43rd AIAA Aerospace Sciences Meeting and Exhibit
10-13 Jan, Reno Hilton, Reno, Nevada
AIAA-2005-0600

Study of MHD Assisted Mixing and Combustion in Counter-Flow Stream

***A.Bocharov*, I.Klement'eva, A.Klimov and V.Bityurin**
Institute of High Temperatures of the Russian Academy of Sciences
Moscow, Russia

INTRODUCTION

The paper is a continuation of efforts intended to develop the tools capable of predicting and analyzing processes occurring in plasma-assisted mixing in non-premixed flows. In [1, 2] the concept of mixing and igniting the non-premixed reagents due to MHD effect has been developed and demonstrated. Based on the results obtained in those studies, the application discharge model has been developed in [3]. It was found that main discharge characteristics are in good agreement with those obtained from numerical simulations of the discharge. In [4] numerical simulations on mixing and combustion of propane in counter-flow jets have been carried out.

In the current paper further development of the discharge model is performed. The emphasis is made on the interaction of the arc with external magnetic field and with the cold flow. Lagrangian approach is developed to describe the motion of arc, change of its shape, potential breakup and re-connection. The thermodynamic and electric characteristics at every point of the arc are calculated with the model [3], and the arc current is found from the external circuit relationships.

The small-scale experimental facility was developed to study an MHD-assisted mixing and combustion. The counter-flow jets of airflow and fuel were considered both experimentally and numerically. The discharge was creating between wire and hollow electrode in the presence of magnetic field aligned with airflow. Numerical and first experimental results on MHD-assisted mixing and combustion are presented.

EXPERIMENTAL SETUP

Experimental facility designed to study MHD assisted mixing and combustion is shown in Fig.1. The main airflow comes into the test section from left to right; the fuel (propane) is injected from right to left.

Mixing takes place within the quartz tube surrounded with magnetic coil (Helmholz coil). Magnetic field is aligned with the airflow. The discharge is created between thin wire electrode also aligned with the airflow and external electrode of cylindrical shape positioned near the insulating quartz tube. Some details of facility elements can also be seen in Figs. 2 and 3. Fig.4 shows a scheme of both numerical and experimental studies.

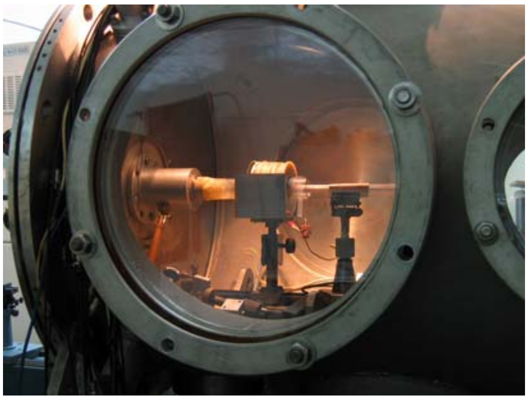

Fig.1. General View of experimental setup.

Fig.2. Close-up of experimental setup.

Typical experimental conditions in the test section were as follows. Static pressure varied from 10 kPa to 25 kPa. Airflow velocity was about 100 m/s . Steady-state (of ~1 sec duration) magnetic field 0.24 Tesla was generated by the magnetic system. The discharge current of 1 Amp and external voltage 1 kV were typically registered.

Discharge and ignition occurs in the inter-electrode gap surrounded by the magnetic coil (in the center of figure).

The discharge visualization was provided with the high speed digital camera Basler A504K of maximal resolution 1280×1024 (pixel size 10mkm^2) and maximal speed 500fps for maximal resolution. The exposure time is from 10 mks.

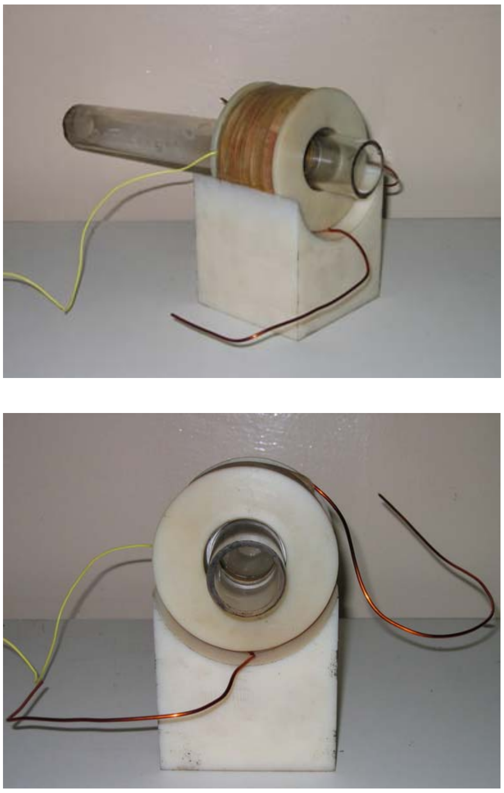

Fig.3. View of magnetic coil with airflow pipe.

EXPERIMENTAL RESULTS

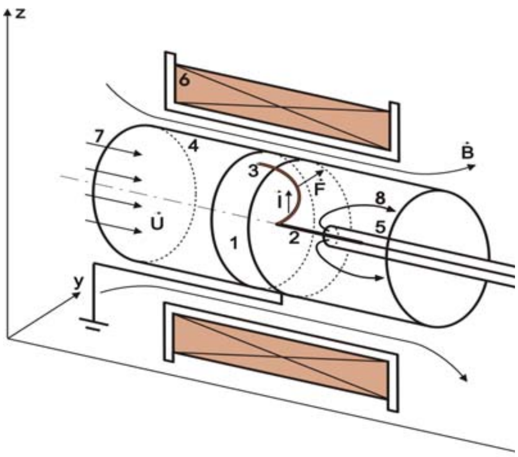

Fig.4. Schematic of experiment on MHD-assisted mixing and combustion. 1 – annular electrode, 2 – central wire electrode, 3 – discharge channel, 4 – surrounding quartz tube, 5 - fuel injection pipe, 6 – magnetic coil, 7 – airflow, 8 – injected fuel.

Three operational modes were tested in this experimental study:
(1) - discharge in magnetic field without flow;

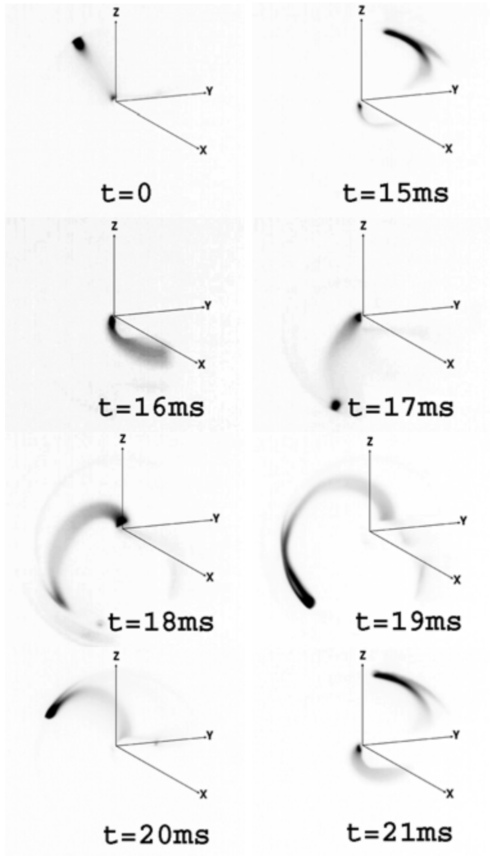

Fig.5. Evolution of the discharge in magnetic field without airflow and fuel injection. P=20kPa, I=0.9Amp, U=650Volts.

(2) - discharge in the magnetic field and with airflow;
(3) - discharge in magnetic field and airflow with injection of propane.

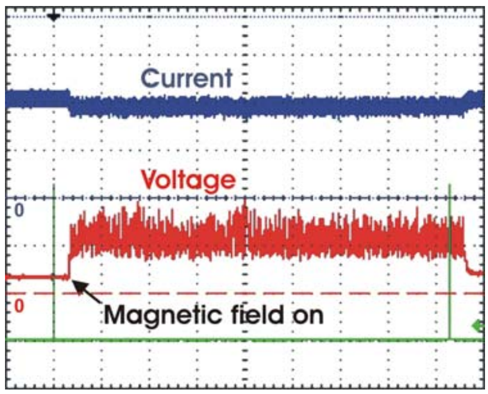

Fig.6. Discharge electrical characteristics in magnetic field for non-flow conditions.

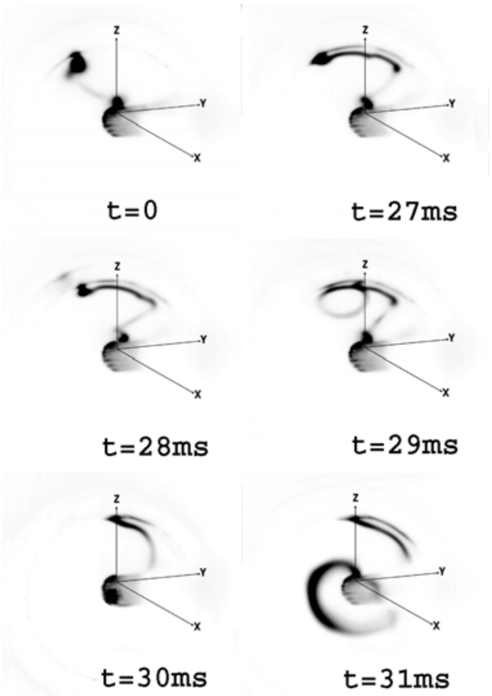

Fig.7. Evolution of the discharge in airflow and magnetic field. P=10kPa, I=0.8Amp, U=1.2kV.

Fig.5 shows the evolution of the discharge for the first case. The current flows from the origin of the

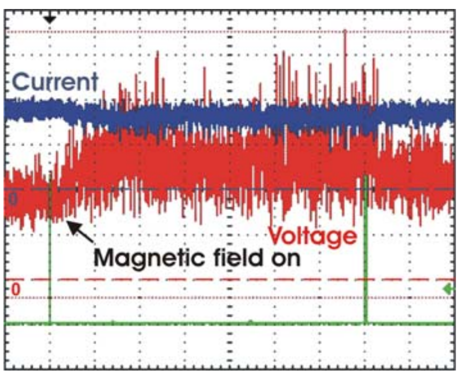

Fig.8. Discharge electrical characteristics in magnetic field for flow conditions.

coordinate axes shown in figure to the cylindrical electrode. Magnetic field is directed along the X-axis. The time moments after switching on the magnetic field are also shown.

The discharge current and voltage traces are plotted in Fig.6.

The magnetic field starts with delay of 32 msec after recording starts. It can be seen that power input into the discharge channel is increased when magnetic field switched on. It corresponds to our earlier

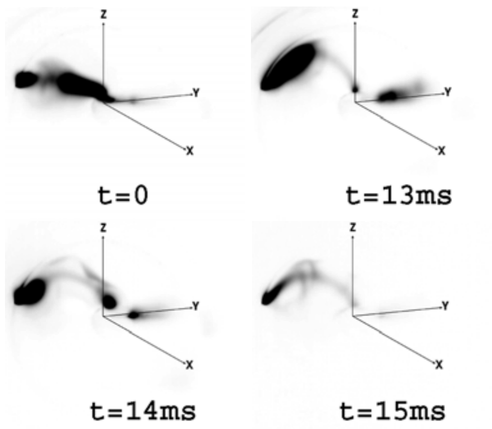

Fig.9. Evolution of the discharge in airflow and in magnetic field with injection of propane. P=20kPa, I=0.85Amp, U=1kV.

observations of the magnetic field effects on transverse discharge characteristics [3]. The discharge shape is obviously defined by interaction with the transverse magnetic field forming a spiral. The important detail of the discharge shape observed is

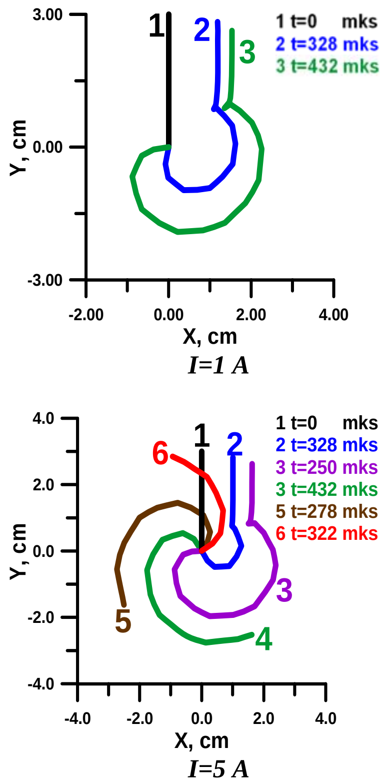

Fig.10. Evolution of the discharge in magnetic field.

the higher curvature of the arc channel near the central electrode.

Fig.7 represents the evolution of discharge in magnetic field and in the presence of airflow. The air flows along the X-axis from the left to the right (in figure). Experimental conditions and time moments are pointed out in the figure. The corresponding oscillograms are presented in Fig.8. Note, that intensity of the arc voltage fluctuations are much more strong pronounced even prior to magnetic field switched on. The higher fluctuation level reveals very well known phenomena of arc-cross flow interaction.
The visualization has shown clearly the flow effects on the discharge shape becoming more irregular near outer wall. Nevertheless, the spiral feature of the discharge is still very well pronounced. Another effect of the flow is the significant discharge elongation resulted in the bright spots well pronounced at the both electrodes (compare frame 2-5 of Fig.7).
Finally, the third operational mode (discharge in flow and magnetic field plus propane injection) is presented in Fig.9. Strong illumination from discharge area corresponds to combustion of injected propane. The shape of discharge becomes much more irregular.

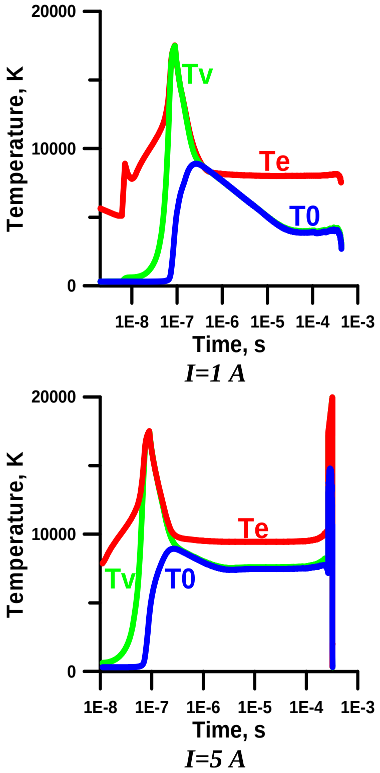

Fig.11. Evolution of the discharge characteristics.

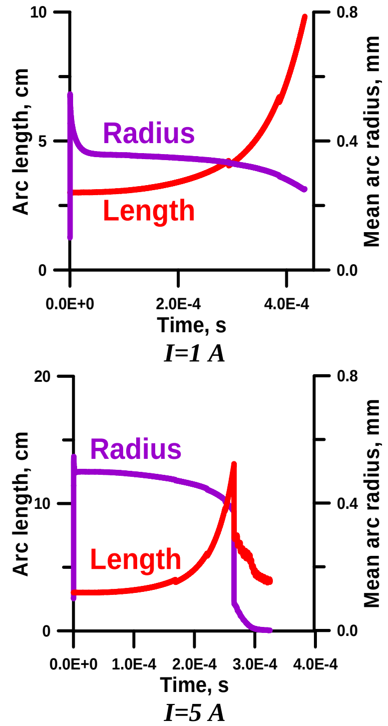

Fig.12. Evolution of the channel length (red) and radius (blue).

NUMERICAL SIMULATION

Numerical simulation of the evolution of the constricted discharge in flow and magnetic field
In the current paper further development of the discharge model is performed. The emphasis is made on the interaction of the arc with external magnetic field and with the cold flow. Lagrangian approach is developed to describe the motion of arc, change of its form, potential breakup and re-connection. The thermodynamic and electric characteristics at every point of the arc are calculated with the model [2], and the arc current is found from the external circuit relationships.
MHD assisted mixing in the cold flow was considered for the discharge configuration similar to experimental one. The discharge is assumed to occur between wire (central electrode) and hollow electrode, that is the hollow electrode of radius of 3 cm restricts second end of the arc, see also Fig.4. Two cases corresponding to applied voltage of 1 kV and 5kV are referred as 1 Amp and 5 Amp discharge, respectively. For both cases the resistance 1kOm was set. Constant magnetic field 0.1 Tesla was specified. The results presented below were obtained for the velocity of airflow 30m/sec, that is quite close to the experimental value (~60m/sec). Fig.10 demonstrates

the shape of the arc at different time moments shown in figure. Fig.11 represents time-dependent behavior of the mean arc temperatures for the cases presented in Fig.10. Fig.12 shows the evolution of arc radius and length. Jumps of the characteristics at the end of

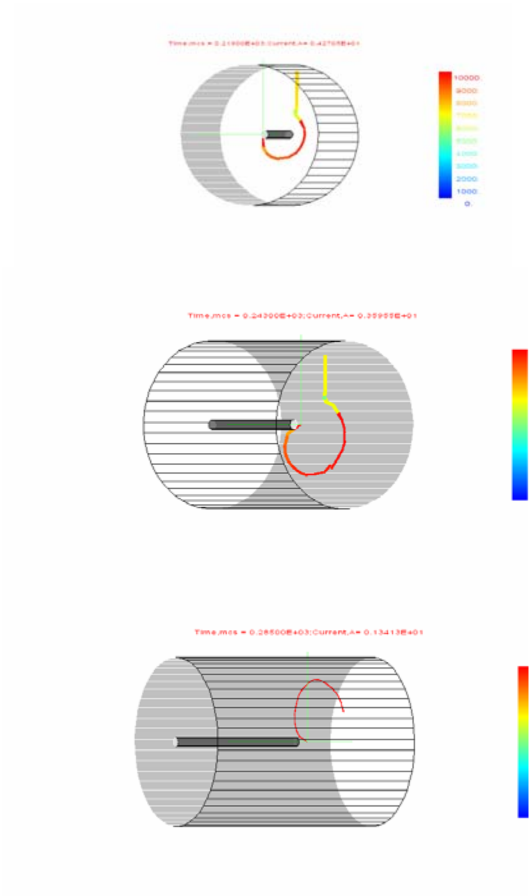

Fig.13. Visualization of the discharge (numerical simulation). Color corresponds to local temperature.

the considered time period correspond to the breakdown of discharge. In the numerical model the latter occurs because the arc becomes long and thin, i.e. its conductance becomes high enough. Therefore, the electric current through the arc vanishes at fixed external voltage. Fig.13 demonstrates 3D visualization of the 5A discharge.

DISCUSSION

The comparison of the experimental and numerical simulation results has shown that in both cases the main features of the discharge channel evolution are similar.

The limited time resolution of the high speed camera used for visualization doesn't allow evaluating accurately the rotation frequency of the discharge channel in the transverse magnetic field under experimental conditions. From the other hand the numerical simulation procedure is still unstable for the parameters closed to the experimental values. For these reason, the most important quantitative comparison experiments with calculation is not available yet.

In the simulation one of the serious problems revealed is a proper description of the near-electrodes region where the discharge channel «fed» by the mass. The total mass of the discharge channel is one the most important parameter of the approach used here.

Despite of the still existing problems both in experimental technique and numerical methods the main positive results has been obtained at this stage of study; the proposed concept of the MHD assisted intensification of the mixing and combustion control in co- and counter flow streams has been proved experimentally and numerically. The **J×B** body force works effectively under practical conditions to increase the reacting volume near the contact surface of the fuel and oxidizer, the configuration tested in the first experiments seems to be rather suitable for the proposed technique, because the flow field provokes the arc to locate along the contact surface.

CONCLUSIONS

The numerical model of evolution of the electric discharge in the flow and magnetic field has been developed and tested for the conditions close to the experimental ones. Two cases of the discharge evolution were considered corresponding to different applied electric voltage values. In both cases the magnetic field was aligned with the airflow. It was revealed that the arc channel takes the shape of spiral with maximal curvature near the central electrode, where one end of the arc is assumed to be fixed. At the second, hollow electrode the permanent re-connection of the discharge takes place. As a whole, the evolution of discharge looks like a rotation due to action of electromagnetic force and re-connection of the arc at the external hollow electrode. This rotation of the arc is considered as the key feature responsible for the extended mixing and ignition of the non-premixed flows.

The experimental facility has been designed to test and confirm the idea of MHD-assisted mixing and combustion in non-premixed cold counter-flow jets. Preliminary experiments on the study of the electric discharge in the counter-flow jets of airflow and fuel (propane) and in the presence of magnetic field were carried out. The behavior of the discharge similar to the predicted one has been experimentally registered.

Comparison of the results of numerical simulation of the discharge with experimental observations shows that the main features of the discharge in the flow and

magnetic field are captured well by the numerical model.
Further efforts should be concentrated on the quantitative evaluations of the performance of mixing and combustion with the method developed.

ACKNOWLEDGEMENTS

The authors wish to acknowledge EOARD for sponsorship of this work through ISTC Contract 2196p . In addition, we recognize contribution by D.Baranov, A.Kuznetsov, D.Yarantsev of IVTAN.

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