies is that the same models of the surface MHD Power Generation/Flow and Flight Control Systems are used in two different experiments: (1): at subsonic high frequency plasmotron driven facility, and (2) at hypervelocity MHD assisted wind tunnel.

The recent experimental results on power extraction obtained with the new models at the Hypervelocity MHD Driven Wind Tunnel Facility and some preliminary 2D simulation are discussed in this paper.

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II. Model Definition

To study MHD interaction in high-speed seeded air at Hypervelocity MHD

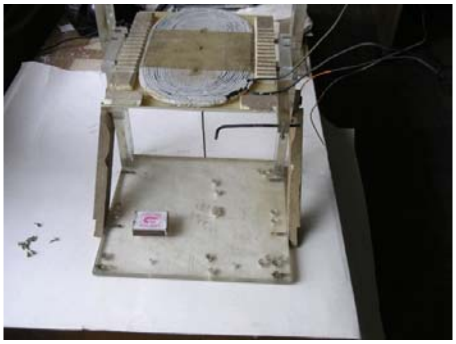


Fig.3. The model on the holder during assemblage.

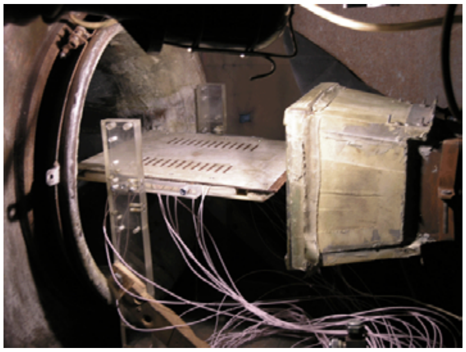


Fig.4. The model in the test section

Wind Tunnel Facility (HV MHD WT) the compact MHD generator the model of the same design as used at HFP WT was fabricated. The insignificant modifications were introduced into the model configuration in order to fit the test section requirements. This model shown in Fig.1 through Fig.4 comprises 13 pairs of stripped electrodes located at one of surface of the thick plate.

This surface is coated with the layer of thermal-protective ceramics. Within the plate body the oval-shaped magnetic system is mounted. The magnetic system represents the coil with 20 turns of copper wire of 2 mm diameter (Fig.2). Such a compact model has advantaged in that it can be positioned into the core of flow, and no flow halt takes place as was with the earlier models. These compact MHD generator models were used in both HV MHD WT Facility and in HFP WT Facility.

Six runs have been carried out at HV MHD WT Facility in which standard flow in test section has been performed. The MHD generator model described above was positioned in the core of the flow at angle-of-attack 2 grads just at the secondary nozzle exit (Fig.4). The maximum current in the magnetic coil was 8 kAmps that corresponds to the maximal magnetic field near the model surface about 2 Tesla.

III. Measurements

The electric characteristics were measured with 4-Channel digital oscillograph ACK-3107. This device is capable of measuring the input signals of frequency up to 100 MHz.

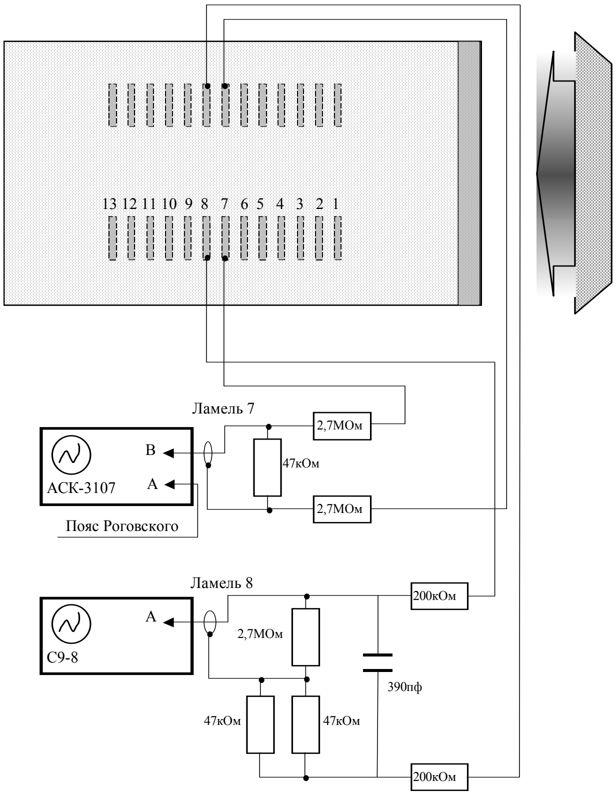


Fig.5. The schematic diagram of the electrical measurements.

The schematic diagram of the measurements is shown in Fig.5.

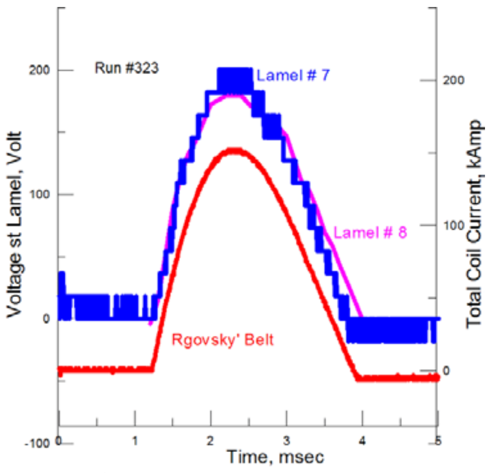


Fig.6. Potential variation in Run 323.

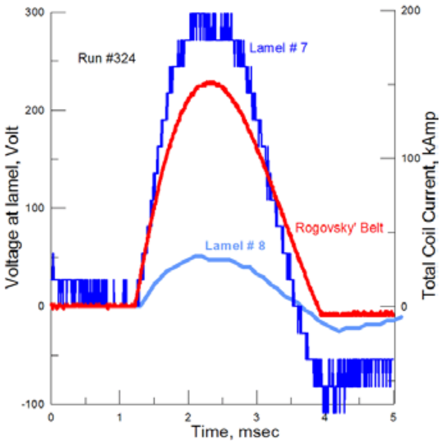


Fig.7. Potential variation in Run 324.

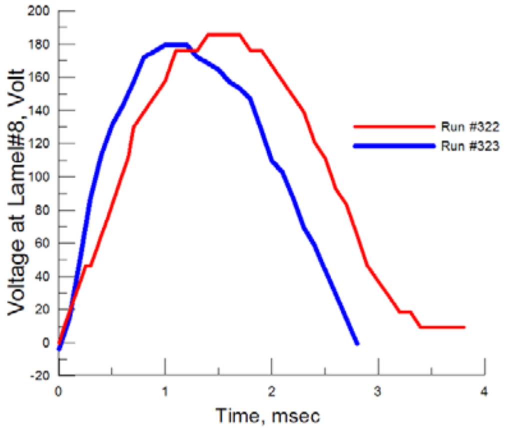


Fig.8. Comparison of the potential variations in Runs 322 and 323.

Photography was made with the digital camera Image Citius C100.

The Faraday voltage has been measured between electrodes of first and seventh electrode pair. This voltage ranged in between 200 – 360 Volts in different runs and was found to correlate well with the current feeding the magnetic system. Fig.6 through Fig.8 represent the voltage and Rogovsky belt signal obtained in one of the runs as function of time.

The MHD interaction process has been recorded with the 2000 fps camera with applying the optical filter designed for atomic oxygen 777.2 nm spectral line. Typically five frames appeared to capture the MHD interaction time period.

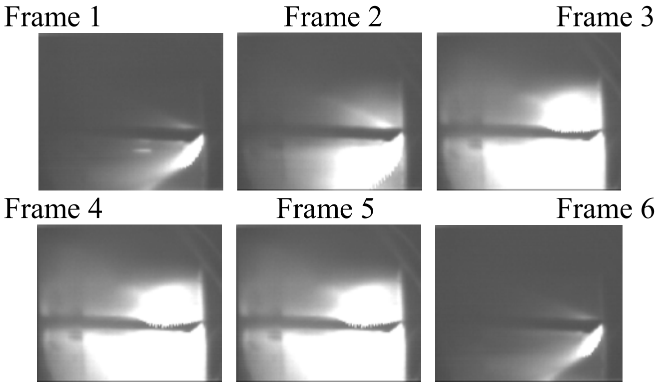


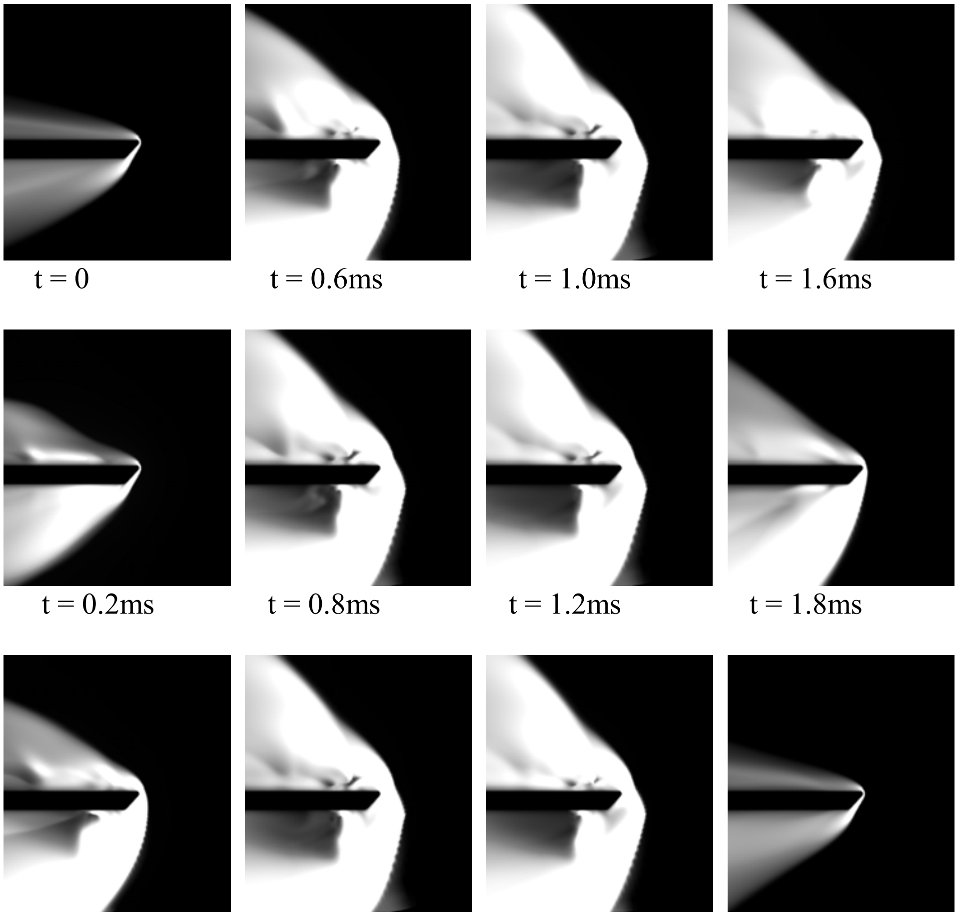
Fig.9. Visualization of flow around a thick plate;
2 ms magnetic field pulse; Bmax ~2 T.

The comparison of the potential variation in twoo runs 322 and 323 could hel in principle to evaluate the effective resistance of the near electrodes area. The potential curve recorded in Run 322 is shifted due to a capacitor introduced into measurement scheme. The interpretation of this effect is now in progress.

Visualization of the flow is presented in Fig.9. In the pictures the flow comes on the plate from right to left. The flow angle-of-attack is ~2.0 grad. Visualization reveals some new features of MHD interaction in comparison with those found in the previous studies of MHD flow over the wedges. Namely, more intensive interaction takes place below the opposite (bottom) side of the plate. This is probably due to skewed leading edge of the plate. The fact of MHD interaction around the plate, rather than other phenomena, detected with higher luminosity has been checked through the numerical simulations.

IV. Numerical Simulation

Numerical simulations of MHD flow around the plate have been carried out with the computational model proved to be adequate to simulate flow in HV MHD WT Facility. It is based on solution to Navier-Stokes equations for hypersonic flows coupled with solution to equations for quasi-steady electrodynamics field. There two key features

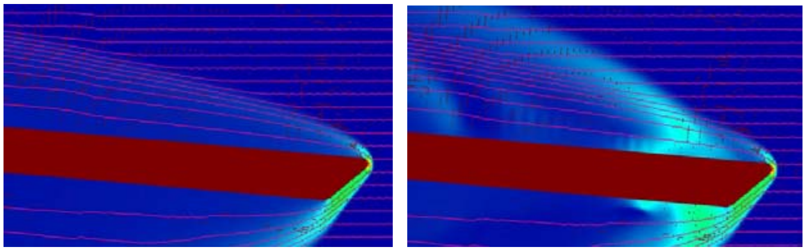


t = 0 t = 0.6ms t = 1.0ms t = 1.6ms

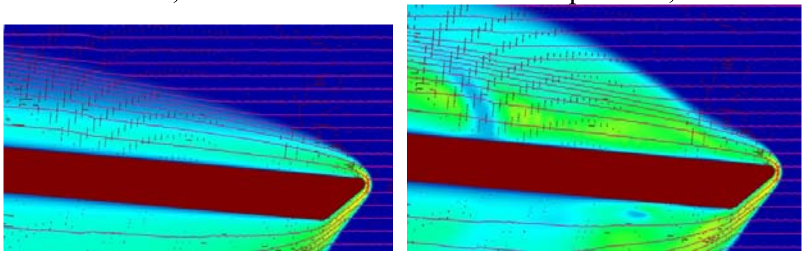
t = 0.2ms t = 0.8ms t = 1.2ms t = 1.8ms

t = 0.4ms t = 0.9ms t = 1.4ms t = 2.0ms

Fig.10. Numerical simulation of flow around a thick plate.
2ms sinusoidal magnetic field pulse; Bmax = 2T.



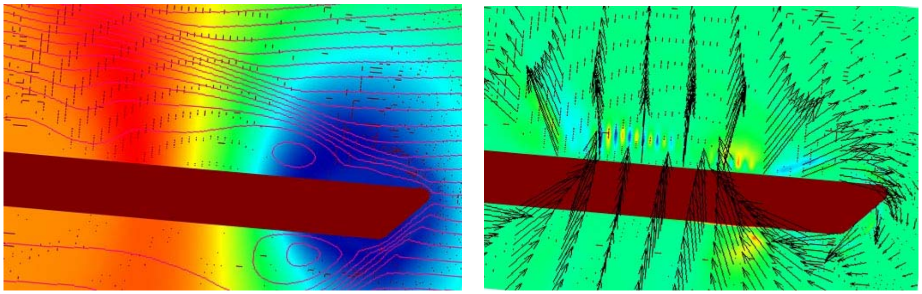
Pressure, B = 0 Temperature, B=0



Pressure, B = 2T Temperature, B = 2T

Fig. 11. Pressure, temperature and flow stream lines for AoA=5^o case

taken into account in solving the electrodynamics equations, namely, the electric conductivity model and Hall effect. It was taken in simulations that electron concentration appears in high temperature region behind the bow shock at the leading edge of the plate, with maximum value of 1%. The electric conductivity and Hall parameter are then estimated with known electron-neutral and charged-particles collisions. The magnetic system used in computations exactly simulates the real one. 2 ms current pulse has generated sinusoidal magnetic field with maximum value of magnetic induction at the upper plate surface as large as 2 Tesla. The following gas dynamics parameters were specified as initial and inlet boundary conditions.



Potential (filled) and current stream lines

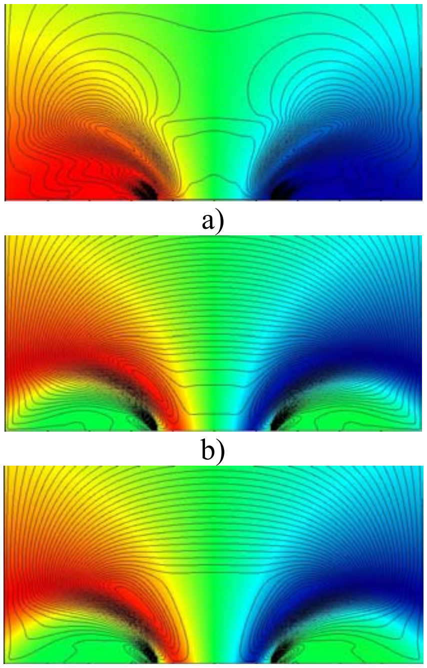
Faraday current density and B-field vectors

Fig. 12. Electrodynamics parameters foe the case B = 2T.

Fig.10 demonstrates the time-dependent evolution of MHD flow during the magnetic field pulse. In the pictures, the temperature field is shown. It is seen that in general evolution of temperature field agrees with experimental frames, i.e. high luminosity correlates with the temperature rise in the regions of interaction. In turn, dramatic changes in the temperature filed are due to MHD interaction below and over the plate.

Gasdynamics and electrodynamics parameter distribution in the center plane in flow direction are presented in Fig.11 and Fig 12. for the case of AoA = 5o.

The electrodynamics parameter distributions in the central cross flow plane are presented in Fig.69. The only small details are changed due to the dramatic loading conditions.


a)

b)

c)

Fig. 13. Potential and current streamlines in the cross flow plane.

a) Faraday open circuit, Hall short circuit;

b) Faraday short circuit, Hall open circuit;

c) Faraday short circuit, Hall short circuit.

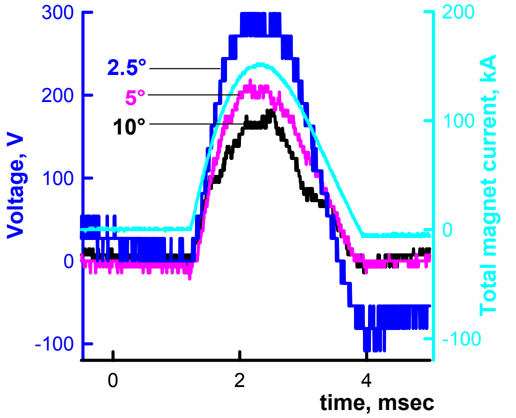
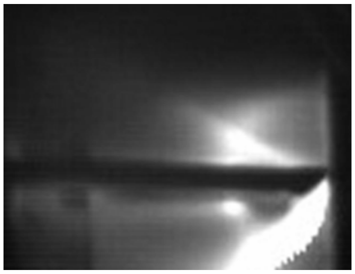
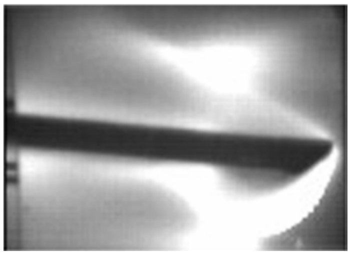


Fig.15. Faraday voltage at 7th electrode pair for three values of AoA (2.5°, 5°,and


AoA = 2.5°


AoA = 5°

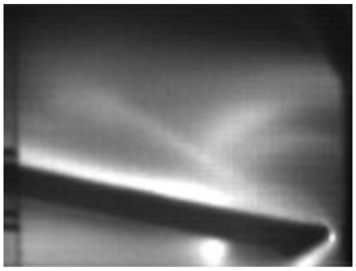

AoA = 10°

Fig.14. Vizualization of the flow field for different Angle-of-attack at approximately maximal magnetic field strength.

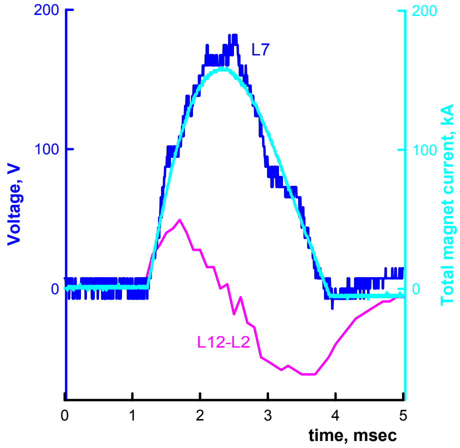


Fig. 16. Faraday (blue curve) and Hall (pink curve) during the magnetic field pulse (light blue curve).

The most disappointed experimental fact at this stage is that there is no current measured even in the case of short circuit conditions. The preliminary explanation is that the contact resistance (at the flow-electrode interface) is too high and the induced voltage at the level of 300V is not enough to breakthrough this resistance.

The measured Hall (longitudinal) voltage between 12th and 2nd electrode pairs is plotted in Figs.15, 16. The behavior of the Hall voltage is not understandable and needs probably more deep 3D analysis.

V. Power Extraction Experiment with Pin Electrodes at HV MHD WT

The pin electrodes were installed at the HV Model 6 at the first electrode pair. The pin is a copper made cylinder of ~2 mm in diameter and ~ 20 mm length. The pin was screwed into the lamel normal to the working model surface as it is shown in Fig.17 through Fig.19. Two successful runs were performed with this configuration. The angle-of-attack was the same for both runs and equal to 10°.

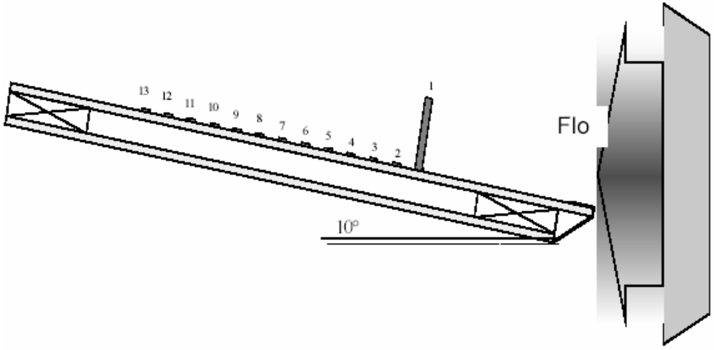


Figure 17. Positioning of the Model #6 with pin electrodes at Lamel 1 in the test section.

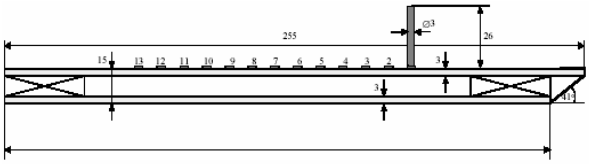


Figure 18. Side view of Model #6 with pin electrode at Lamel 1

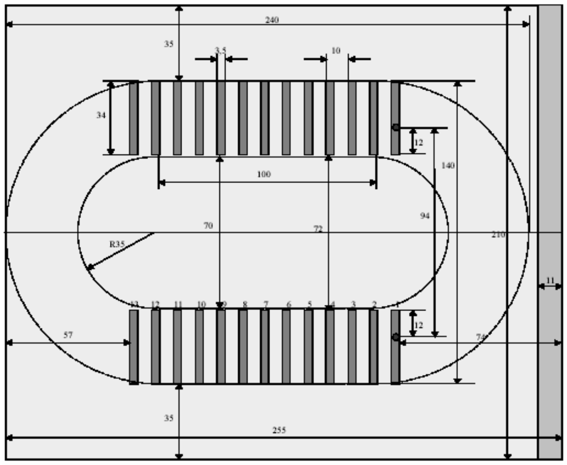


Figure 19. Model #6 with pin electrode at Lamel 1. Upper side view.

All operational parameters of the runs were also the same except the load resistance of the first electrode pair. In the first run of the series the load resistance was 1kOhm, and in the second run this value was 100 Ohms. Some parameters of the measurement scheme were also changed (see for details Fig.20 and Fig.22, correspondingly).

Besides of the electrical parameters measurements the now standard visualization with fast digital camera Citius was used.

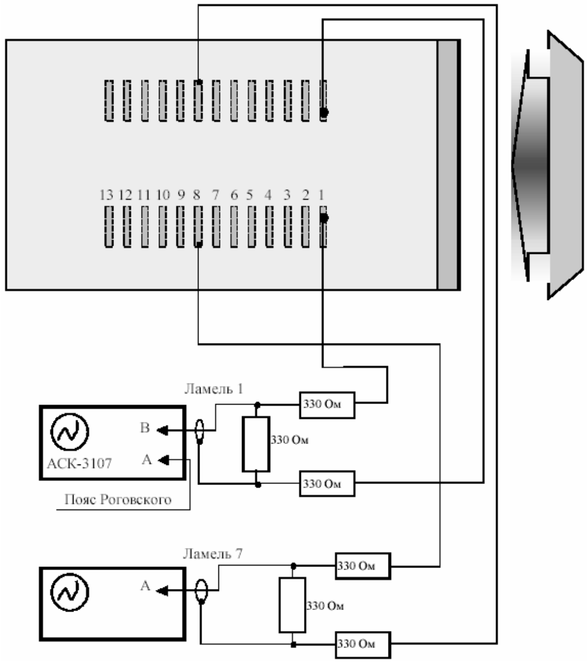


Figure 20. Schematic diagram of the potential measurement at Model #6 in run #331.

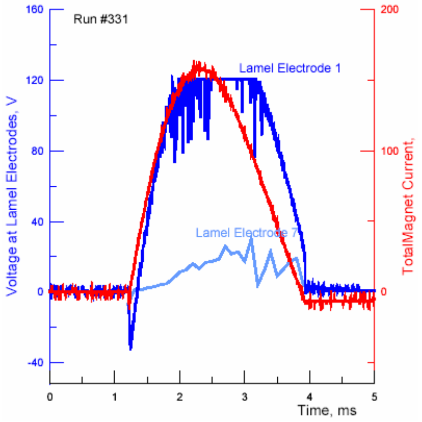


Figure 21. Schematic diagram of the potential measurement at Model #6 in run #331.

In Fig.21 the time evolution of the voltages at the first (‘pinned’) and sevenths (flush mounted) electrode pairs along with the Rogovsky’s belt record are plotted. The dark blue line represents the first pair voltage. The top of the curve is cut due to scaling missing. Nevertheless, the maximal value is estimated as high as 150-170 Volts. The maximal load current is about 0.2 A that corresponds to the maximal power extracted at the level of 30 Watts. The voltage fluctuation visible near the maximal value is probably due to arcing and electrode erosion processes (during the run the pins have lost 25-30% of the length). The voltage of the sevenths electrode pair is found as significantly lower – only ~20 Volts at its maximal value. It should be noted that the voltages jump at the moment of magnetic field is practically the same as it was found in the HFP experiments described above. (The magnet power supply systems are basically the same!) However, due to the high velocity in the HV MHD experiments **u**×**B** contribution into the total e.m.f. acting in the flow is much greater than $\partial B/\partial t$ part.

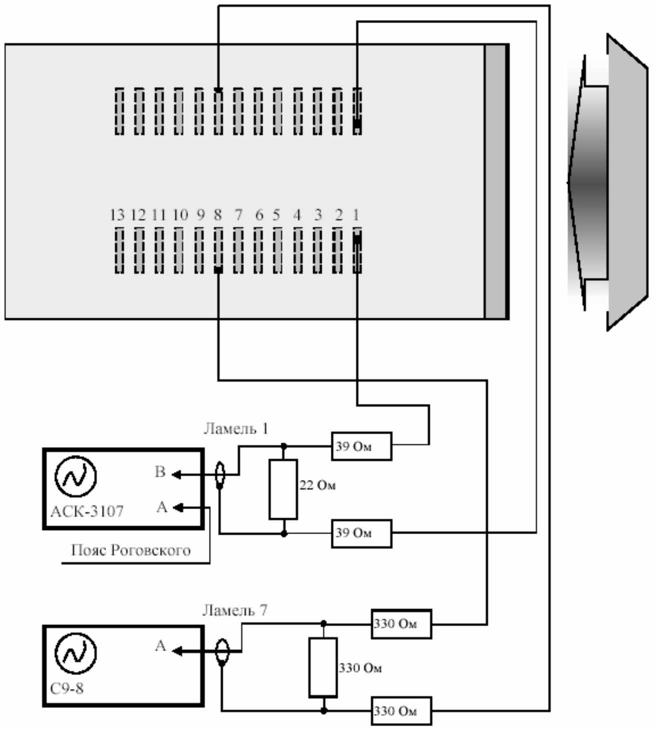


Figure 22. Schematic diagram of the potential measurement at Model #6 in run #332.

The second run of the series was conducted with ten times lower load resistance. The results are plotted in Fig.23. Unfortunately in this run the seed injection system worked unstable and several no current intervals are found on the voltage curve. Nevertheless, the result is now the record of the power extraction experiment in hypersonic flows. The maximal power reached exceeds 60Watts per electrode pair. (The level of 10 Watts/electrode was firstly demonstrated by our team mo re than three years ago with a very simple single-used model. In the previous run the level of 30 Watts/electrode was reached.)

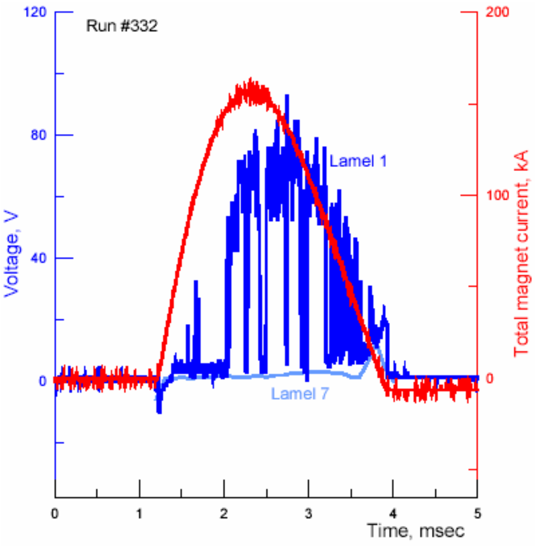


Figure 23. Rogovsky' belt signal (red), and voltage at the first pin (blue) and the seventh flush mounted electrode pairs in run#332. Load resistance100Ohm.

The linear extrapolation based on these two runs gives the maximal power extraction for the experimental conditions as high as 70 Watts/electrode that is only slightly higher than the result of the second run. It means in particularly that the effective flow resistance in respect to single electrode pair loaded is about 200 Ohms. It corresponds to

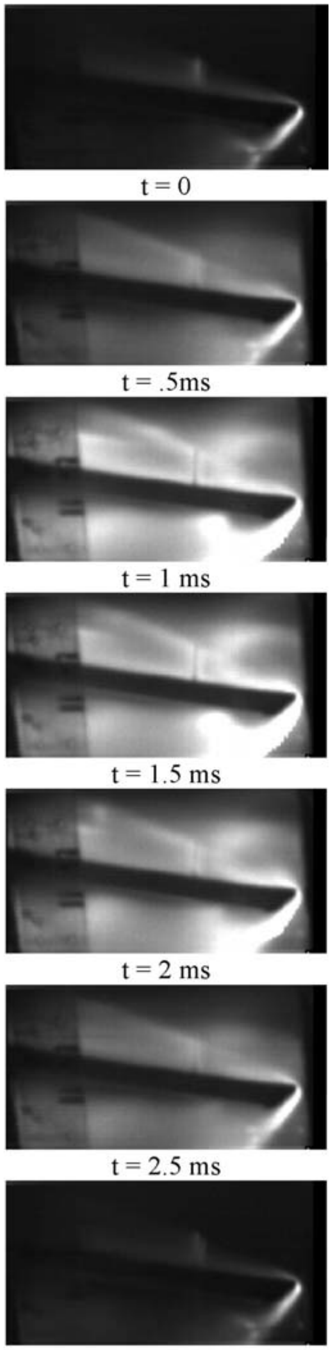

t = 0
t = .5ms
t = 1 ms
t = 1.5 ms
t = 2 ms
t = 2.5 ms
t = 3 ms

Fig. 24 Flow visualization of the run 331 (Load resistance 1kOhm). Magnetic filed pulse covers time interval 0.5 ms – 2.5 ms

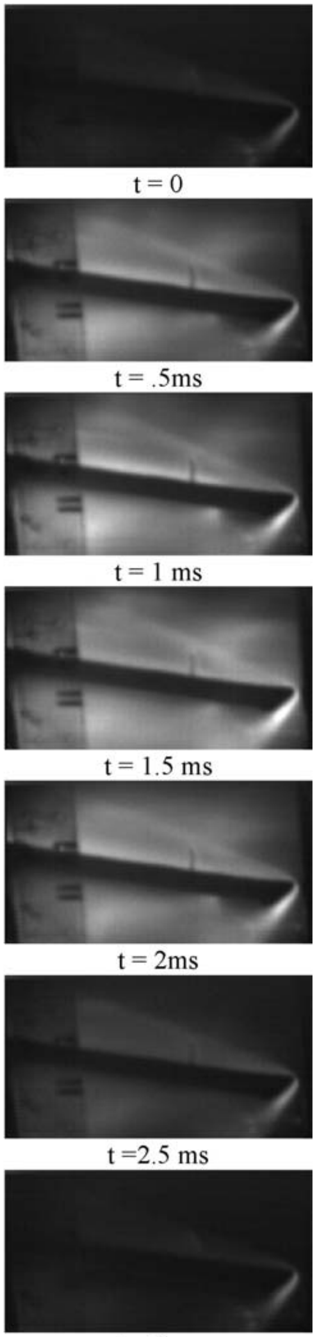

t = 0
t = .5ms
t = 1 ms
t = 1.5 ms
t = 2ms
t =2.5 ms
t = 3ms

Fig. 25. Flow visualization of the run 332 (Load resistance 100 Ohm). Magnetic filed pulse covers time interval 0.5 ms – 2.5 ms

rather very low of effective conductivity of ~ 5mhO/m, that could be attributed to the strong reduction by Hall effect (Hall parameter is not less than 10 at least).

The flow visualization of these runs is presented in Fig.24 and Fig.25 (note that the different brightness between two runs is mostly due to different exposure time rather than due to the physical conditions).

The most recent result on the power extraction with pin electrodes is the level of power extraction ~ 100W/electrode that allows us to evaluate the total power extraction reached ~ 1kW – a psychologically very important value of a 'macroscopic' amount for our small-scale experiment. The record of voltage measured at the load resistance of 100Ohms is presented in Fig.26. (Note that voltage axis marked with 1/5 value corresponding to voltage divider used in the experiment.) The improvement utilized in this experiment has allowed the 'screening' effects of upstream pin electrodes on the downstream ones.

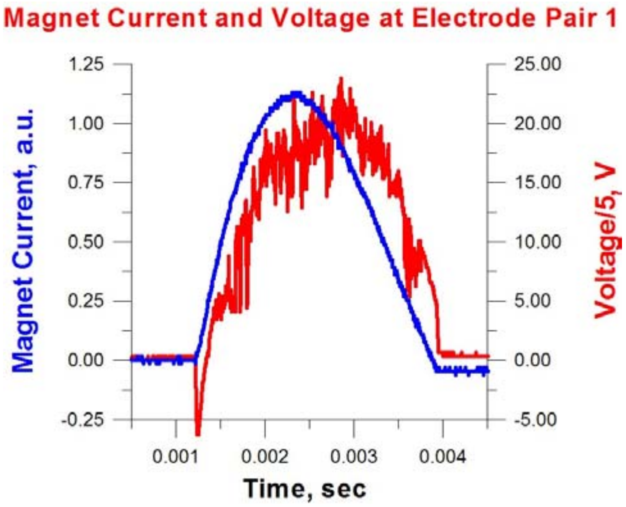


Figure 26. Rogovsky' belt and electrode voltage traces as in the most recent experiment at HV MHD facility.

VI. Smaller Nozzle Experiments

Fig. 27. Model in the test section with Smaller Nozzle before test

Fig.28. Model after the test

The most recent experimental series was conducted with smaller secondary nozzle cross-section to check the effects of flow parameters on the MHD power extraction. The metal made nozzle has approximately two times smaller exit cross-section area. It was resulting in lower Mach number and, correspondingly, in higher static pressure. All other operation parameters were kept at the standard level.

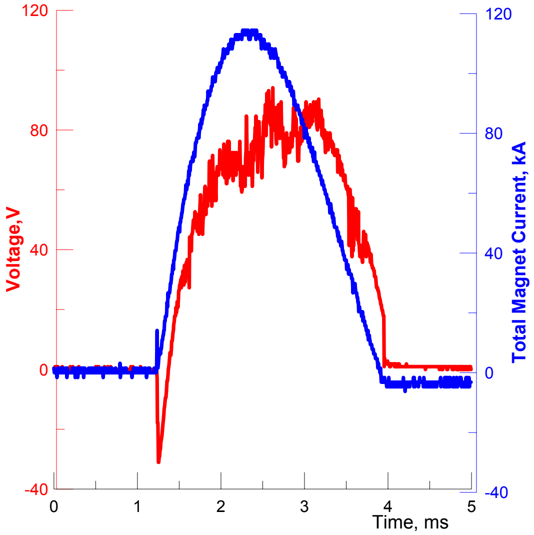


Fig.29. Electrode Voltage and Magnet Current Evolution in Run #338.
R_{load} = 25 Ohm.

In Fig. 27 the renovated model installed in the test section is shown before the test, and in Fig.28 the post test conditions of the model are clearly seen.

The interesting result is that the power output is very conservative, and in the last series of experiments with lower nozzle cross-section exit was practically the same and even slightly higher within the experimental data dispersion.

VII. Conclusions and Lessons Learned

The study of the power extraction with the surface MHD generator proposed for two purposes: (1) to provide the significant electrical power on board during hypervelocity flights in atmosphere, and (2) to use MHD interaction directly through body force and energy redistribution in flow around vehicle and indirectly by using the electrical power extracted from airflow, has confirmed in principal both ideas.

The level of the extracted power in small scale experiment is about several percent of total enthalpy flux, or in absolute values – above 1kW for the model by 0.2cm×0.2 cm.

The MHD interaction and flow field features are significantly 3D, and any 2D simulation can provide under such conditions only qualitative information.

The near-electrode processes are probably dominating in the level of power extraction.

The Hall effect is obviously important, and results in more sophisticated MHD generator configuration for more effective performance.

The next steps of this study will be the surface phenomena investigation along with more detailed and precise description of the experimental conditions.

Leeson 1.

Experimental and theoretical studies of this effort demonstrate undoable the real prospective for MHD applications in aerospace technologies. Electrical power extraction stable demonstrated in more than 20 runs is probably one of the first candidate to be validated in flight experiment. For the proper electrode design and a flight-weight magnetic system the on-board MHD generator can convert significant amount of the reentering vehicle kinetic energy into electricity for on-board usage.

The 'classical' MHD flow control scheme for reducing the heat flux peaks has been also proved by extrapolation of the experimental data to the hypersonic flight conditions.

Prospective of MHD application for internal flow control depends strongly on the availability of not-expensive technique providing the acceptable level of electrical conductivity. Such a problem was out of scope of this program.

Lesson 2.

On-ground MHD experiments on MHD flow/flight control is extremely complicated and expensive. The experimental facilities used in this program were designed for different purposes only slightly related to the main task of MHD research program. For this reason the substantial part of the research efforts was spent to specify the flow conditions in the test sections. Many questions are still unanswered that affects on the conclusions made in this study.

Experimental bed for effective MHD experiments has to be designed, constructed and equipped specifically for MHD (non-conducting test section walls, perfect insulation from the ground, and so on).

Economical MHD pulse operation mode results in the not yet resolved problems of flow parameters diagnostics (pressure, heat flux,…).

The airflow cross-section at the facilities used limits dramatically the size of the model.

Lesson 3.

The experimental characteristics obtained at the very simple model were over predicted at the planning of the experiments mostly because of the complete information on experimental conditions was unavailable. In particularly, the dramatic impact of Hall effect occurs probably due to uncontrollable leakage of net Hall current generated at the model.

In such of incomplete information on experimental conditions the role of the accurate and reliable numerical simulation supporting the experiments becomes critically important.

From the other hand the numerical model has to treat adequately too many factors and physical and technical details and can hardly compensate the uncertainness in actual experimental conditions.

Again, the experiment of fundamental study should be as simple as possible.

Lesson 4.

The study of MHD interaction at a body in airflow must involve rather extended region and must not be localized by the area of particular interest (such as, for example, a vicinity of upstream stagnation point of a blunt body). The wake interaction found at the cylinder results in formulation of a novel concept to use MHD interaction for reentry trajectory modification.

This concept – MHD parachute, could provide dramatic reduction of the peak and integral heat and dynamic loads along the descend trajectory by intensive deceleration in the upper atmosphere. In this case the reentry mission could be much faster and, consequently, the operational requirements to the magnet system become much softer and probably acceptable from technological and economical points of view.

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