Ignition of gaseous and liquid hydrocarbon fuel in supersonic flow by means of plasma generator

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Abstract. The paper describes experimental research of the surface electrical discharge influence on the ignition and combustion of the gaseous and liquid hydrocarbon fuel in supersonic airflow without mechanical flameholders. Electrodes of plasma generator are integrated with injectors of gaseous fuel. Tests were carried out on the experimental setup T131B in TsAGI. Diagnostics includes schlieren visualization, measurements of pressure distribution and discharge voltage/current. It is shown that new scheme of plasma generation and pilot fuel injection is rather effective and provides ignition of liquid hydrocarbon fuel in hot supersonic airflow \((T_0=750\ \text{K})\) and ethylene ignition in cold \((T_0=300\ \text{K})\) supersonic airflow.

1. Introduction
Plasma assisted combustion in supersonic flow is considered as a promising technology for the future scramjet engines. Several labs all over the world carry out the researches in this direction. Detailed review of the electrically driven combustion (not only supersonic) was made in [1]. In particular, paper [2] describes experimental research and flow modelling of ethylene and JP-7 (liquid fuel) combustion in supersonic flow by means of direct-current (DC) constricted arc. Flames for both fuels were observed by means of planar laser-induced fluorescence. Ignition of hydrocarbon fuels by means of plasma torch in supersonic flow was studied in [3]. The recent study in ONERA [4] demonstrated the ignition of the hydrogen by means of multi-electrode quasi-DC discharge in cold \((T_0=270\ \text{K})\) supersonic flow. Experiments with multichannel spark igniter are described in [5]. Igniter was mounted on the bottom wall of cavity in supersonic channel and demonstrated the capability of ethylene ignition.

Previous research showed [6-11] that surface electrical discharge can initiate ignition of ethylene and provide flameholding on the plane wall of supersonic duct T131B without mechanical flameholders. At the conditions of T131B experimental setup ethylene, as well as ethylene+liquid fuel ignition required simultaneous operation of the two plasma generators arranged along the flow. Preliminary experiments with new scheme of plasma generation, which includes anodes integrated with fuel injectors, on the experimental setup PWT-50 of JIHT RAS in the cold flow \((T_0=300\ \text{K})\) demonstrated higher efficiency of this method [10-11]. This study describes results of experiments and computational modelling for the same plasma generator on experimental setup T131B in TsAGI at higher flow parameters (pressure and temperature). Testing at the conditions of setup T131B is important, because this allows us to perform experiments in a hot flow and with liquid fuel.
Parameters of the experiments on T131B of TsAGI are listed in the Table 1:

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Mach number at the entrance                    | \( M = 2.5 \)                              |
| Static pressure inflow                         | \( P_{st} = 0.4 - 0.5 \) atm               |
| Stagnation temperature                         | \( T_0 = 300 - 900 \) K                   |
| Duration of steady state mode                  | \( \Delta T = 10 - 30 \) s                |
| Duration of the fuel injection                 | \( \Delta T_{fuel} = 0.2 - 4 \) s         |
| Duration of the discharge generation           | \( \Delta T_{dis} = 0.1 - 0.4 \) s; single and pulsed periodic |
| Fuel type                                      | hydrogen, ethylene, liquid hydrocarbons (LH) |
| Mass air to fuel ratio                         | \( \lambda = 12 - 18 \) for ethylene      |
|                                                | \( \lambda = 1 - 4 \) for LH              |
| Electric power                                 | \( W = 8 - 22 \) kW                       |
| Voltage of power source                        | up to 5 kW                                 |
| Type of power supply                           | quasi-DC                                   |
| Cross-section (h:w)                            | 3:10, width = \( d \)                     |

Arrangement of plasma generators and pilot fuel injection is presented in the Figure 1. Two plasma generators are mounted on the plain wall of the supersonic duct. The downstream generator consists of single ceramic insertion that forms the wedge and includes the raw of electrodes (cathode-anode-cathode…) that is transversal to the flow direction. The breakdown occurs between the neighbor electrodes but after that, discharge may also connect to the metal wall downstream the ceramic insertion. Operation of this generator is described in more detail in [7]. The upstream plasma generator has electrodes integrated with fuel injectors [10]. Each electrode is an anode and it is mounted in separate ceramic insertion with the duct wall being a cathode.

![Figure 1. Scheme of plasma generation and discharge photo.](image)

Liquid hydrocarbon fuel was injected using pylons installed on the distance = 3d upstream the first plasma generator integrated with gaseous fuel injectors. Such arrangement of pylons provides a good mixing of hydrocarbon fuel with airflow before its interaction with ethylene ignited by electrical discharge.
2. Numerical simulation

Numerical simulation of the flow was performed by means of FlowVision 3.10.02 CFD software [12] for the aerodynamic duct T131B. Flow simulation was made by solving 3D unsteady Navier-Stokes equations with modified k-ε turbulence model of FlowVision (URANS approach). Rectangular grid with local adaptation to the flow structure was used in simulation. The simulation project consists of the half of the aerodynamic duct. Boundary condition of zero gradient of the physical parameters was applied on the symmetry plane. Incoming flow conditions correspond to the T131B incoming flow with stagnation temperature 700K. In the first part of this work the influence of pylon for the liquid fuel injection on the supersonic flow structure was investigated. Flow around the pylon results in complex oblique shock wave structure, as it is shown in Figure 2. It provides an uneven pressure distribution with local maxima and minima of pressure along the test section. But such pressure distribution is undesirable for discharge operation because the local pressure maximum in the discharge breakdown area could prevent the normal discharge activation. Therefore, based on the calculation, the position of the discharge for future experiments was corrected so that the discharge initiation was organized in the region between two shock waves and in the absence of strong pressure gradients.

At the next step of simulation the variation of the energy release simulating fuel combustion was performed for obtaining the information about pressure distribution in the case of high completeness of combustion and further comparison with experimental one. Plasma-assisted combustion for cases of ethylene injection on the supersonic flow structure was investigated. Flow around the pylon results in complex oblique shock wave structure, as it is shown in Figure 2. It provides an uneven pressure distribution with local maxima and minima of pressure along the test section. But such pressure distribution is undesirable for discharge operation because the local pressure maximum in the discharge breakdown area could prevent the normal discharge activation. Therefore, based on the calculation, the position of the discharge for future experiments was corrected so that the discharge initiation was organized in the region between two shock waves and in the absence of strong pressure gradients.

At the next step of simulation the variation of the energy release simulating fuel combustion was performed for obtaining the information about pressure distribution in the case of high completeness of combustion and further comparison with experimental one. Plasma-assisted combustion for cases of ethylene injection was modelled by means of volumetric heat sources. The geometry of such volumetric heat source is shown in the Figure 3. Calorific power of the ethylene and liquid fuel is about 48 MJ/kg; ethylene air to fuel ratio in experiments was about $\lambda=16-12$. It was assumed in modelling that completeness of combustion of the ethylene is 100% so the power applied to the volumetric heat source was about 330 kW. Mach number distribution for described case is presented in Figure 3. It is clearly seen that high energy release caused by combustion should result in formation of subsonic separation regions in the duct.

![Figure 2. Grid and shock wave structure in the test section behind the pylon](image)

![Figure 3. Mach number distribution at the ethylene combustion (front and top view).](image)

Simultaneous combustion of liquid fuel and ethylene was simulated by the volumetric heat source with a higher volume. In this case the heat source was the same length as at ethylene only combustion simulation but occupied the entire cross section. Equivalent total air to fuel ratio was in the range of $\lambda=5-1.7$. Based on the simulation results the following conclusions can be made: separation propagation during combustion occurs from the sidewalls due to the rectangular shape of the channel. Analysis of Mach number distributions for different energy releases that are corresponding to the different fuel flow rates show that the flow has a supersonic or transonic core down to $\lambda=2.5$. At lower air to fuel ratio the flow become subsonic close to location of the plasma generator. And thermal choking of the duct occurs if the air to fuel ratio is less than $\lambda=1.7$. 


3. Experimental data

3.1. Experiments in the cold flow
Iginition of the ethylene was achieved by means of upstream plasma generator at the air to fuel ratio $\lambda$ less than 14 and discharge power about 15 kW for the conditions of the cold flow ($T_0 = 300$ K). Dynamics of the static pressure downstream the wedge is presented in the Figure 4. Iginition causes the pressure rise within the discharge region. As a result, discharge becomes unstable, several plasma filaments (of four) stop operating (see Fig.4, $U_2$ voltage) in this configuration. The flame is gradually blown away by a flow and combustion does not reach the stationary level.

![Dynamics of static pressure downstream the wedge at ethylene injection $\lambda_{\text{C}_2\text{H}_4} = 12$ and voltage of discharge filaments. Saturation of discharge voltage corresponds to the shutdown of discharge filament operation.](image)

Figure 4. Dynamics of static pressure downstream the wedge at ethylene injection $\lambda_{\text{C}_2\text{H}_4} = 12$ and voltage of discharge filaments. Saturation of discharge voltage corresponds to the shutdown of discharge filament operation.

Figure 5 presents schlieren visualization of the flow structure without discharge, with discharge and during the combustion. Regions disturbed by the discharge and combustion are emphasized on the photos by the magenta line

![Schlieren photos of the flow structure: a – supersonic flow $M=2.5$; b – discharge; c – ethylene combustion. $\lambda_{\text{C}_2\text{H}_4} = 12$.](image)

Figure 5. Schlieren photos of the flow structure: a – supersonic flow $M=2.5$; b – discharge; c – ethylene combustion. $\lambda_{\text{C}_2\text{H}_4} = 12$.

3.2. Experiments in the hot flow
Hot flow experiments were made for the $T_0 = 750$ K. Ethylene was injected through the upstream plasma generator and liquid fuel was injected through the one or two pylons that were mounted upstream the plasma generator.

Single plasma generator occurs to be insufficient to ignite the liquid fuel, therefore experiments with liquid fuel were carried out with two plasma generators. Two central anodes of the each generator were used during simultaneous operation of two generators. Total discharge power remains unchanged but the length of plasma area along the flow is increased that leads to the increasing of the plasma-fuel interaction.
At the ethylene injection the air to fuel ratio was varied within the range of $\lambda = 18 \div 12$, and for liquid hydrocarbon $\lambda$ was from 4 to 1. If liquid hydrocarbon air to fuel ratio was less than 2.5 two pylons for injection were used. Liquid fuel ignition was obtained for the whole range of flow rates for the discharge power about 15 kW and $T_0 = 750$ K. Reducing the liquid fuel and ethylene flow rate caused just to the reducing of the pressure rise due to the combustion, as it is seen in the Figure 6.

![Graph](image1)

**Figure 6.** Static pressure dynamics for different fuel flow rates of $\text{C}_2\text{H}_4$ and liquid fuel.

Liquid fuel air to fuel ratio less than $\lambda = 1.7$ caused to the massive flow separation within the discharge area according to the static pressure distribution along the channel. Thermal choking of the aerodynamic duct occurs at the $\lambda = 1$. If liquid fuel injection was less than $\lambda = 2.2$ than combustion becomes unstable with pressure pulsations that influence on the discharge operation, Figure 7. Detailed analysis of voltage measurements for all plasma channels allows concluding that downstream plasma actuator is shutting down first and ~2ms later the upstream actuator is shutting down too. After ~2ms of downtime the upstream actuator resume the operation, and ~3ms later the downstream actuator resume the operation too and then normal operation of all plasma filaments takes place about 5ms. The frequency of oscillations was about 120Hz. Such dynamics of discharge operation corresponds to the pressure wave motion in combustion chamber.

![Graph](image2)

**Figure 7.** Dynamics of the pressure and discharge current at liquid fuel combustion at $\lambda = 1.7$. 

Comparison of modelled and experimental pressure distributions in Figure 8 shows that completeness of combustion in experiments may be estimated as 25-30%. Nevertheless, it should be noted that position and volume of the volumetric heat source in modelling was not changed depending on fuel mass flow rate.

Figure 8. Static pressure distributions: dash lines – modelled; cont. lines – experimental.

4. Conclusion

The conclusion can be made that for the first time the new scheme of the discharge-fuel interaction based on integration of the electrodes and fuel injectors allowed to ignite the ethylene without using of additional plasma actuator on the T131B testbed at low temperature conditions ($T_0 = 300$ K, $P_o = 0.4$ atm). Future optimization of this approach may allow reducing the length of the supersonic combustion chamber. Nevertheless, in the hot flow ($T_0 = 750$ K) ignition of the liquid hydrocarbons causes the significant pressure increase and unstable discharge operation, as a result, an additional plasma generator is needed in order to sustain the combustion. Mechanisms of the interaction between the discharge and gas jet within the supersonic flow are a subject of further research.

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References

[1] Leonov S B, Electrically driven supersonic combustion. *Energies* 2018, *11*, 1733.
[2] Jacobsen L, Carter C, Baurle R, Jackson T, Williams S, Bivolaru D, Kuo S, Barnett J and Tam C-J, Plasma-Assisted Ignition in Scramjets. *J. Propuls. Power* 2008, *24*, 641–654.
[3] Takita A, Shishido K and Kurumada K, Ignition in a supersonic flow by a plasma jet of mixed feedstock including CH4. *Proc. Combust. Inst.* 2011, *33*, 2383–2389
[4] Vincent-Randonnier A, Packan D, Sabelnikov V, LeJouan F, Roux B, Roux P and Leonov S, First Experiments on Plasma Assisted Supersonic Combustion at LAERTE Facility; AIAA Paper 2017-1975; AIAA: Reston, VA, USA, *2017*. 
[5] Shengfang Huanga, Yun Wub, Huimin Songa, Jiajian Zhuc, Zhibo Zhanga, Xiliang Songc, Yinhong Lib, Experimental investigation of multichannel plasma igniter in a supersonic model combustor, *Experimental Thermal and Fluid Science*, 2018, 99, 315-323.

[6] Leonov S; Carter C and Yarantsev D, Experiments on Electrically Controlled Flameholding on a Plane Wall in Supersonic Airflow. *J. Propuls. Power* 2009, 25, 289–298.

[7] Yarantsev D A, Firsov A A, Chernyshev S L, Nikolaev A A and Talyzin V A. Ignition and flameholding of hydrocarbon fuel in supersonic flow by means of surface electrical discharge, *AIAA SciTech Forum, 2019*, San Diego, California

[8] Yarantsev D A, Leonov S B, Firsov A A and Savelkin K V, Experiments on Hydrocarbon Fuel Ignition by Means of Electrode Discharge in Supersonic Combustor without Mechanical Flameholders, *16th International Workshop on Magneto-Plasma Aerodynamics*, April 5-7, 2017, Moscow

[9] Savelkin K V, Yarantsev D A and Leonov S B, Experiments on Plasma-Assisted Combustion in a Supersonic Flow: Optimization of Plasma Position in Relation to the Fuel Injector, *Journal AerospaceLab*, 2015

[10] Firsov A A, Savelkin K V, Yarantsev D A and Leonov S B, Plasma-enhanced mixing and flameholding in supersonic flow. *Phil. Trans. of the Royal Society A*, 2015, 373.

[11] Savelkin K V, Yarantsev D A, Adamovich I V and Leonov S B, Ignition and flameholding in a supersonic combustor by an electrical discharge combined with a fuel injector. *Combustion and Flame*, 2015, 162, 3, 825-835.

[12] Zhluktov S V, Aksenov A A, Karasev P I, Simulation of separation flow using two-parametric turbulence model] // Computer Research and Modeling, 2016, V. 8, N.1, P. 79–88