HiSST: International Conference on High-Speed Vehicle Science Technology
26–29 November 2018, Moscow, Russia

Mixing enhancement of wall-injected fuel in supersonic flow by spark discharge

Aleksandr A. Firsov[1], Evgeniy V. Dolgov[1], Ruslan G. Rakhimov[1], Michael A. Shurupov[1], Sergey B. Leonov[1,2]

Abstract

This paper presents the result of experimental and numerical study of long spark plasma actuator for mixing of the fuel with supersonic flow for scramjet applications. The afterspark channel decay in ambient air was studied using high speed schlieren system based on fast 8-frame electron-optical image converter camera. For the first time, it is directly demonstrated a strong correlation of jet instability with a local curvature of the discharge channel. Formed at the moment of breakdown, the small-scale perturbations of contact surface between the thermal cavity and surrounding gas lead to formation of small-scale gasdynamic perturbations, which, then, are amplified and transferred by the fast escaping jets caused by bends of discharge. Numerical simulation of mixing enhancement by long spark discharge in supersonic airflow was performed. It is shown that long spark discharge stretches the interface between airflow and transonic jet of a model fuel blown out from a wall-arranged injector in normal to wall direction.

Keywords: *plasma-assisted mixing, supersonic flow, spark discharge, jet instabilities*

1. Experimental research

The mixing intensification is of particular importance due to a limited residence time of fuel in supersonic combustion chamber. A stable ignition and an effective combustion have a need of controlled mixing especially at the phase of cold start-up. The submicrosecond long spark discharge is one of candidates [1] to resolve this problem. It has specific localization in the mixing layer [2] and a relatively small energy deposition (E<2 J/pulse) due to the short duration of the discharge (t=0.1 2μs). Using the schlieren method, it was shown experimentally that the employment of pulse discharge in supersonic flow contributes to the intensification of mixing of components [3-4]. Turbulent gas motion in the post-discharge zone stretches the interface between two gases and increases the rate of mixing of fuel with air in the high-speed flow. The work described in this paper focused on gas-dynamic processes, which appeared at the spark discharge interaction with ambient gas, and on its application to mixing intensification in a supersonic airflow.

The experimental setup consists of controlled spark gap 30-50mm and schlieren imaging system. The electrical circuit for generation of a high-voltage discharge allows the voltage on discharge gap up to U = 120 kV. The 8-frames framing camera for schlieren system is based on an optical scheme with image sharing through semi-transparent mirrors. Each image capturing channel includes an electron-optical image intensifier and CMOS camera. Images of the early stage of the discharge channel were acquired using high optical zoom. It was observed that, at the initial time moment t~20 μs, small inhomogeneities of boundary along entire length of the discharge channel appear. These perturbations look of weak amplitude, but actually they represent local density gradients along entire spark. These inhomogeneities later become the points of origination for development of small scale vortices due to Rayleigh–Taylor instability. The development of jet at the decay of the discharge channel arises due to the departure of shock waves from the boundary of the spark discharge. In the case the discharge channel bent, the shock wave, resulting from pulse heating in the plasma filament, consists of divergent and convergent parts out of the elbow and inside the corner correspondingly. Convergent shock wave results in pressure increase followed by low pressure area that leads to

[1] *Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), af@jiht.org*
[2] *University of Notre Dame, USA, sleonov@nd.edu*

Copyright © 2018 by the author(s)

formation of jet structure. Experimental verification of this mechanism was performed using high-speed schlieren system. The result of visualization is presented in Figure 1 for spark gap = 50mm. Even small bends lead to significant anisotropy of afterspark channel decay. At the same time, it is seen that intensification of initial small disturbances takes place up to 100μs. Previous experiments were performed for a discharge crossing the core of the stream [1-2]. However, in the case of wall based injection into the supersonic flow (without pylons) the jet of fuel locates near the wall and the approach based on surface spark discharge looks more reasonable.

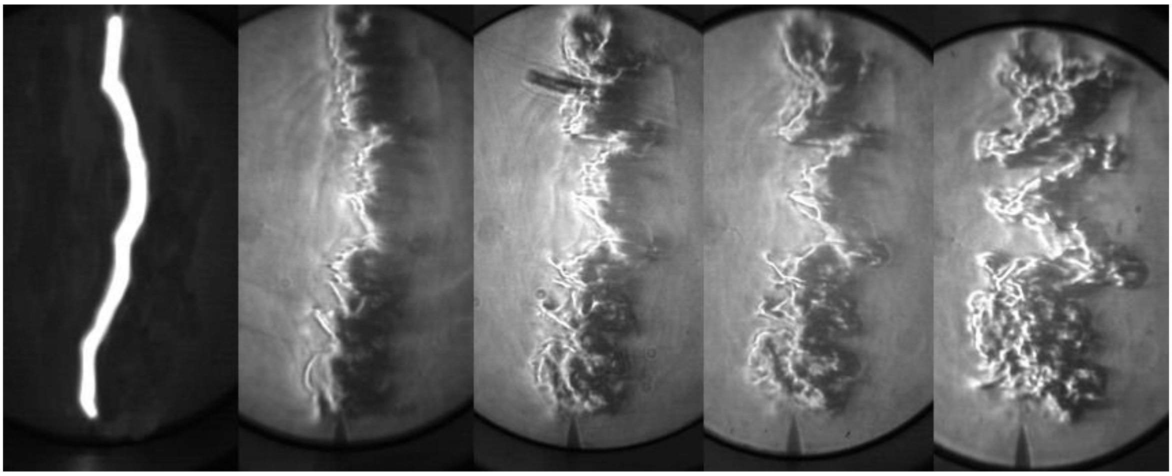

Fig 1. Jet instabilities formation by the bends of the discharge filamentand superposition of small disturbances with jets (0 μs, 50 μs, 100 μs, 150 μs, 350 μs)

2. Numerical simulation

Numerical simulation of air-fuel mixing by electrical discharge in supersonic flow was performed using FlowVision CFD software to check capabilities of surface spark discharge. Simulation was based on solution of three-dimensional unsteady Reynolds averaged Navier–Stokes equations accompanied by k-ε turbulence model. The number of grid cells with the adaptation near jet was approximately 1×106 elements. The following boundary conditions were used: the symmetry condition was set to both side planes of calculation domain; no-slip conditions and wall functions on top and bottom boundaries. Free supersonic out was set on outlet boundary and supersonic flow conditions corresponding to experimental one were set on inlet boundary: M=2, Pst=22000 Pa, T0=170 K. The injection of fuel was carried out through a hole with a diameter of 4 mm and the steady-state instantaneous consumption in the simulation was 0.5 g/s. The geometry of test section corresponds to experimental one – 340×70×70 mm. The control effect Influence of plasma filament produced by spark discharge was simulated by volumetric heat source. This approach demonstrated a good comparison of experimental results and simulation data for spark discharge in ambient air [5]. In this work, we considered three discharge geometries: transverse and longitudinal discharges 9 mm long and longitudinal curved discharge 14 mm long. The diameter of the heat source was 1.0 mm in all geometries. It was initiated for time period 100 ns with power peak density 5.0×1014W/m3. The energy released by volumetric heat source (at recalculation to full volume including area cut off by a XZ plane of symmetry) was 300 mJ per 10 mm. Due to the fact that use of combustible fuel may be dangerous, often a model gas is used. In this study of mixing of fuel and oxidizer the model gas CO2 was used in simulation and is planned to use it in future experimental research.

As a result of the numerical simulation, it was found that for the same energy input for transverse and longitudinal discharges, the heat source influence on the mixing is different. Transverse discharge results in more significant perturbations. The major portion of disturbances of the flow in all cases was observed at 30-100 μs. The interface between the fuel and oxidizer was larger in the case of longitudinal curved discharge, Figure 2. This fact confirms the benefit of using the jet instability for mixing enhancement by electrical discharge. Further, we plan to perform detailed numerical simulation with varying parameters and different configurations. Selected configurations will be tested experimentally.

Copyright © 2018 by the author(s)

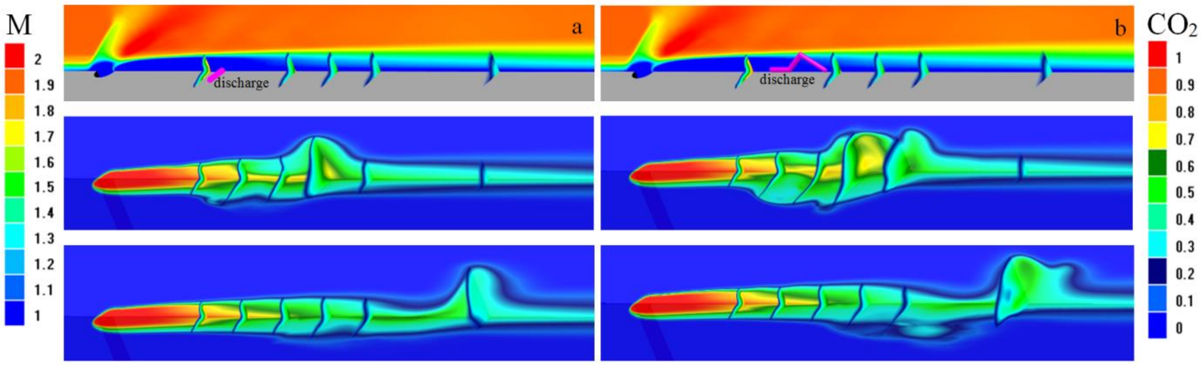

Fig 2. The result of numerical simulation for selected geometries of the discharge:
a – transverse discharge, b - longitudinal curved discharge.
Mach number distribution (top, 0 μs) and distribution of CO2 mass fraction (50, 130 μs).

Summary

Using the high-speed 8-frame schlieren visualization system, the time-resolved experimental data were obtained.It was observed that, at the initial time moment (spark discharge breakdown), small inhomogeneities of boundary along entire length of the discharge channel are realized. For the first time, it is directly demonstrated a strong correlation of jet instability with a local curvature of the discharge channel. It was experimentally confirmed that intensification of initially weak disturbances due to Rayleigh–Taylor instability takes place up to 100μs and a superposition of this small-scale disturbances and jet flow based on spark channel bends was observed. For the case when discharge channel is straight it was observed the effect of suction of cold gas from the electrodes area into the center of heat cavity. Both described effects of afterspark channel decay are beneficial for intensification of air-fuel mixing in a supersonic flow.

To verify the influence of a spark discharge on mixing, a numerical simulation of a spark discharge in a supersonic flow near fuel jet was performed. The jet and discharge was located near the wall. It was observed that spark discharge improves the mixing of jet with supersonic airflow. The interface between the fuel and oxidizer has a bigger surface in the case of longitudinal curved discharge than at the straight plasma channel. This fact confirms the benefit of using the jet instability for mixing enhancement by electrical discharge. Further, we plan to perform detailed numerical simulation with varying parameters and different configurations. Selected configurations will be tested experimentally.

Acknowledgments

This work is supported by Russian Science Foundation grant № 17-79-10494.

References

1. Leonov S.B., Isaenkov Yu.I., Firsov A.A. - Mixing Intensification in High-Speed Flow by Unstable Pulse Discharge // AIAA 2009-4074
2. Leonov S.B., Isaenkov Y.I., Shneider M.N., Firsov A.A., Yarantsev D.A. - High-Power Filamentary Pulse Discharge in Supersonic Flow // AIAA 2010-259
3. Leonov S. B., Isaenkov Y. I., Firsov A. A., Nothnagel S. L., Gimelshein S. F. and Shneider M. N. – Jet regime of the afterspark channel decay // Phys. Plasmas, 2010, V.17, I.5, paper 053505
4. Shurupov M. A., Leonov S. B., Firsov A. A., Yarantsev D. A., Isaenkov Yu. I. - Gasdynamic instabilities during decay of the submicrosecond spark discharge channel // High Temperature, March 2014, Volume 52, Issue 2, pp 169–178
5. Firsov A.A., Shurupov M.A., Yarantsev D.A., Leonov S.B., Shneider M.N. - Mixing Actuation by Unstable Filamentary Discharge // AIAA 2013-1188

Copyright © 2018 by the author(s)