Introduction

Plasma-assisted combustion (PAC) of the hydrocarbon fuel in subsonic and supersonic airflow was studied in our previous works [1-5].

It well knows that there are some difficulties in a scram jet technology, connected with bad fuel ignition, mixing and combustion in supersonic airflow. Active radicals and exited molecules generated by electrical discharge in fuel-air mixture could activate and accelerate chemical combustion reactions considerably [1-6]. It is known also that active radicals such as \(O, H, OH, NO, CN\) and others, vibration exited molecules play important role in a combustion process. Non-equilibrium discharge could generate these particles effectively and selectively. So, PAC study is very important for internal and external combustion in gas dynamics.

Main goal of our previous researches was plasma-assisted combustion (PAC) study in airflow at parameters closed to scram jet ones. Present work is continuation of the previous ones [1-5]. Four main tasks are studied in this work, namely:

- Advanced plasma-assisted fuel-airflow mixing;
- Study of the stable external and internal plasma-assisted ignition and combustion in supersonic airflow;
- Control of the aerodynamic model F’s characteristics (such as drag, surface pressure distribution, base pressure) by the local plasma-assisted combustion formation.

New plasma generators (PG) were used in these plasma-assisted experiments.

External plasma-assisted combustion near aerodynamic model F was studied in this work also. Plasma formations near aerodynamic model 1/6 in supersonic airflow were used in wind tunnel experiment to change its aerodynamic characteristics our previous works [8,15]. High plasma effectiveness (~200-300%) was obtained in these plasma aerodynamic experiments namely [15]. Unfortunately mean power input in plasma formation was considerably small (~3kW) in comparison with airflow kinetic power (~400kW). So, mean drag decrease was small (~6%) also. According our opinion on-board plasma-combustion generator with small fuel injection could decrease model’s drag more considerably due to:

- Strong collective properties in cluster plasmoid generated by this plasma generator in airflow (carbon cluster plasmoid),
- Additional power (plasma power + chemical combustion one).

Cluster plasma formation could dissipate bow shock wave effectively [7,8,16]. In the result of bow SW dissipation a wave drag is decreased also.

Experimental sets up

Experimental set up WT-1.

Internal PAC is studied in wind tunnel WT-1. This experimental set up was described in [1,5] in detail. Modified variant of the WT-1 used at low-pressure regimes is shown in Fig.1. Supersonic airflow \((M<2, P_{st} <1\text{Bar}, T_{st} <1000K)\) is created in this experimental set up.

Set up WT-1 is equipped with two HF plasma generators in test section. First HF electrode is used to heat incoming airflow and generate air radicals. Second HF electrode is used to generate radicals in fuel-air mixture. Propane is injected through second HF electrodes (5). Valve (3) disconnects vacuum chamber and atmosphere. Vacuum chamber is equipped by the optic windows (10). Optic diagnostic instrumentation (shadow laser device, spectroscope and others) is arranged near these windows namely. Pressure sensors (7), thermocouples (8), chemical probes (6), mass gas flow sensor (4) are used in this set up. Transparent quartz tubes in the WT-1 help us to use optical diagnostic instrumentation in PAC experiment.

Main technical characteristics of the WT-1:

- Airflow mass flux < 20 g/s
- Propane mass flux < 2 g/s
- Supersonic airflow parameters in small tube \(M<2, P_{st} <1\text{Bar}\)
- Gas temperature in arc heater \(T_0 < 1000K\)
- Mean power of the HF plasma generator \(N_d < 2 \text{ kW}\)
- Mean power of the plasma generator PG-jet \(N_d < 3 \text{ kW}\)
Powerful streamer HF discharge with the mean power up to 10kW is used in test section of this set up at the first time. Characteristic length of the HF discharge generated by this plasma generator is about 50-100cm, Fig.2. Parameters and physical characteristics of this HF streamer discharge in cold airflow and hot airflow are studied now.

**Experimental Setup Wind Tunnel WT-2**

Scheme of the experimental set up WT-2 is shown in Fig.3. Nozzle (1) creates supersonic airflow with Mach number 2. Output diameter of the supersonic jet is about 140mm. Model F (4) is arranged near nozzle. Propane is injected through model F’s needle (2). Electric discharge is created in the head part of the model F (Fig.3), or between model F’s needle (2) and external electrode.

Parameters of airflow in setup WT-2:
- Mach number \( M \approx 2 \)
- Static pressure about 1Bar
- Stagnation temperature about 300K
- Airflow jet diameter more than 140 mm

Model F’s characteristics:
- Diameter 30 mm
- Length 80 mm
- Needle diameter 6 mm
- Needle length 42 mm
- Model material Nylon
- Stagnation propane pressure < 16 Bar

On-board plasma generator (PG) creates combined discharge (DC+ pulse repetitive discharge).

Combined discharge has the following parameters:
- DC voltage <6 kV
- DC current <100Amp
- Ignition pulse voltage <30 kV
- Ignition pulse duration ~3-10 mcs
- Pulse repetitive frequency <10 kHz
Experimental results obtained in the WT-1

Fuel-airflow advanced plasma-assisted mixing by pulse repetitive HF streamer discharge. It was revealed that there is fast fuel transportation through the rotated long HF streamer with high velocity (up to 1000m/c), [5]. Example of this fast transportation is shown in the Fig.2. Excited propane molecules are transported through HF plasma formation from high voltage electrode up to nozzle (towards incoming rotated airflow). It is easily to record propane transportation through HF plasmoid due to characteristic red luminescence of the fuel excited molecules. Pulse repetitive HF streamer discharge is used to accelerate fuel-airflow mixing and plasma-assisted combustion. It was revealed that pulse repetitive HF streamer discharge generates intensive acoustic waves (acoustic noise) and turbulence in airflow. These gas dynamic disturbances stimulate fuel-airflow mixing namely. A number of theoretical and experimental researches will be fulfilled to study of the advanced plasma-assisted mixing.

Optical spectroscopy and plasma chemical kinetics. Optical spectroscopy method and chemical analysis are used to study plasma and radical generation in fuel-airflow. It was revealed that radicals (CN, C, O) and exited carbon clusters (Nc~107-108cm3, diameter – 104-105cm3) play important role in plasma chemical kinetics. There are very intensive optical lines of the exited CN molecules in the optical spectrum, [5].

It is very important to note that charged carbon clusters could have local high electric potential up to 1000V, [7]. There is a high electric field (about E~107-108V/cm) near these particles also. So, these charged clusters could stimulate radical generation and molecule excitation considerably. It was revealed that PAC was changed dramatically at charged cluster particles generation (rich fuel-air mixture regime with carbon particle generation). In this case non-homogeneous yellow-red flame was generated. This flame consisted of many tiny yellow-red filaments, Fig.4. Its diameter was less than 1mm. So, it is need to study plasma-assisted combustion kinetics with charged excited clusters very carefully. Simulation of the plasma chemical kinetics of the propane-air mixture is started now.

Pressure and temperature measurements. Stable plasma-assisted combustion behind HF pylon-electrode was created in supersonic airflow in the WT-1. Gas-flow parameters (Tst, Pst, P0) after combustion region were measured by pressure and temperature sensors, Fig.5. Propane mass flow is measured by sensor also.

Experimental conditions were the followings:
- Static pressure Pst=30 Torr
- Airflow stagnation temperature T0=300 K
- Propane mass flux Gp~1 g/s
- Airflow mass flux Gair~20 g/s
- Gas flow static temperature behind combustion region Tof~2100…2500K
- Mach number M<2

Theoretical estimations based on experimental results and published work [9] were the followings:

\[
\frac{P_{of}}{P_0} = \left[ \frac{\gamma (\gamma - 1)}{\gamma - 1} \right] \left[ 1 - \frac{T_{of}}{T_0} \right]^{\frac{\gamma - 1}{\gamma - 1}} \sim 0.8 \quad (1)
\]

\[
\frac{Q}{C_p T_0} \sim 7 - 8 \frac{Q}{(C_p T_0)} \sim 7 - 8; \quad T_{of} \sim 2100…2500 \text{ K}
\]
where $P_{of}$, $T_{of}$ – stagnation pressure and temperature after combustion region, $P_0$, $T_0$ – stagnation pressure and temperature before combustion region, $\gamma = C_p/C_v$.

It was obtained good agreement between experimental results and theoretical estimations (1).

It is proved that there is total fuel combustion in test section in our simulations. Chemical analysis of the final combustion products proves this supposition also [1].

*Single HF streamer discharge* with distant propane injection in the WT-1’s test section is shown Fig.6. HF streamer discharge is created behind pylon-electrode (1). Propane is injected through tube (2) near pylon (main injection
location) and through pylon (1, additional injection location). Supersonic airflow is heated and excited by HF streamer discharge before propane injection tube. Propane injection tube was located in the variable distance from the pylon. It was revealed that it is possible to create stable PAC at previous airflow excitation and airflow heating by HF discharge before propane injector only. There is optimal distance between pylon and injection tube in this plasma generator. This distance is about 30-50mm in our experiment (M~2, $P_0$~1Bar). It was revealed that this plasma generator activates chemical combustion reactions in propane-airflow considerably. Small electrical power (about ~1% of total chemical power) is needed for the ignition and combustion of the propane-airflow mixture. Note that best fuel combustion in airflow (without toxic impurities) was obtained by means of this plasma generator namely.

**Conclusion of this part**

Optimization of the HF plasma generator in the WT-1 was considered in this work. Experimental results on plasma-assisted ignition and plasma-assisted combustion obtained by the HF plasma generator are discussed in this work.

Advanced fuel-airflow mixing was obtained by pulse repetitive HF streamer discharge. Theoretical model of this advanced plasma-assisted mixing is created now.

Charged and excited clusters play active role in plasma chemical kinetics of the plasma-assisted combustion.

**Experimental results obtained in the WT-2**

Stable PAC near model F was created in the wind tunnel WT-2, Fig. 3. However the local PAC was created near discharge region only. Propane combustion stopped after discharge area.

![Fig.6. HF-pylon-electrode in quartz test section of the WT-1](image)

![Fig.7. a.- Model F1 with external PAC in supersonic airflow (M~2, discharge current- $I_d$~5 Amp), b.- Supersonic flow (M0~ 2) around model F with PAC (M~2, discharge current- $I_d$~5 Amp), shadow photo](image)
This local PAC formation was rotated around model axis in some experiments. Some part of the injected propane was non-ignited and non-burned near model F (non-full combustion regime). Shadow photos and video frame analysis prove this conclusion.

It was revealed that bow shock wave (SW) modification (dissipation) near model F took place in PAC experiment, Fig.7. In turn this SW modification changed surface pressure distribution. Pressure sensor located on head part of the model F (sensor #1) recorded the pressure decrease up to 23%, Fig.8. Lateral surface pressure sensor and base one recorded small surface pressure increase. It was revealed that there is no surface pressure change in the model F at plasma generation without propane injection.

**Plasma-assisted combustion geometry**

It was revealed that plasma-assisted combustion was located (concentrated) inside the gas-dynamic cone created by injected propane jet at small electric current \( (I_d<10 \text{ Amp}) \), Fig.7.

The spherical shape of the plasma-assisted combustion region was recorded at large electric current \( (I_d=10-100 \text{ Amp}) \), Fig.9. It is unusual experimental result from the point of view of the traditional gas dynamics. It is interesting to note that there is no flame tail after this combustion sphere. Combustion formation has spherical sharp boundary.

Significant voltage and current pulsations \( \delta V/\delta I = 50-100\% \), \( T_{\delta I}=100, F_{\delta I}=10-30 \text{kHz} \) in DC discharge near model F in supersonic flow were recorded at propane combustion, Fig.10. Minimal breakdown gap \( L \) (distance between electrodes) was decreased considerably at propane injection (in comparison with the case without it): more than 3 times (from \( L_p=10 \text{mm} \) up to \( L_p=3 \text{mm} \)). This result could be explained by effective electron death in the fuel-air mixture and combustion products. It is well known that propane molecules and combustion products have large electron attachment coefficients.

**Discussions**

1. It is very simple to estimate typical value of the model F’s drag power (incoming airflow mechanical power):

\[
N = F_d V = (P_n dS) V
\]

where \( P_n \) – surface pressure, \( dS \) – surface element, \( V \) – airflow velocity, \( F_d \) – drag force.
This value is about 70kW in our experiment. Note that electrical discharge power (~3kW) is much less than the value $N$. So, possible model F’s drag decrease has to be small due to plasma generation. In other hand the chemical power ($N_{ch} \approx \lambda \cdot m \approx 40$ kW, where $m \approx 1$ g/s is propane mass injection, $\lambda$ – is propane combustion heat release) connected with propane combustion is closed to the value $N$. So, the possible drag decrease has to be large due to external PAC. Estimated model F’s drag decrease is about 20-30% in real PAC experiment in wind tunnel.

2. Five models F were tested in wind tunnel experiments. Different plasma generators were tested in these models. Obtained experimental information helps us to select optimal model F’s design and plasma generator design. It was revealed that model F with internal electrodes (Fig.3) is best one. This model has very large conical plasma formation near needle. So, fuel full combustion is possible near this model due to this optimal plasma formation. Plasma assisted combustion is created near head part of the model F and decrease surface pressure effectively in this case. Fuel combustion is continued on the lateral model surface and base area also.

3. Stable plasma-assisted combustion near model F in supersonic airflow ($M\approx 2$) is created at large electric current ($I_p > 10$ Amp) only. PAC formation shape is transformed from conical one (at small electric current) up to spherical one (at large electric current). So, PAC formation has not good aerodynamic shape at large electric current. This result is not clear today. It is need to continue to study of this phenomenon in detail in future experiment.

Conclusions of this part

1. Three aerodynamic models F were designed, manufactured and tested. External PAC was used in these models.
2. Stable external PAC was created in subsonic and supersonic airflow near the model F.
3. Preliminary experimental results on surface pressure decrease in the model F by external PAC were obtained.

References


