



Partner Project # 1810P

**Optimization of Plasma Generators (PG) and Operation Modes of  
Plasma Assisted Combustion, Delivery #4, Final Report.**

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13. ABSTRACT (Maximum 200 words)  <p>This report results from a contract tasking Institute for High Temperature - RAS (IVTAN) as follows: Plasma assisted engine combustion is a newly developed field of basic science that brings together the fields of engine combustion physics and plasma physics. This project is devoted to a fundamental study of optimal regimes of stimulated burning of engine fuel/air mixtures by means of structural, non-equilibrium plasma formations (plasmoids). MTC, IVT RAS has significant experience in this field, and has produced breakthrough experimental results. For the first time, we have obtained stable engine combustion, stimulated by streamer HF discharge of a very poor fuel/air engine mixture (Argon: Propane= 9:1), in a gas mixture engine flow. In addition, we have experimental results in gas engine flows of advanced mixtures with plasma formations. We plan to continue our research in the field of plasma assisted engine combustion with non-equilibrium plasmoids. These plasmoids will be created by highly efficient plasma generators (PG) of the following types:</p> <ul style="list-style-type: none"> <li>*PG HF for creation of streamer corona discharge</li> <li>*PG-jet, plasma generator of erosive plasma jet</li> <li>*PG-Comb. Combined discharge could be created by combined PG (PG HF+ PG- jet) in a repetitive pulsed mode, and the main plasm parameters can be changed independently. Electron concentration can be controlled by the PG-jet, and the electron temperature can be controlled by the external HF electric field.</li> </ul> <p>The main goals of this work are to study the following</p> <ul style="list-style-type: none"> <li>*optimal radical generation in an engine fuel/ air mixture by plasmoids</li> <li>*stability of the burning of the engine fuel/ air mixture in an engine gas flow stimulated by plasma formations</li> <li>*advanced mixtures of engine fuel in an engine gas flow by structural plasmoids</li> </ul> <p>We also plan to design, manufacture and test new improved PGs for the study of stimulated engine fuel burning. We plan to create a experimental aerodynamic set up for these PG tests. Plasma and aerodynamic parameters will be measured by modern optical and electronic instrumentation, including optical spectroscopy, optical interferometry, microwave interferometry and others.</p> <p>Meeting ISTC Goals and Objectives</p> <ul style="list-style-type: none"> <li>*This project provides weapons scientists and engineers in Russia to redirect their talents to peaceful activities</li> <li>*This project promotes the integration of Russian scientists into the international scientific community</li> <li>*This project supports basic research for peaceful purposes. Our team consists of highly qualified specialists, most of who do hav backgrounds as weapons scientists.</li> </ul> <p>Role of Foreign collaborators</p> <ul style="list-style-type: none"> <li>*Progress, information, and technical reports will be delivered during the course of the project in order to obtain comments and suggestions</li> </ul>				
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## Content

1. Introduction
2. Chapter 1. Hot wind tunnel.
3. Chapter 2. The optical emission spectrum.
4. Discussion and conclusion.

## Designations

PAC- plasma assisted combustion,

HF- high frequency,

PG- plasma generator,

PG-jet -plasma generator of erosive plasma jet,

HWT- hot wind tunnel

WT- wind tunnel

$\tau_1$  - ignition characteristic time

$\tau_2$  – combustion characteristic time

## Introduction.

Accordinging Statement of Contract Work No 1810P it is need to prepare Final Report (Delivery #4) with the description of all results obtained during fulfillment of Tasks 1-6 and main conclusions.

It is needed to note that we consider this Contract Work as a long-term one. We plane to continue a study of plasma assisted combustion (PAC) in a hot supersonic airflow in the frame of new Contract Work will be started in this year. Parameters of a hot supersonic airflow will be closed to scram jet one.

This Report consists of Introduction, 2 Chapters and Conclusion.

The Chapter 1 is devoted to description of a new experimental set up: hot wind tunnel (HWT). Namely this experimental set up will be used in next Contract Work. Design of this installation will be modified and improved during preliminary experimental Program. Some of new experimental results obtained in this HWT are considered in this Report, namely

- Stimulation of propane- air mixing by streamer HF discharge, (advanced mixing of fuel-air flow).
- Transformation of structural streamer HF discharge into homogeneous torch HF discharge in a hot combustion zone,
- Small characteristic ignition and combustion times ( $\tau_{1,2}$ ) obtained in PAC experiment.
- Parameters of a single HF streamer in airflow.

Analysis of optical spectra obtained in a HF streamer discharge and PAC is considered in Chapter 3. Chemical analysis of final products of plasma assisted combustion obtained by mass spectroscopy in a new setup are considered in this Chapter also.

Main conclusions of this Contract Work are presented in last Chapter.

## Chapter 1.

### Hot wind tunnel.

Schematic of experimental set up (Hot Wind Tunnel, HWT) is shown in Fig.1. We can compare this setup with scram jet channel will be used during PAC experiment in CIAM [1].

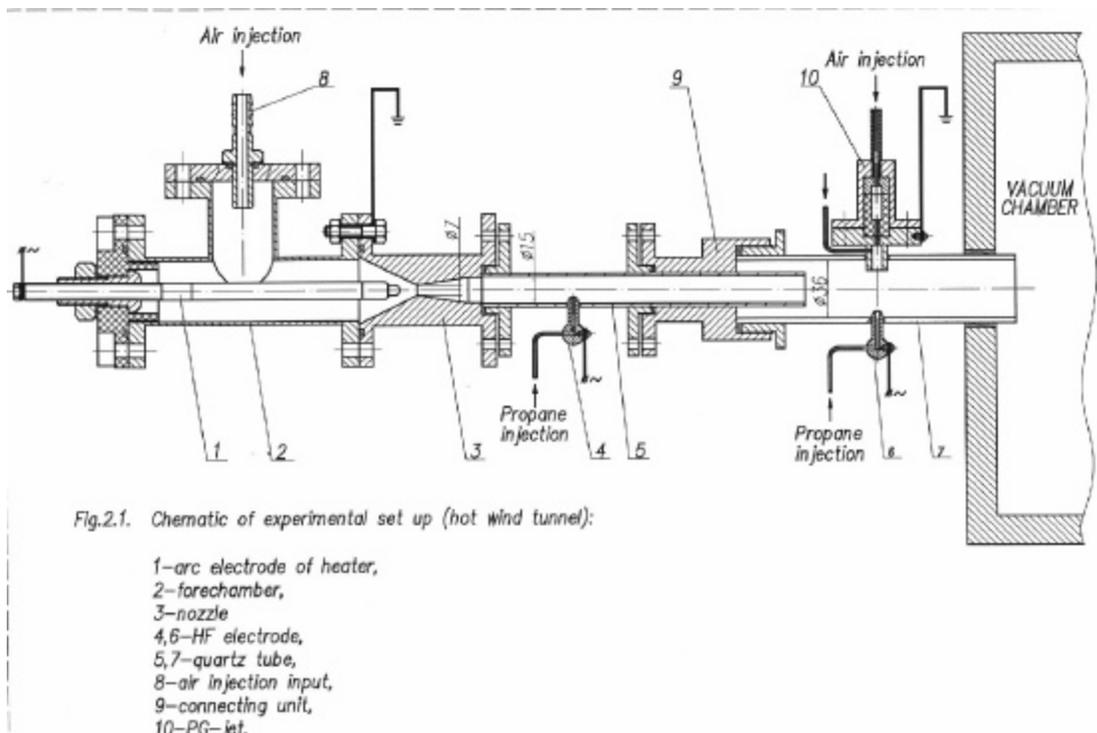


Fig.1. Schematic of experimental setup HWT.

One can see that HWT has all peculiarities of CIAM's set up [1], namely

- Supersonic airflow channel (5),
- Arc discharge heater (1),
- Vortex separation zone for fuel mixing (9),
- HF discharge igniter (4,6),
- PG-jet igniter (10).

Set up consists of two quartz tubes:

- Small tube (5) with inner diameter 17 mm and length ~400 mm,
- Large tube (7) with inner diameter 40 mm and length ~1000 mm.

HF plasma generator (HF PG) and PG –jet (erosive type) are located in large quartz tube in position near separation mixing zone. There is additional possible HF PG position (4) near nozzle in small tube. Possible locations of propane injection:

- HWT cross sections located near a separation mixing zone between small and large tubes (9) and near nozzle (3), (main injection),
- Through HF hot electrodes and PG- jet (additional injection).

Using of quartz tubes in our experiment help us to use optical diagnostic instrumentation to study plasma assisted combustion.

Main technical characteristics of HWT:

- Airflow mass flux  $< 20 \text{ g/s}$ ,
- Propane mass flux  $< 1 \text{ g/s}$ .
- Supersonic airflow parameters in small tube  $M < 2, P_{st} < 1 \text{ Bar}$ 
  - Gas temperature in arc heater  $T_o < 2000\text{K}$ ,
  - HF power of the igniter  $N_d < 2 \text{ kW}$
- Mean power of PG-jet  $N_d < 3 \text{ kW}$

Supersonic airflow in nozzle was rotated to obtain homogeneous arc discharge in some experiments.

### **Positive peculiarities of HF streamer discharge in a supersonic flow.**

Stable HF streamer discharge in a cold airflow in HWT is shown in fig.2. Stable PAC created by HF streamer discharge is shown in fig.3. It was revealed that HF streamer discharge has a number of important positive properties (peculiarities) in PAC experiment (comparing with other types of electric discharges), namely:

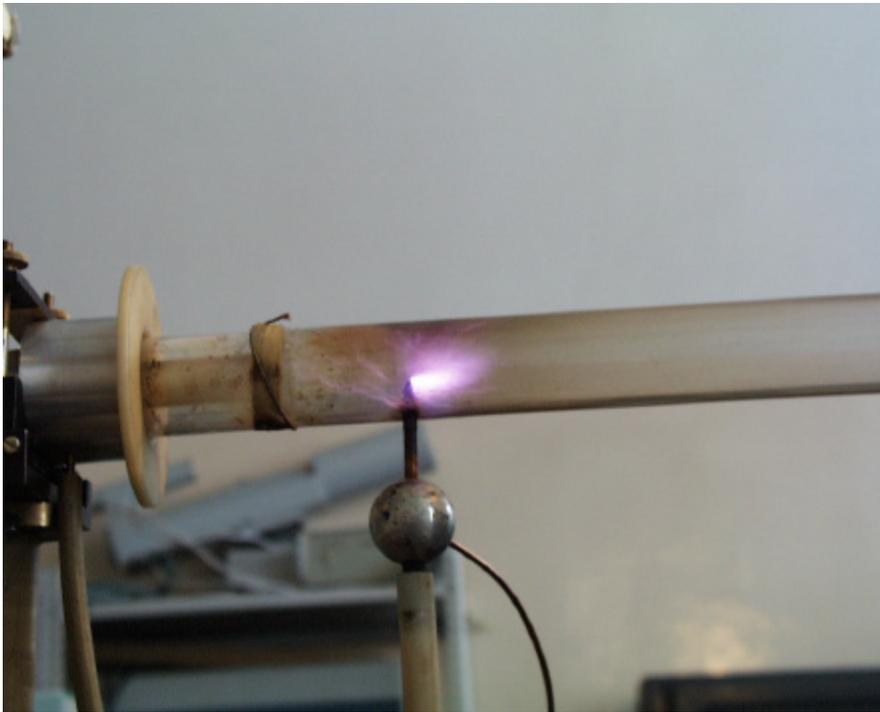


Fig.2. Stable HF streamer discharge in a cold airflow in HWT,  
 $M \sim 0,8-1,2$ ;  $P_{st} \sim 1$  Bar,  $T_o \sim 300K$

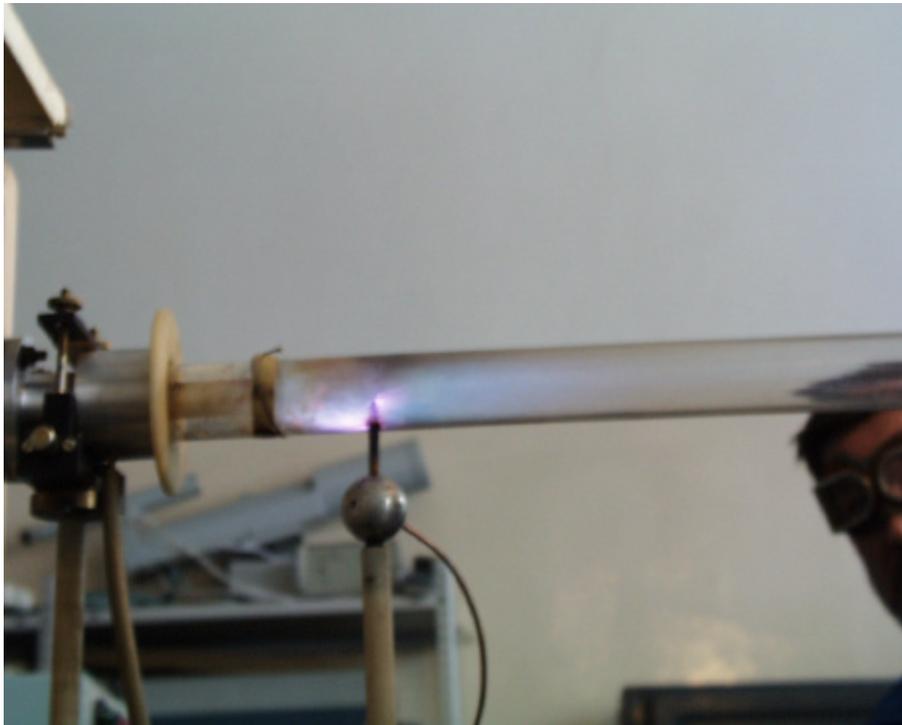


Fig.3. Stable PAC created by HF streamer discharge,  $M \sim 0,8-1,2$ ;  $P_{st} \sim 1$   
Bar,  $T_o \sim 300K$

1. HF discharge was ignited and burned near a mixing contact surface between propane injection and airflow (near a gas density gradient region) as a rule. In fig.2 one can see that normal position of HF streamer discharge is a region near a hot electrode in a cold supersonic airflow without propane injection. HF streamers are concentrated near airflow separation zone behind this electrode. HF discharge changes its position and shape considerably after propane injection and its further ignition and burning, fig.3. One can see that stable HF discharge creation and its burning are realized near mixing zone (near gas density gradient region) in this case namely. It is very important result (see below).
2. HF streamer discharge could disturb contact mixing surface and stimulate propane- air mixing. Really in our previous experiments [2,3] it was revealed that streamer HF discharge could increase aerodynamic jet noise and airflow turbulence considerably. So, advanced mixing stimulated by streamer HF discharge could be obtained in PAC experiment. It is needed to study this type of the mixing in future experiments.
3. It was revealed that fuel could penetrate deeply in airflow through a HF streamer channels, Fig.4 (right). Note that propane was injected through HF electrode and small propane jet was created along nozzle axis in a top part of HF electrode. However propane injection and its combustion were recorded inside of a curved streamer channel, Fig.4. So, fuel injection and its combustion are concentrated inside of curved (non-straight) streamer channel. So, study of physical and chemical properties of single HF streamer is very important for PAC optimization. Propane transportation through streamer is a very fast process. Estimations and measurements are proved this conclusion.





Fig.4a. HF streamer discharge in airflow ( $M \sim 0,4$ ,  $P_{st} \sim 1$  Bar) without propane injection (a), with it (b). Airflow and propane injection directions are from down side up of the photo to its topside.

Really it is very easily to obtain (on base of characteristic streamer lifetime and its length, see below) that mean velocity of propane transportation inside a streamer channel is about

$$V_{fl} \sim 10^3 \text{ m/s and more.}$$

1. It is very important to note that HF streamer discharge is volume one. Each consequent streamer has a separate trajectory in a space and time. So, radical generation and ignition of fuel-air mixture are created in airflow volume region but not near metal wall of HWT (or scram jet).
2. Velocity of HF streamer propagation could be very high about

$$V_{str} \sim 10^3 - 10^5 \text{ m/s.}$$

It depends on discharge parameter  $E/N$ , [4]. So, HF streamer could deeply penetrate through airflow without drift. Measured characteristic lifetime of a single streamer in our experiment is about

$$T_{str} \sim 50 - 100 \text{ mSecs.}$$

So, estimations of a characteristic streamer length is

$$L_{str.th} \sim 50 - 100 \text{ mm.}$$





Fig.4b. HF streamer discharge in airflow ( $M \sim 0,4$ ,  $P_{st} \sim 1$  Bar) without propane injection (a), with it (b). Airflow and propane injection directions are from down side up of the photo to its topside.

Measured streamer length is about

$$L_{\text{str.exp}} \sim 50 \text{ mm.}$$

$L_{\text{str.exp}}$  is very closed to a theoretical value.

1. Characteristic plasma parameters of a single HF streamer are the followings (see our previous Reports [5,6]):

- Electron concentration  $>10^{15} \text{ cm}^3$
- Electron temperature 1-10 eV
- Gas temperature 1000-1500K,
- Specific energy storage  $\sim 1-10 \text{ J/cm}^3$

This plasma formation is non-equilibrium one and it has a very high-energy storage. So, it could stimulate plasma chemical reactions and radical generation in a fuel-air mixture.

2. HF discharge is very adaptive and self-organized one. It was revealed that streamer HF discharge is transformed to diffusive (torch) one in combustion region after fuel ignition (in a hot gas region, with gas temperature  $T_g > 2000\text{K}$ , see below), fig.3,4. This result is very important one from the point of view of transportation and transformation of HF power. There is a good transportation of HF power in a diffuse HF discharge namely. Torch HF discharge has a small resistance and a large value of a current density consequently. Main part of HF energy in a torch discharge is transformed in a gas heating. Torch HF discharge is very closed to equilibrium one. There is a positive reverse coupling in a torch discharge namely. It amplifies hot gas disturbances (after ignition by a HF streamer discharge) in a combustion region considerably. It was revealed that luminosity of PAC is not stationary in a space and time, fig.4. It is interesting to note that flame pulsation frequency is equaled to streamer generation one. Amplitude of PAC luminosity is much higher than flame one without HF discharge or streamer one. Intensive acoustic noise was generated

during this PAC experiment also. So, active mixing and stimulation of combustion by HF discharge was recorded in our experiment.

3. Internal and external PAC stimulated by HF discharge were studied in our experiment. External PAC in a cold supersonic flow is shown in fig.5. Experimental conditions were following ones:

Mach number	$M < 1.2,$
Static pressure	$P_{st} \sim 1\text{Bar},$
Stagnation temperature	$T_o \sim 300\text{K}$
Propane mass injection	$< 0,4 \text{ g/s}$
HF frequency	$13,6 \text{ MHz}$
Mean HF power	$< 2 \text{ kW}$
Anode current	$\sim 0,6 \text{ A}$
Output voltage	$< 10 \text{ kV}$

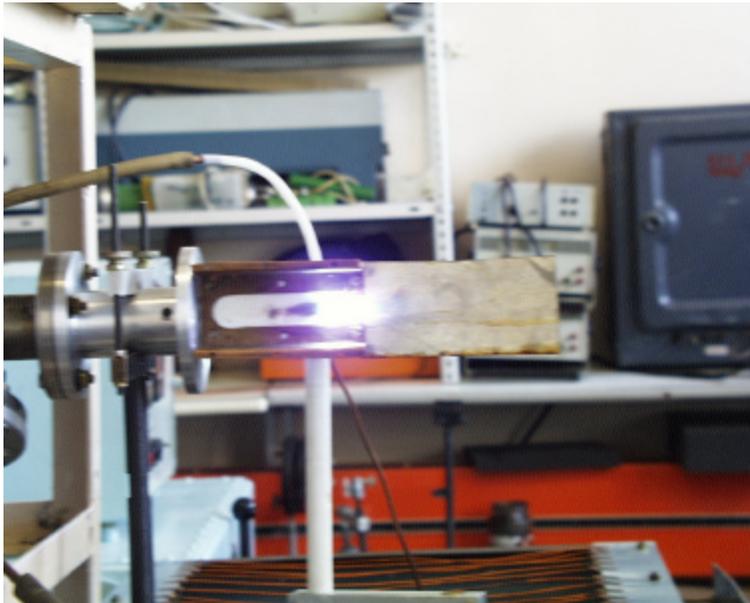


Fig.5. External PAC. Streamer HF discharge in metal section (lateral wall is absent). Propane injection through pylon.  $M=0,8-1,2;$   $P_{st} \sim 1$  Bar,  $T_o \sim 300\text{K}$

4. Very small characteristic ignition time  $\tau_1$  and combustion time  $\tau_2$  were measured in this external PAC experiment:

$$\tau_1 \sim 30\text{-}50 \text{ mcs}, \tau_2 \sim 100\text{-}150 \text{ mcs}$$

5. Gas temperature  $T_g$  in PAC region was about 2100- 2600K. This temperature was measured by two methods:

- Thermocouple method,
- Optical spectroscopy (see below).

6. External PAC was generated at a constant static pressure

$$P_{st} \sim 1 \text{ Bar} \sim \text{Const.}$$

7. Physical characteristics (luminosity) of streamer HF discharge in were studied in airflow, Tabl.1.

Tabl.1

Stagnation pressure, $P_o$	Streamer life-time, $T_l$ , mSecs	Streamer generation frequency, F,kHz
2 Bar	$\sim 50$ mSecs	$\sim 2$ kHz
3 Bar	30-50 mSecs	$\sim 10$ kHz
4 Bar	20-40 mSecs	$\sim 20$ kHz

One can see that streamer generation frequency is increased at airflow velocity increase. It reaches up to  $F_1 \sim 10$  kHz and higher at supersonic airflow velocities ( $P_o > 3\text{Bar}$ ). Remember that characteristic length of a single streamer is

$$L_{str.exp} \sim 50 \text{ mm},$$

characteristic airflow velocity is

$$V_f \sim 300\text{-}400 \text{ m/s}.$$

So, we have quasi-continuous regime of plasma generation in airflow. If you remember that there is PAC “memory” in airflow (characteristic time of fuel combustion after ignition by HF streamer without plasma, see

Report 3, [6]) that it is clear that continuous PAC is possible in a supersonic airflow. Namely this type of HF discharge was optimal one in PAC experiment.

8. It was revealed that small water vapour injection could stimulate PAC.
9. Estimations of plasma efficiency in PAC experiment. Mean HF power used in this experiment is  $N_d \sim 100-1000\text{W}$ . Total chemical power is about  $N_{ch} \sim 16-17\text{ kW}$ , (it corresponds to propane mass flux  $m \sim 0,4\text{ g/s}$ ). So, ratio  $\eta = (N_d / N_{ch}) 100\% = 0,6-6\%$ . Maximal radical concentration has to be closed this value also.

## Chapter 2

### **Measurement of gas temperature in PAC experiment by optical spectroscopy**

Optical spectra were obtained in a streamer HF discharge and PAC in HWT. Experience obtained in our previous experiments [5,6] was used in present experiment. Tungsten HF electrode was used in test section of HTW. So, optical lines of evaporated metals were absent during present experiment. Parameters of airflow were the followings:  $M < 0,8$ ;  $P_{st} \sim 1$  Bar,  $T_o \sim 300K$ . Second positive system of nitrogen was recorded during experiment with HF streamer discharge to measure a gas temperature inside of a single streamer. Spectra were recorded in two separate sections placed in 30 and 55mm from the nozzle. Besides these sections were located behind the discharge ignition electrode at 10mm from it. Optical spectra were recorded in HF discharge region with fuel injection and without it. Optical radiation from discharge plasma region was focused in spectrograph input slot. Its width was about 0.15 mm. Optical spectra were recorded in a high sensitivity film with effective time exposure  $\sim 5-10$  second. So, these spectra are integral ones. Spectra were analyzed in the range  $\lambda \sim 3300 - 4300$  A. The characteristic spectrum obtained in HF streamer discharge in airflow is presented in Fig.1. One can see that the optical bands with sequences  $\Delta V = -4, -3, -2, -1$  ((0-0) transition, second positive nitrogen system) are presented in this spectrum only. As a rule we used the rotational level intensities of the molecular (0-3) band (edge of the  $\lambda_1 = 4059$  A and  $\lambda_2 = 3998$  A) of this spectrum for simulation analysis. Method of gas temperature measurement was discussed in our previous reports [5,6]. It is need to note that a rotational (gas) temperature was obtained on base of rotational level processing

(from 16 up to 27-28 ones of the R-branch). Some results of this simulation are presented in Fig.6

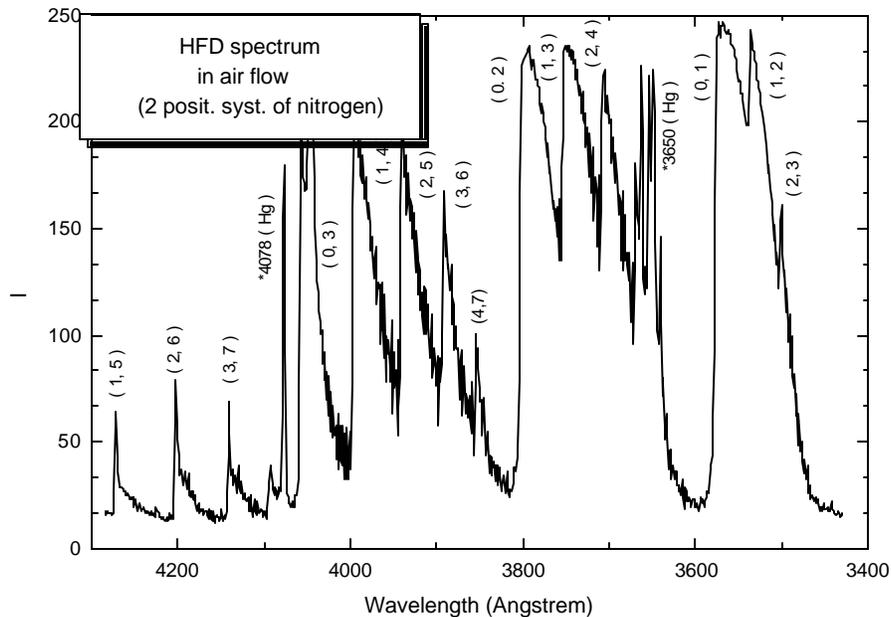


Fig.6. Characteristic optical spectrum obtained in HF streamer discharge in airflow,  $M \sim 0,8$ :  $P_{st} \sim 1$  Bar,  $T_o \sim 300K$ ,  $I_d \sim 0,6$  Amp

This rotational level distribution is closed to Boltzmann's one. So, it is possible to obtain the rotational temperature  $T_R$  of discharge plasma. Gas temperature dependence on HF current was obtained in this experiment ( $S = 55mm$ ), Tabl.1.

Tabl.1

$I = 0.5$ A	$I = 0.7$ A	$I = 0.8$ A
$T = 1000 - 1200$ K	$T = 1200 - 1400$ K	$T = 1600$ K

It was revealed that airflow ( $M = 0.4 - 0.8$ ) did not change gas (rotational) temperature of HF streamer practically.

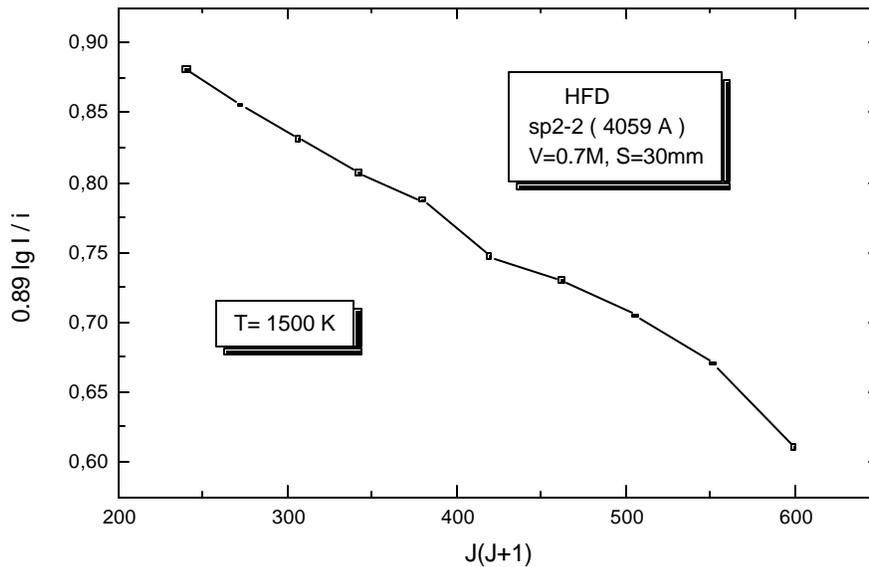


Fig.2. Dependence of the relative intensities [I] of the rotational optical lines on the quantum number J

The fuel injection in discharge zone changed optical spectrum dramatically: the intensities of some molecular nitrogen bands were decreased or disappeared. Characteristic optical lines of a chemical flame (CN, CO and others) are created in spectrum. Characteristic optical spectrum of PAC is shown in Fig. 3. Rotational (gas) temperature was determined on base of the processing of the rotational optical lines (from N=16 up to N=27-28, R-branch) in this experiment also. It was revealed that gas temperature was depend on propane injection flux. For example, mean gas temperature in PAC region was  $2100 \pm 200$  K in the case of small fuel injection (0.1 g/s). On another hand mean gas temperature in PAC region was about 2400-2700K in the case of large fuel injection (1 g/s). This result was proved by pyrometer measurement also.

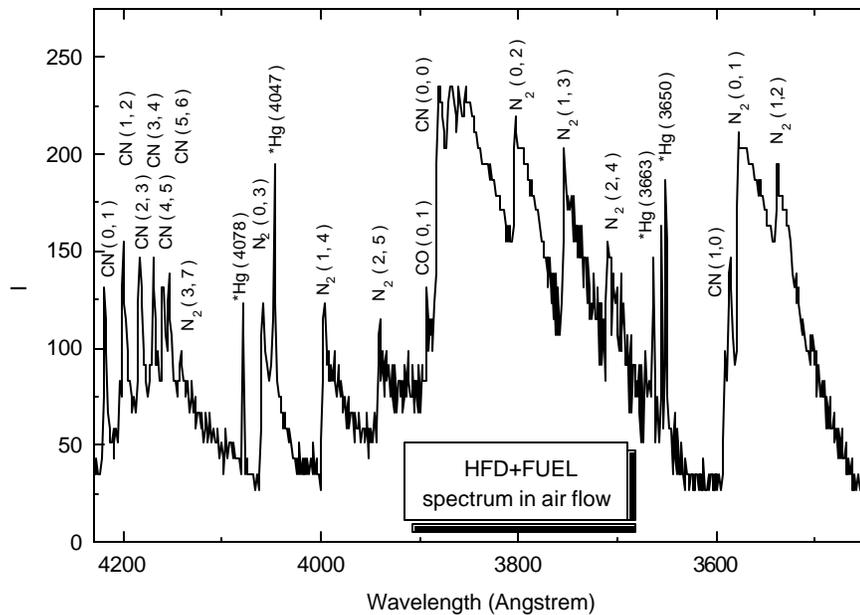


Fig.3. Characteristic optical spectrum of PAC in airflow ( $M \sim 0,8$ ) with propane injection.

### Conclusion

1. Improved new optical spectra of HF streamer discharge with propane injection and without it were obtained in airflow in HWT. Experience obtained during previous PAC experiment was used in present experiment.
2. Gas temperature inside HF streamer discharge measured by optical spectroscopy method is about  $T_g \sim 1000-1600K$ . This temperature depends on HF anode current strongly.
3. Measured gas temperature in PAC region is about  $T_g \sim 2600K$ .
4. It is need to record the radical optical lines (IR band of optical spectrum) and study PAC dynamics in a space and time.

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## **Main conclusions of Contract Work**

1. Three types of the modified PGs were designed, manufactured and tested during PAC experiment, namely:
  - Tesla's coil HF plasma generator for HF streamer discharge generation in an airflow,

- PG- jet for generation of erosive plasma jet in an airflow,
- PG- Comb for combined discharge generation (streamer HF+ erosive plasma jet).

Mean power of each PG is about 2-3 kW.

Main parameters of plasma formations created by these PGs are the followings:

- Electron concentration  $10^{11}-10^{15} \text{ cm}^3$ ,
  - Electron temperature 0,6- 10 eV
  - Gas temperature 1000- 6000K.
2. Volume streamer HF discharge was created in a metal test section in a supersonic airflow using a small dielectric insertion for electrode arrangement. It was a difficult technical problem. Our solution is very useful for a scram jet technology.
  3. Hot wind tunnel was created to study PAC in a subsonic and supersonic airflow. Main technical characteristics of HWT:
    - airflow parameters  $M < 2, P_{st} < 1 \text{ Bar}$
    - Airflow mass flux  $< 20 \text{ g/s}$ ,
    - Propane mass flux  $< 1 \text{ g/s}$ .
    - Gas temperature in arc heater  $T_o < 2000\text{K}$ ,
    - HF power of the igniter  $N_d < 2 \text{ kW}$
    - Mean power of PG-jet  $N_d < 3 \text{ kW}$

HWT is consisted from two quartz tubes. This HWT design helps us to use optical diagnostic instrumentation in PAC experiment.

4. Following diagnostic instrumentation was used in PAC experiment:
  - Optical spectroscopy,
  - IR spectroscopy,
  - Ion mass spectroscopy,
  - Thermocouples,

- Pressure sensors,
- Video camera and digital camera,
- PMA with optical filters,
- Optical pyrometer.

This instrumentation was calibrated in test section with a well-known glow discharge before PAC experiments.

5. Stable volume streamer HF discharge was created in a supersonic (subsonic) airflow ( $M < 2$ ,  $P_{st} < 1$  Bar). It was transformed to a diffuse torch HF discharge in a hot combustion region at gas temperature  $T_g \sim 2000K$ . Characteristic plasma parameters of a single HF streamer are the followings:

- Electron concentration  $> 10^{15} \text{ cm}^3$
- Electron temperature  $1-10 \text{ eV}$
- Gas temperature  $1000-1500K$ ,
- Specific energy storage  $\sim 1-10 \text{ J/cm}^3$

6. Stable external and internal PAC stimulated by streamer HF discharge was generated in a supersonic (subsonic) airflow ( $M < 2$ ,  $P_{st} < 1$  Bar).

Optimal parameters of HF PG for generation of stable PAC in airflow are the followings:

- Anode current  $I_d > 0,4 \text{ A}$ ,
- Streamer generation frequency  $F_{str} > 10 \text{ kHz}$ ,

Optimal location of a streamer HF discharge is a separation vortex zone behind pylon- electrode.

7. Very small characteristic ignition time  $\tau_1$  and combustion time  $\tau_2$  were measured during PAC experiment ( $M < 1,2$  ,  $P_{st} < 1\text{Bar}$ ,  $T_o \sim 300K$ ), namely:

$$\tau_1 \sim 30-50 \text{ mcs}, \tau_2 \sim 100-150 \text{ mcs}$$

8. Generation of various radicals was measured in PAC experiment, such as: CH, CH<sub>2</sub>, O, O<sub>3</sub>, CN, and others. Maximal relative concentration of radicals in PAC experiment is  $\sim 10^{-2}$  (our estimations).
9. Final products of PAC are H<sub>2</sub>O and CO<sub>2</sub> only (no toxic impurities and propane).
10. Additional small water vapor injection (propane: water  $\sim 100: 1$ ) could intensify PAC (increase a gas temperature and combustion rate).
11. Optimal PG-jet design has the following characteristics:
  - Discharge channel with large length  $L_d \sim 60-80$  mm
  - Discharge current  $I_d \sim 50-80$  Amp
  - Discharge voltage  $U_d \sim 1-2$  kV
  - Pulse duration  $T_i = 1-10$  ms
  - Time frequency  $F > 10$  Hz
  - Propane mass flux  $< 1$  g/s
12. It was revealed that combustion-detonation transition of a propane-air mixture in a cold supersonic airflow could be possible at PG- jet control.
13. Bad quality fuel (such as paraffin, wax, oil and others) could be used in PAC stimulated by a new PG-jet.
14. There is a combustion “memory” – relaxation process of a fuel combustion after plasma generation (after switch off the electric power in a discharge). Characteristic time of this process is about  $T_m \sim 10$  ms in a case of erosive pulse discharge.
15. Best PG for PAC is PG-Comb (PG HF+ PG-jet). There are a good radical generation and a gas heating in this PG namely. In a result active and very fast PAC stimulated by PG-Comb is possible in airflow. Note that best fuel combustion in airflow (without toxic impurities) was created by means of this PG namely.