Study of Internal and External Plasma Assisted Combustion in Supersonic Gas Flow

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14. ABSTRACT

The Project is devoted to basic study on the field of external and internal plasma assisted combustion. This effort consists of three Tasks: Task #1 is titled "Internal plasma assisted combustion controlled by improved plasma generators in metal channel at conditions similar to Scramjet"; Task #2 is tilted "External plasma combustion experiment in a supersonic flow (M~2, Pst=1 Bar)". This is a study of flow around model F with plasma combustion generator in wind tunnel; Task #3 is tilted "Study of supersonic flow around model E with combined plasma generator (PG Comb= PG HF +E beam)". Here, the main plasma parameters could be changed independently in PG- Comb. Electron concentration will be controlled by E-beam. Electron temperature could be controlled by external HF electric field. The main goals of this work is a study of following: Optimal radical generation in fuel/ air mixture and combustion control by non equilibrium plasmoids, Advanced mixture of fuel in gas flow by structural plasmoids.

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Final Technical Report
ISTC Project #2127P

Study of Internal and External Plasma Assisted Combustion in Supersonic Gas Flow

(from 1 January 2002 up to 31 December 2004)

Dr. Klimov Anatoli Ivanovich
Project Manager
High Temperature Institute RAS

January 2005

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Contents:

Notifications

φ - fuel-airflow equivalence ratio;

τ_1- ignition time;

τ_c- combustion time;

DC – direct current;

EB – electron beam;

HF – high frequency;

HFD - high frequency streamer discharge;

HWT - hot wind tunnel;

I_d - discharge current;

M- Mach number;

MW – microwave;

N_d - discharge power;

N_e- electron concentration;

PAC - plasma assisted combustion;

PG -plasma generator;

PRD - pulse repetitive discharge;

P_{st} - static pressure;

Re - Reynolds number;

SW - shock wave;

T - pulse duration;

T_g - gas temperature;

T_R- rotation temperature;

T_v- vibration temperature;

U_d- discharge voltage;

UV – ultra violet;

VACh - Volt- Ampere characteristics of the electric discharge;

WT - wind tunnel.

Introduction

The Objective of this Project is study of internal and external plasma- assisted combustion (PAC) of hydrocarbon fuel in high-speed airflow.

It well knows that there are some difficulties connected with ignition, mixing and combustion of hydrocarbon fuel in supersonic airflow. These difficulties are connected with large characteristic ignition time τ_i and combustion time τ_c of hydrocarbon fuel in supersonic airflow at the parameters closed to scramjet ones. Additional active radical and vibration exited molecule generation in airflow can decrease these characteristic times considerably [1-14]. The active radicals O, H, CH, OH, NO, CN and vibration exited molecules play important role in combustion process. Recently it was revealed that three radicals CN, C2, CH2 play most important role in plasma-assisted combustion namely [1-14]. Non-equilibrium electric discharge can generate these radicals effectively. It was obtained that characteristic propane ignition time τ_I and propane characteristic combustion time τ_c in supersonic airflow M~2 could be decreased up to factor 2…5 by non-equilibrium plasma formation (in comparison with the ones at plasma off), [1]. Minimal measured value τ_I ~ 10-50 μs and minimal measured value τ_c ~ 50-150 μs were measured in supersonic airflow (M~2) in PAC experiment at hydrocarbon fuel injection.

It is very important to note that radical’s concentration in local PAC zone is increased up to 3-4 times by external UV-radiation generated by KrF excimer laser (λ=248 nm), [14]. Note that mean laser power used in this experiment was very small ~4 W only (much smaller than the chemical fuel power ~16 kW). Selective radical excitation is possible by this laser also. So, combined plasma-laser action on fuel combustion may be optimal one in scramjet technology.

The PAC of *non-premixed* hydrocarbon fuel in high-speed airflow (M<2) was studied in our previous works [1-14]. According our opinion and obtained experimental background there are two main problems (tasks) in PAC physics, namely

- Fuel PAC completeness in high-speed airflow,
- Fuel mixing in high-speed airflow.

It was revealed that non-premixed PAC is *non-homogeneous* (cell-type structures in combustion region) and *non-stationary* one as a rule [13, 14]. Strong plasma-fuel combustion interference was revealed in this PAC experiment due to high gas density gradient generation and double electric layer generation on the cell’s surface. Pulse periodic modulation of the discharge and plasma parameters by these PAC cells and soot particles (carbon clusters) was measured in experiment. The typical modulation frequency is about 1-10 kHz. Analysis of the current signal, voltage signal and shadow pictures obtained in PAC experiment, proves the conclusion mentioned above.

Important role of charged and excited carbon clusters (soot particles) in the PAC kinetics and dynamics was revealed and considered in the works [1-14]. There is high local electric potential (φ~ 1000V, q~ 100-1000q_e) and strong electric field near surface of these particles. These particles can accelerate and decelerate the PAC in airflow by its local electric field considerably. So, application of traditional homogeneous combustion kinetics in the non-homogeneous and non-stationary PAC (including high gas gradients, electric double layers, local strong electric field near charged clusters) is not correct. Experimental results on chemical analysis of the final PAC species and PAC completeness prove this conclusion [13, 14]. Final PAC species of lean fuel-airflow mixtures are not consisted of traditional components such as CO2, CO, CH, and others in some PAC regimes. Note that chemical analysis of the PAC species was fulfilled with the help of IR-spectroscopy and ion-mass spectroscopy.

It was revealed that pulse repetitive electric discharge can increase the mixing of propane jet and co-airflow considerably (realization of advanced fuel-airflow mixing in plasma zone), [13, 14]. Anomalous fast transportation of fuel inside HF plasmoid was measured in PAC experiment [1-14]. Typical fuel transportation velocity measured in this experiment was about 100-1000 m/s. Anomalous propane transportation was obtained in combined discharge plasmoid in supersonic airflow also (electron beam + DC discharge) [7, 8]. Fuel can move against supersonic airflow inside of this plasmoid. The physical nature of this phenomenon is not clear up today. We plan to study this task in detail in the frame of new Project.

This Final Report is consisted of two Parts:

Part 1. Quarterly Report (Del.12). Experimental results on fuel PAC completeness in high speed airflow

Part 2. Final Report. Summarized experimental results on external and internal PAC in high speed airflow

Part 1

Quarterly Report (Del.12)

Fuel PAC Completeness in High-Speed Airflow

Experimental study on hydrocarbon fuel PAC completeness in high-speed airflow is carried out in experimental set up HWT-1.

Remember that experimental conditions were the followings:

• Type of electric discharge	Transverse combined electric discharge (DC+ pulse repetitive discharge, PRD)
• DC current	I_d< 1 Amp
• PRD frequency	F~100 Hz
• Pulse duration	T_i~ 1-10 mcs
• Pulse amplitude	U_d~16 kV
• Airflow mass rate	M_{air}<40G/s
• Propane mass flow rate	M_{pr}<1G/s
• Static pressure	P_{st} ~ 1 Bar
• Operation mode	non-premixed regime

The experimental results on PAC completeness were obtained by three independent methods:

- Chromatographic method,
- Calorimetric method,
- IR absorption spectrographic method

So, obtained results are reliable and corrected.

1.1. PAC completeness of a lean propane-butane mixture in subsonic airflow, φ <2

The experimental results on PAC completeness are shown in fig.1.1. One can see that

- C3H8 concentration and C4H10 concentration are decreased up to 130-150 times,
- CO2 concentration is increased up to ~ 9, 3% of the total mass composition.
- CO concentration is about 0,15% of the total mass composition (or ~ 1,6% of the mass concentration of the CO2)
- O2 concentration is decreased from 19,22% up to 11,15%,
- CH4 concentration and C2H4 concentration are increased considerably.

Note that light hydrocarbon (CH_4, C_2H_4, C_2H_6, C_2H_2) concentrations are increased namely. But heavy hydrocarbon (CH_4, C_2H_4, C_2H_6, CH_2CCH_2, trans-C_4H_8-2, C_4H_8-1) concentrations are decreased considerably in this regime.

So, one can see that there is dissociation of initial fuel molecules by electric discharge (creation of light species). But there is no generation of complex heavy molecules in PAC zone in this regime (no polymerisation). PAC fuel completeness measured by IR spectroscopy method and chromatographic method is about 90% in this experiment. Remember that it is impossible to measure water vapour correctly by these methods (due to water vapour condensation on cold retort wall of the chemical probe). If we take into account that argon concentration and nitrogen concentration are constant in gas mixture the corrected fuel conversation value will be about 99,5% in this case. So, completeness of lean fuel mixture is high in airflow at plasma assistance.

It is interesting to compare these experimental results with the ones considered in previous report [1]. There is good correlation of these results. But fuel PAC completeness (burning) is higher than the one measured in previous experiment. This result is explained by the fact that step (vortex separation zone) is absent in combustor chamber in present experiment.

1.2. PAC completeness of a rich propane-butane mixture in airflow (φ <0,125)

The experimental results on PAC completeness are shown in fig.1.2. One can see that

- Initial fuel concentration is decreased considerably: (C_3H_8+ C_4H_{10}) concentration is decreased up to 500 times,
- CO_2 concentration is increased up to ~ 12% of the total gas mass composition.
- CO concentration is about 6,4% of the total gas mass concentration (or ~ 50% of the mass concentration of the CO_2). Its value is higher that the one measured at lean fuel mixture PAC combustion.
- O_2 concentration is decreased considerably from 19,22% up to 3,3%,
- Main hydrocarbon components are C_2H_2, CH_4, C_2H_4, C_3H_6, C_3H_4-1, n-C_4H_{10}, iso-C_4H_{10}, C7+, C_6H_6.

It was revealed that C_2H_2 concentration is about of 0,82%, CH_4 concentration is about of 0,35%, C_2H_4 is about of 0,43 %, C_3H_6 concentration is about of 0,12%, C_3H_{14}-1 concentration is about of 0,35%, n-C_4H_{10}- 0,17%, iso- C_4H_{10}- 0,12%, fig.1.3. Note that heavy components such as C_2H_2, C7+, C_6H_6 are created behind PAC zone in this regime (compare this result with the one obtained in lean fuel mixture). It is well-known that these components are the initial “bricks” for the soot particle “building”. Note that high concentration of soot particles are recorded in this experiment namely. Small concentration of the hydrogen H2 (~0,4%) is recorded in this experiment also. So, high fuel conversion was obtained in this PAC regime.

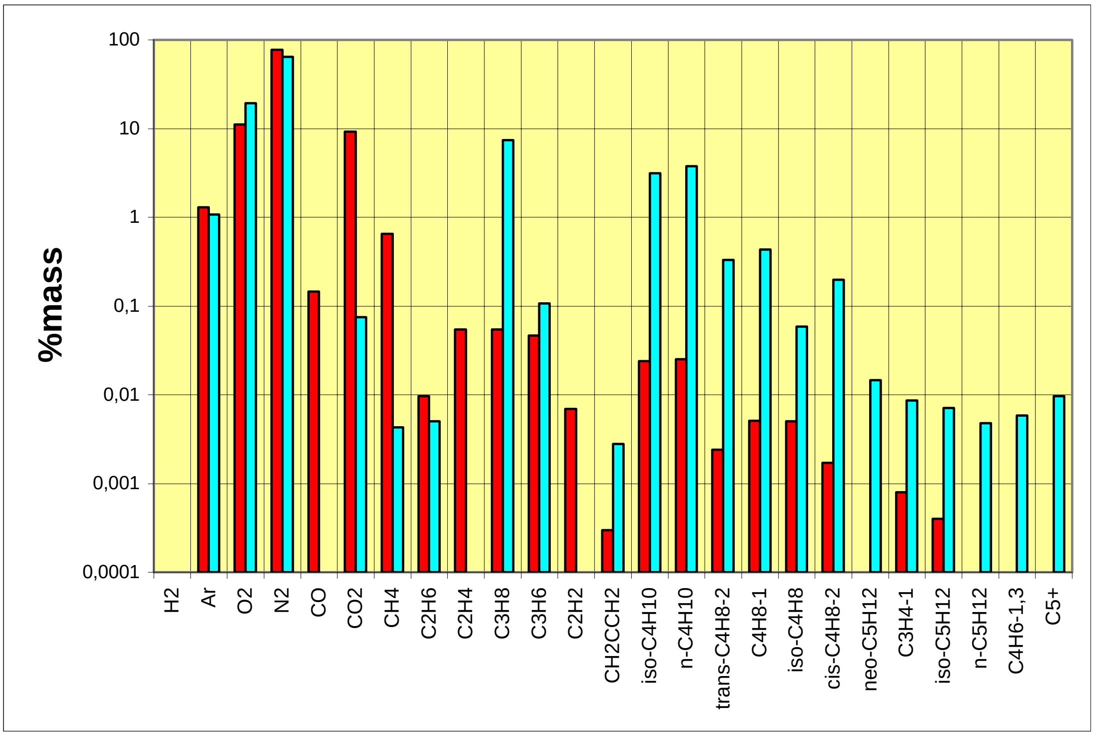

Fig.1.1. PAC species in the HWT-1 with separation zone. Red - lean propane-butane mixture at plasma assistance, φ <2, green - initial mixture at plasma off and combustion off

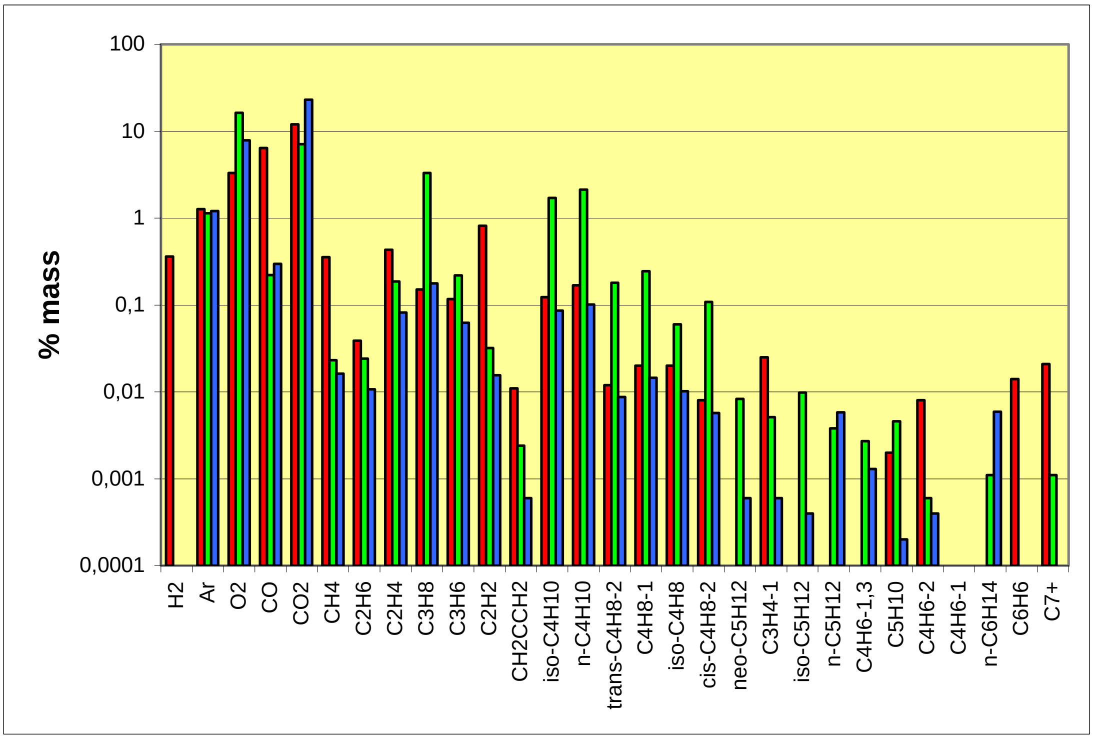

Fig.1.2. PAC species in the HWT-1 without separation zone. Green - a lean propane-butane mixture in subsonic airflow φ <2; red - rich propane-butane mixture, φ <0,125; blue - φ ~1

1.3. PAC completeness of lean propane-butane mixture in supersonic airflow

PAC completeness in cold supersonic airflow (T*~300K) is studied in our experiment also. Modernized experimental set up HWT –1 used in this experiment is shown in fig.1.3. Main technical characteristics and parameters of the modernized experimental set up HWT-1 are the followings:

- Airflow parameters M≤2, P_{st}< 1 Bar
- Airflow mass flux < 200 g/s,
- Propane mass flux < 6 g/s.
- Gas temperature in arc pre-heater T*< 1000K,
- Power of arc pre-heater N_h< 20 kW
- HF power of the igniter N_d< 10 kW
- Operation time T< 10 min

Set up HWT-1 is consisted of two quartz tubes. This design helps us to use optical diagnostic instrumentation in PAC experiment. The powerful HF generator (N_d< 10 kW) is used in this set up. New powerful air-compressor is used in this set up also. Stationary PAC regime in hot supersonic airflow could be realised in this set up at the first time.

HF discharge in supersonic airflow is shown in fig.1.4. It was revealed that this homogeneous discharge is created in separation zone. Note, that small local dielectric insertion with *single* needle-electrode in combustor separation zone is used in this experiment (but not many-electrode design). So, one can use local single-electrode design in combustor separation zone to create homogeneous plasma in total volume of this zone, fig.1.5. It is very interesting and important result for possible technical application in scramjet.

Internal PAC in cold supersonic airflow at M=1,5; P_{st}~ 1Bar, T*=297K is shown in fig.1.6. Lean fuel-airflow mixtures (φ~ 2) are used in this experiment. One can see that bright combustion zone is located inside HF discharge zone. Not bright chemical flame is created behind quartz tube (near duct output) also. Experimental results on of the final PAC species analysis are obtained by IR absorption spectroscopy.

IR spectra were processed and analysed. Fuel PAC completeness is about 30% in this regime. So, PAC completeness of lean fuel mixture in cold supersonic airflow is not high.

PAC study in hot supersonic airflow (T*~ 1000K) in this powerful set up at pre-heater operation is started now. We hope to continue our study on PAC completeness is supersonic airflow at parameters closed to scramjet in the frame of prolongation of this Project next year.

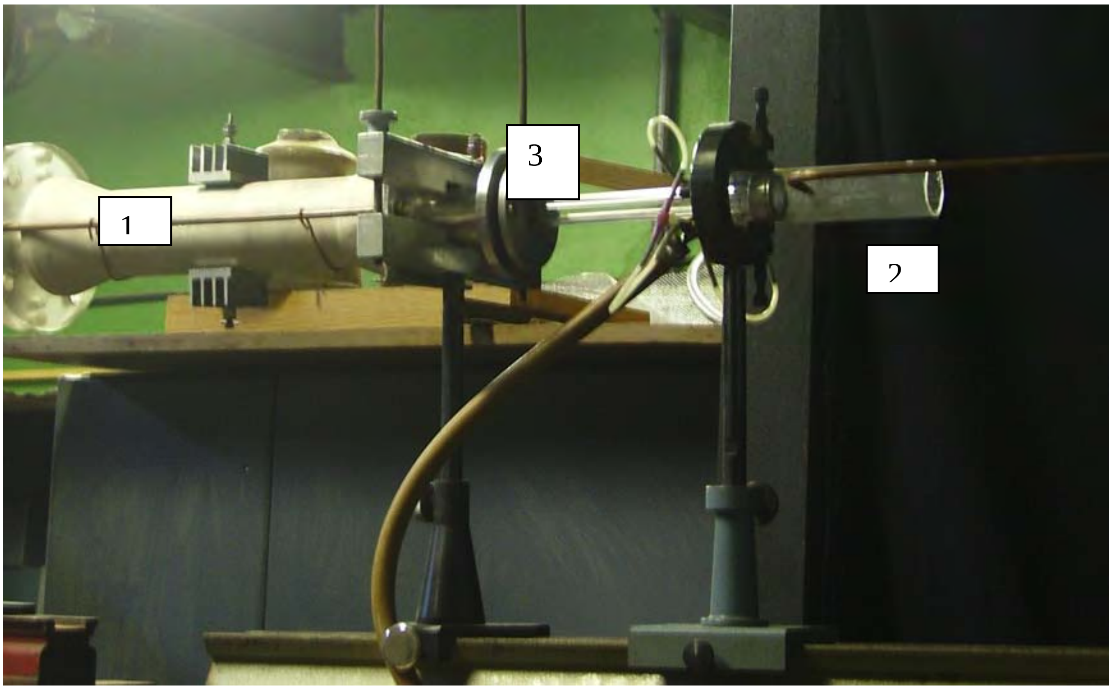

Fig.1.3a. Modernized experimental set up HWT-1. 1 - arc pre-heater, 2 - combustor (quartz tube), 3 - supersonic duct with step

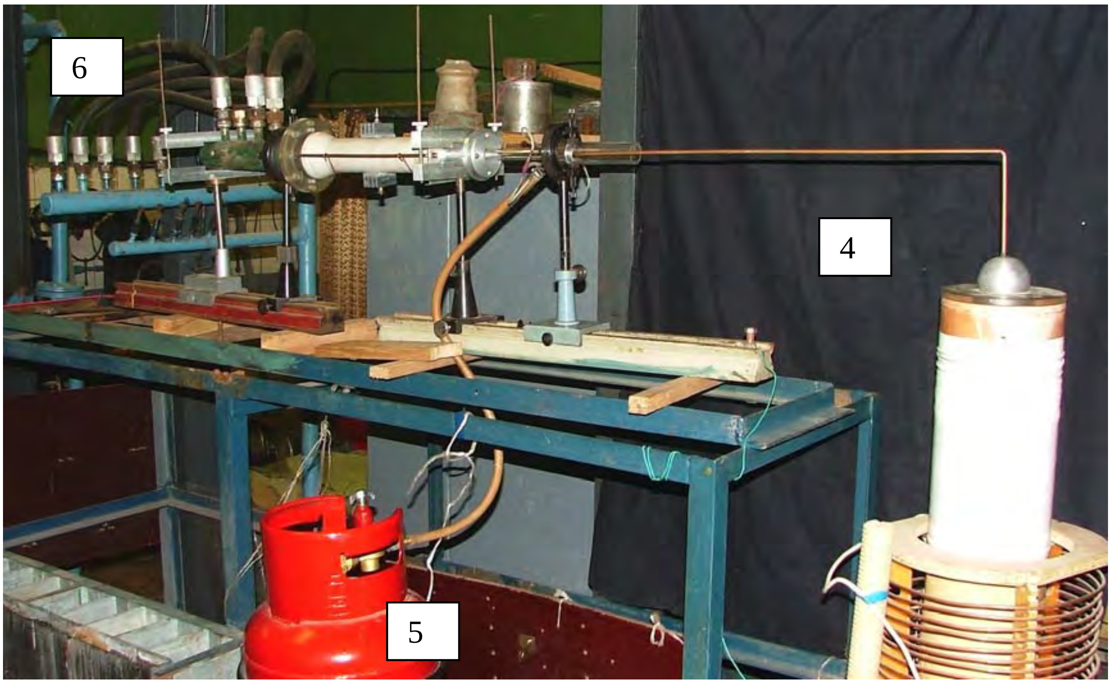

Fig.1.3b. Modernized experimental set up HWT-1. 4 - HF-generator, 5 - propane tank, 6 - compressor tube

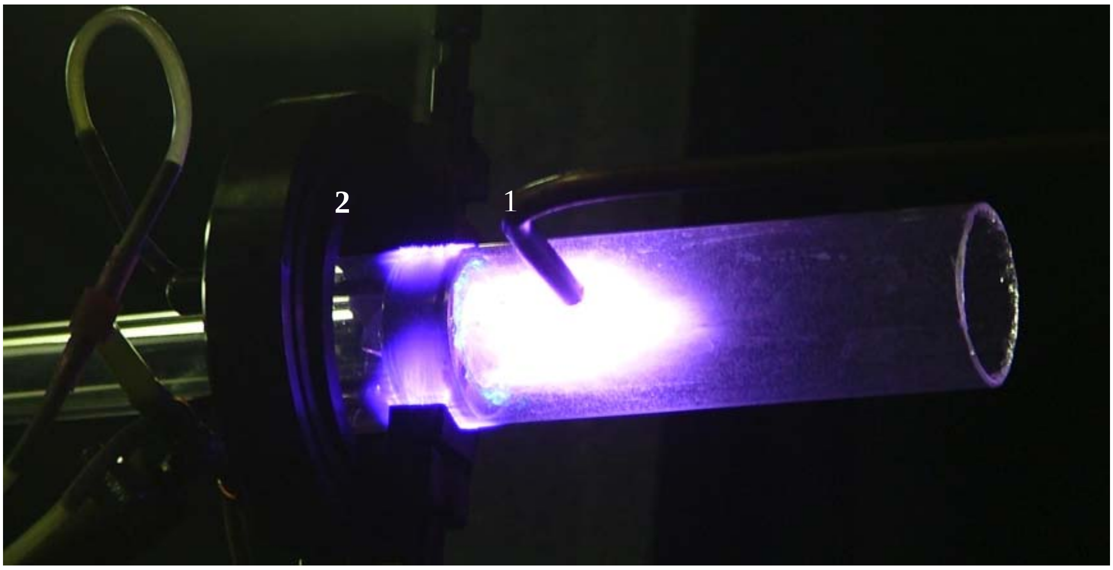

Fig.1.4. HF discharge in supersonic airflow (M=1,2; P_{st}~1 Bar, T*=297K). 1- “hot” HF electrode, 2- grounded step-electrode (propane is injected through this electrode)

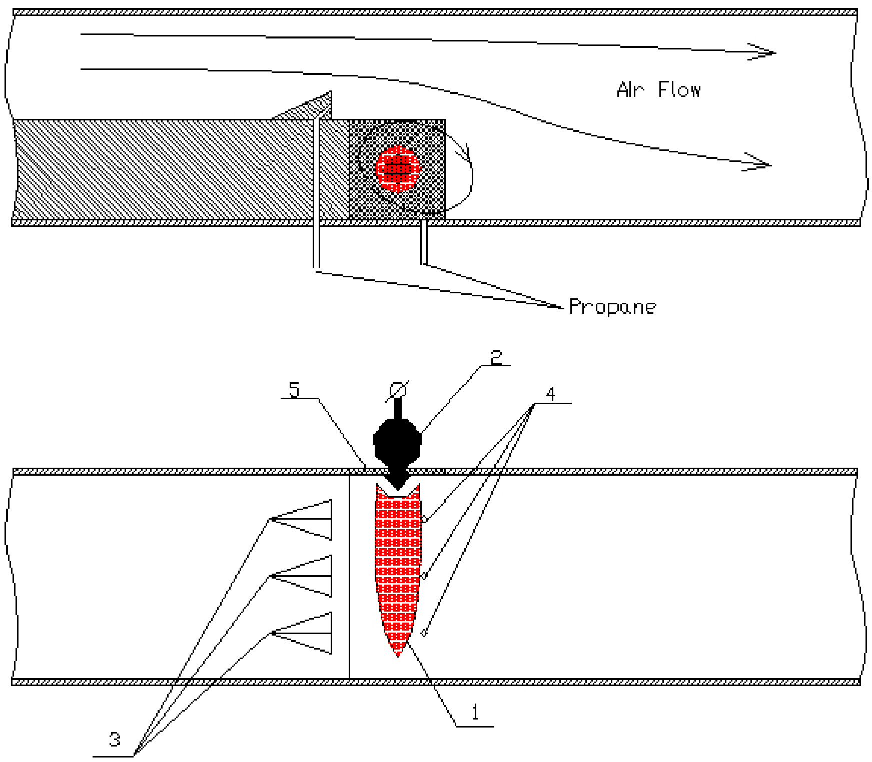

Fig.1.5. HF electrode design in scram jet combustor. 1 – HF-discharge, 2 - HF-electrode, 3 - pylon-fuel injector, 4 - fuel injectors, 5 - ceramic insertion

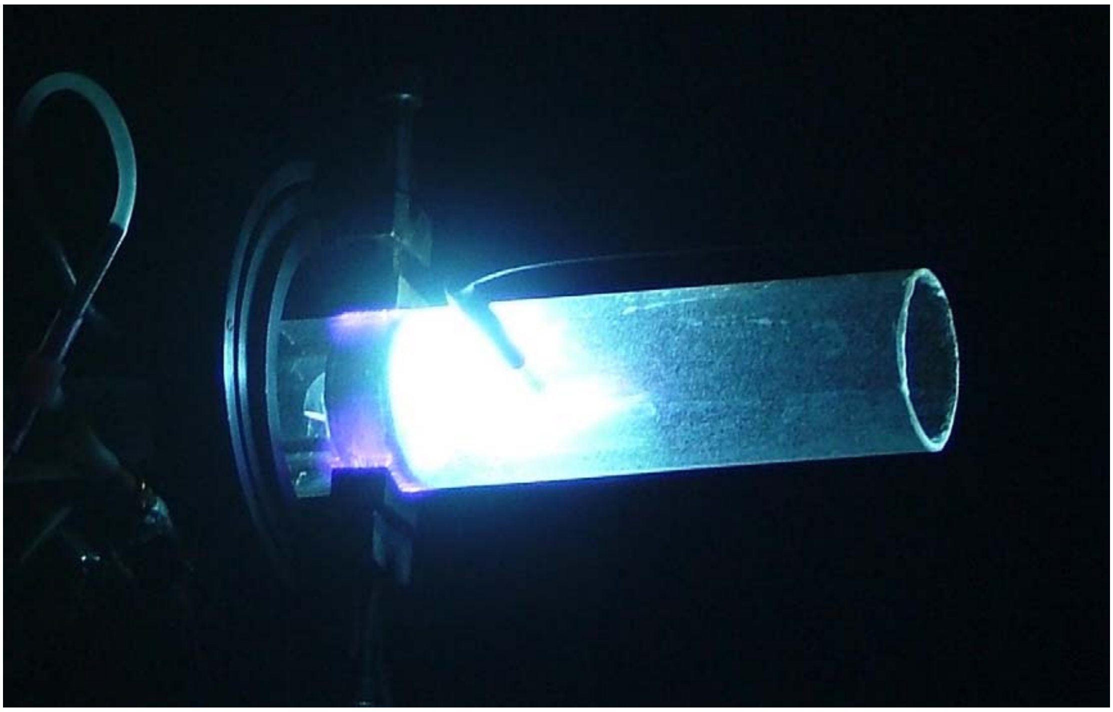

Fig.1.6. PAC of injected propane in cold supersonic airflow (M=1,2; P_{st}~1 Bar, T*=297K). Propane is injected through thin tubes in combustor step.

1.5. Optical spectra in PAC zone

Combined transverse electric discharge (DC+ pulsed repetitive discharge, PRD) is used in HWT-1. Pre-heater is used in these experiments at the first time. Experimental conditions are the followings

• DC current	I_d< 1 Amp
• PRD frequency	F~100 Hz
• Pulse duration	T_i~ 1-10 mcs
• Pulse amplitude	U_d~16 kV
• Airflow mass rate	m_{air}<40G/s
• Propane mass flow rate	m_{pr}<1G/s
• Airflow Mach number	M<2
• Static pressure	P_{st} ~ 1 Bar
• Stagnation gas temperature	T_o<1200K
• Operation mode	non-premixed regime, with pre-heater

Remember that unusual experimental result was obtained in previous Report (Delivery 11, [1, 13, 14]). Three different gas temperatures T_g were measured by optical spectra processing, namely:

- Gas temperature in plasma structure estimated by molecular CN-band is about of T_{g1} ~7000K.
- Gas temperature in plasma structure estimated by C2-band is about of T_{g2} ~5000K.
- Gas temperature in plasma structure estimated by continuous spectra is about of T_{g3} ~2000-2500K.

What is the real gas temperature inside PAC zone? There are two possible answers for this question considered in [1, 13, 14]:

- The first explanation is connected with non-equilibrium plasma formation in PAC zone. Different non-equilibrium plasma-chemical zones are created in PAC region consequently (CN-radical generation- in the first step, C2-radical generation- in the second step and so on).
- The second explanation is connected with complex non-homogeneous structure of PAC zone in high-speed airflow (constricted plasma filaments and diffuse plasma "halo" around them).

Additional experiments were carried out to clear these two mechanisms. Now it is revealed that plasma structure and combustion structure parameters are depended on incoming airflow parameters considerably (in particularly - gas temperature T_g). One can see that Volt- Ampere characteristics of the electric discharge in airflow at pre-heater operation and without it are absolutely different, fig.1.7. Note that voltage pulses and current pulses are connected with plasma structure generation (discharge instabilities). The photos, obtained by high–speed camera, prove this conclusion. Diffuse plasma structures are created in PAC zone in this regime at pre-heater on.

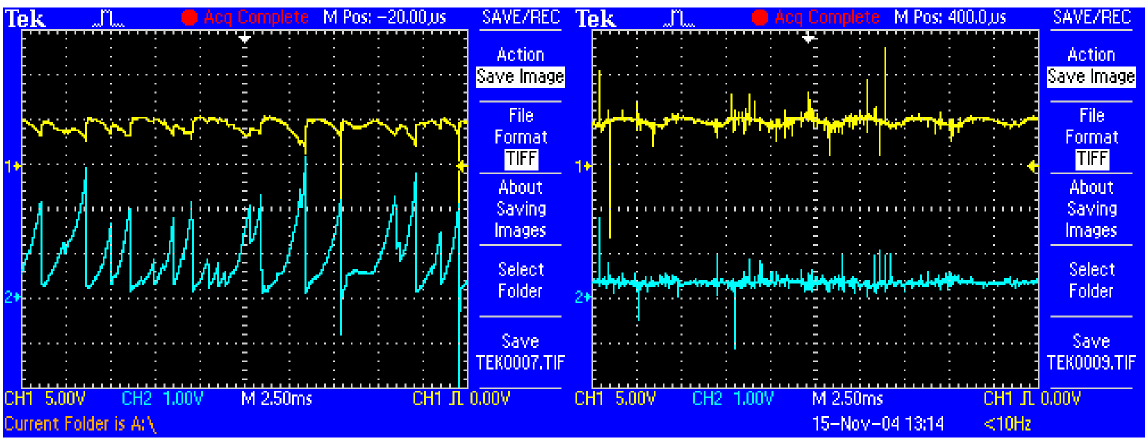

Fig.1.7. Propane PAC in airflow. Voltage (blue) and current (yellow) in transverse electric discharge in PAC zone. Pre-heater on – left, pre-heater off (right). Voltage signal – 1000V/div. Current- 0,5 Amp/div. M~0,1: P_{st}~1Bar; mass airflow- propane ration φ~ 2

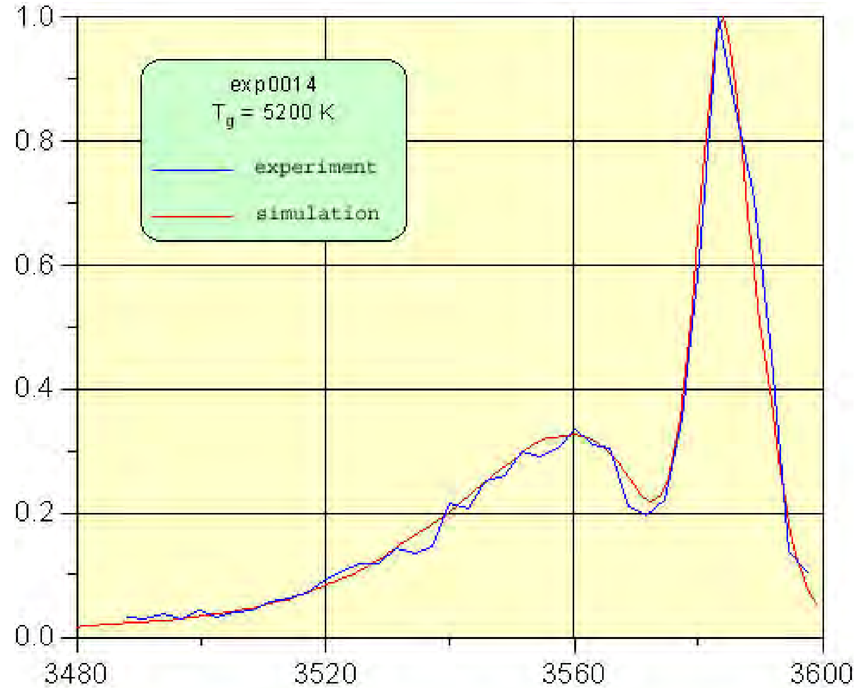

Fig.1.8. Optical spectrum of the CN (0,1) radical. Blue – experiment, red – simulation. *Pre-heater off*, electric power N_e=425W, airflow velocity 10 m/s, static pressure, P_{st}=1 Bar, Φ=3,33

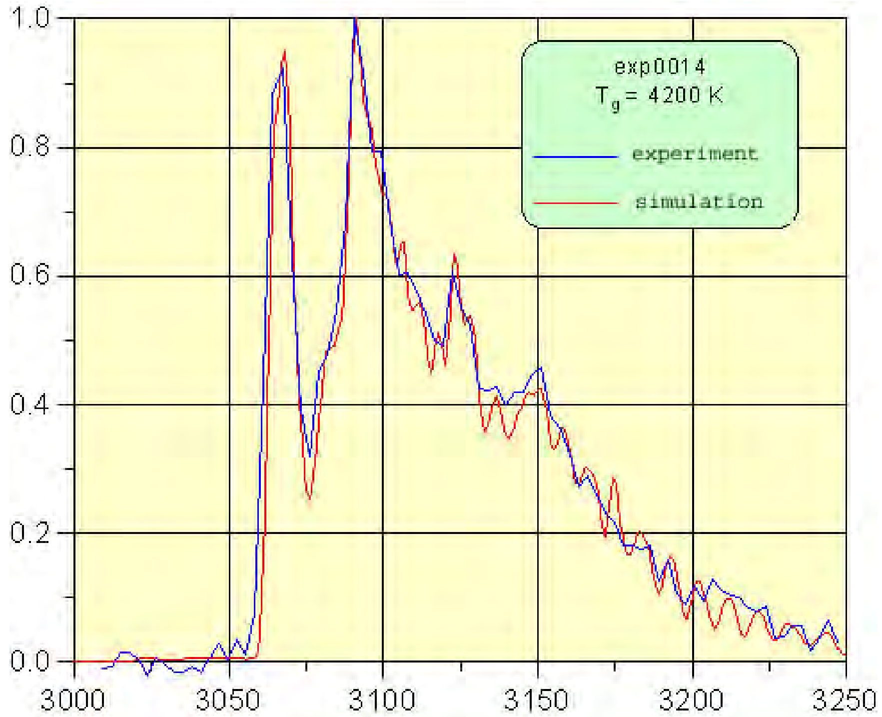

Fig.1.9. Optical spectrum of the OH radical. Blue – experiment, red – simulation. *Pre-heater off*, electric power N_e=425W, airflow velocity 10 m/s, static pressure. P_{st}=1Bar, Φ=3,33

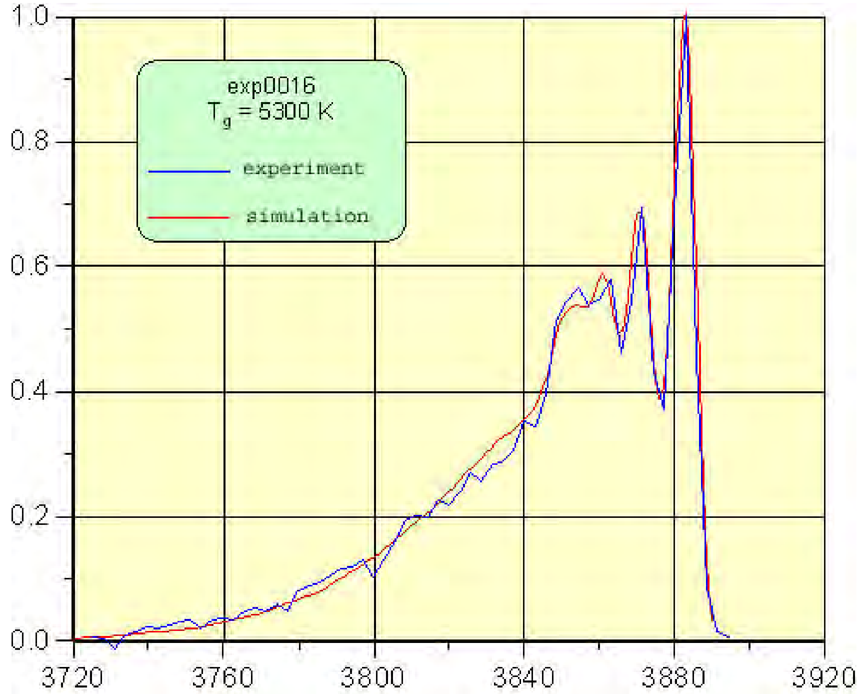

Fig.1.10. Optical spectrum of the CN (0,0) radical. Blue – experiment, red – simulation. ***Pre-heater on***, electric power N_e=425W, airflow velocity 10 m/s, static pressure P_{st}=1 Bar, Φ=3,33, static temperature T=415C, gas flow temperature behind PAC zone T_f=1090C

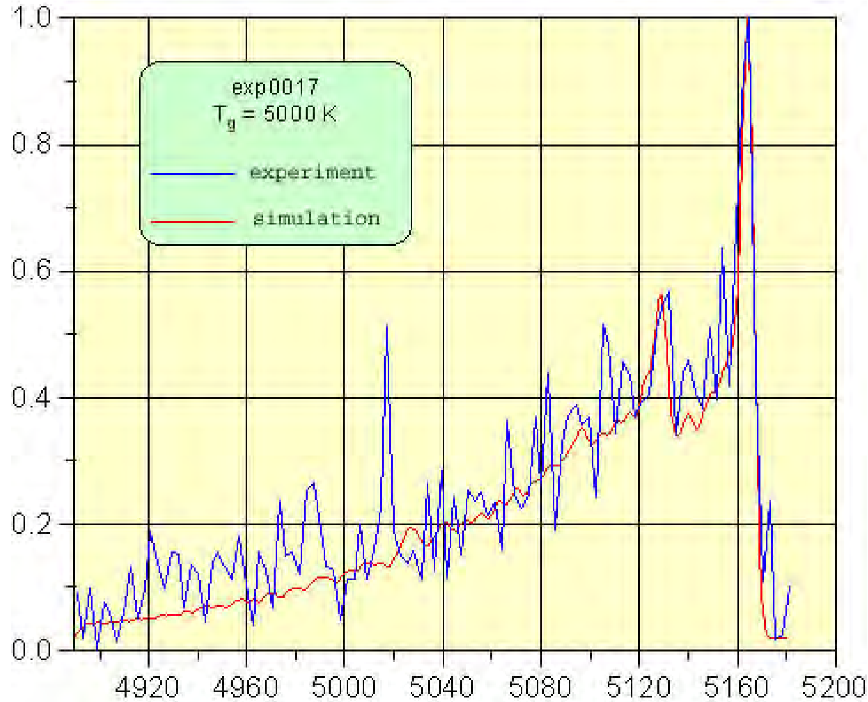

Fig.1.11. Optical spectrum of the C_2 radical. Blue – experiment, red – simulation. ***Pre-heater on***, electric power N_e=425W, airflow velocity 10 m/s, static pressure P_{st}=1 bar, Φ=0,78, static temperature T=415C, gas flow temperature behind PAC zone T_f=1080C

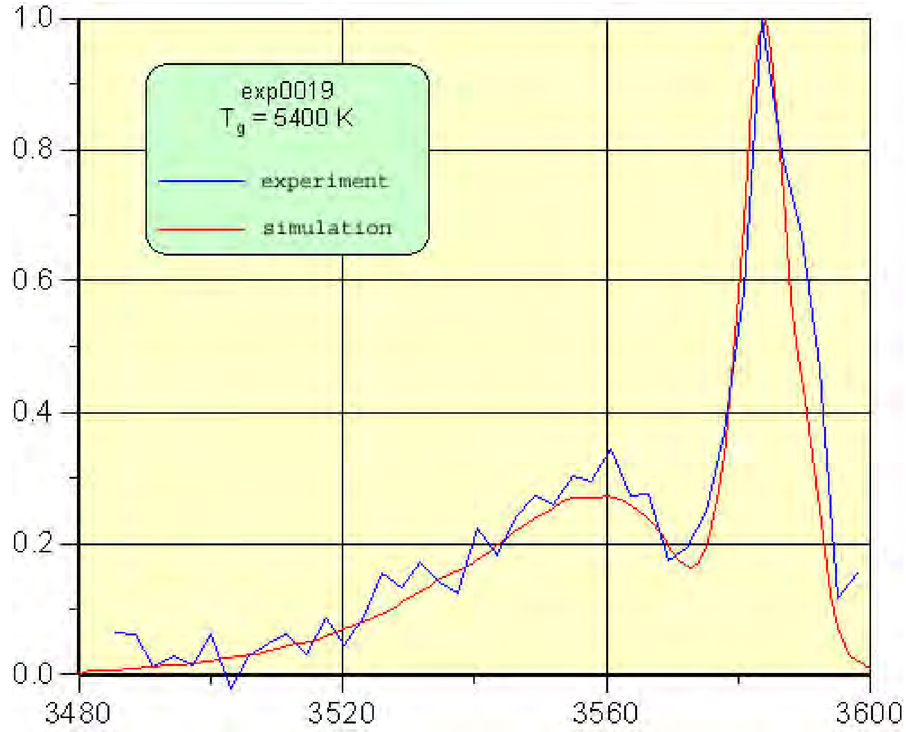

Fig.1.12. Optical spectrum of the CN(1,0) radical. Blue – experiment, red – simulation. ***Pre-heater on***, electric power N_e=425W, airflow velocity 10 m/s, static pressure P_{st}= 1 Bar, Φ= 1,81; static temperature T= 415C, gas flow temperature behind PAC zone - T_f= 930C

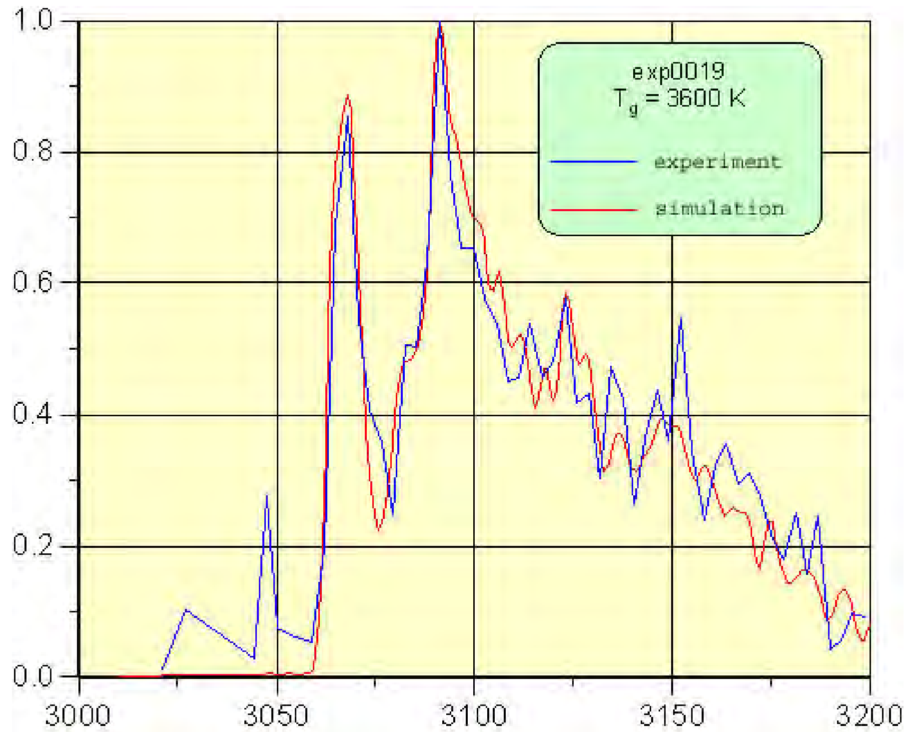

Fig.1.13. Optical spectrum of the OH radical. Blue – experiment, red – simulation. ***Pre-heater on***, electric power N_e= 425W, airflow velocity 10 m/s, static pressure P_{st}= 1 Bar, Φ= 1.81, static temperature T= 415C, gas flow temperature behind PAC zone - T_f= 930C

So, one can suppose that different optical spectra will be recorded in this regime. So, one can suppose that different temperatures will be obtained by these spectra. Typical experimental optical spectra are shown in fig.1.8-1.13 (blue lines). Simulation results are shown in these figures also (red lines). One can see that gas temperatures measured at pre-heater on is very closed to the one at pre-heater off. Note that CN vibration energy distribution function is not Boltsman's one. The energy levels v= 2 – 3 have very high populations (over population). So, the first explanation of the optical spectra (see above) is the correct one namely. Final correct answer on this question is possible on base of detail PAC study in future experiment.

1.6. Self-organized PAC regimes in high-speed airflow

It was revealed that there are three very stable self-organized regimes in PAC experiment. These regimes are characterized by different colours and very *homogeneous* combustion flames, namely:

- Blue flame. This regime is realized in lean fuel mixture, $\phi>1,2$; M<2, $P_{st}\sim1$ Bar.
- Red flame, fig.1.14. This regime is realized in rich fuel mixture, $\phi<0,8$; M=1,2; $P_{st}\sim1$ Bar.
- Green flame, fig.1.15. This regime is realized in fuel mixture at $\phi\sim1,1$; M~,2; $P_{st}\sim200$ Torr.

So, these regimes are depended on the fuel-airflow equivalence ratio. Note these regimes are depended on discharge parameters and airflow parameters also. Combined discharge (high-voltage pulse repetitive discharge + HF discharge) is optimal to create these regimes. High HF discharge current $I_{HF}>1$ Amp was used in this experiment.

It was revealed that CH2 radical is responsible for the red colour flame, fig.1.16.

C2 radical is responsible for the green flame. We plane to continue to study of kinetics of these stable regimes in detail in the frame of new Project.

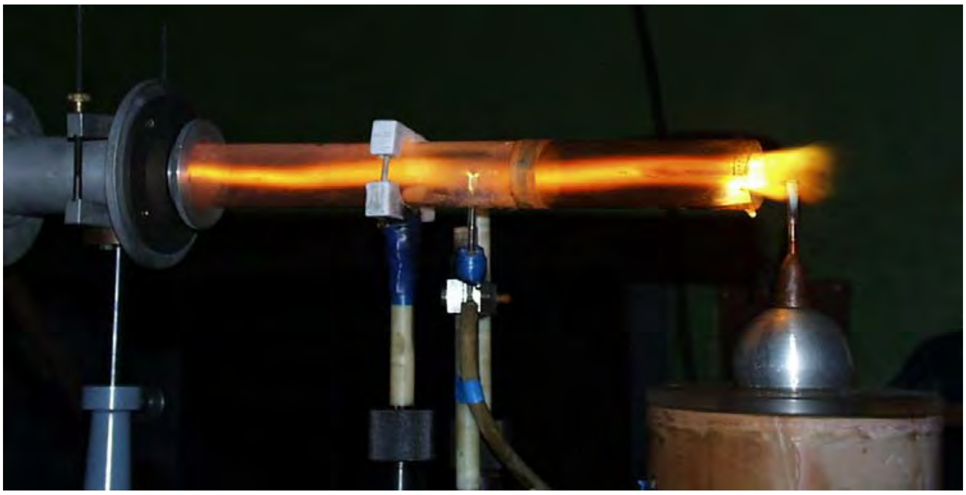

Fig.1.14. Internal PAC. Red flame. HF discharge. M=1,2; P_{st}~1 Bar, fuel-airflow equivalence ratio ϕ=0,7; CH2 radical generation

Fig.1.15. Internal PAC. Green flame. Combined discharge. M~,2; P_{st}~200 Torr, fuel-airflow equivalence ratio ϕ=1,1; C2 radical generation

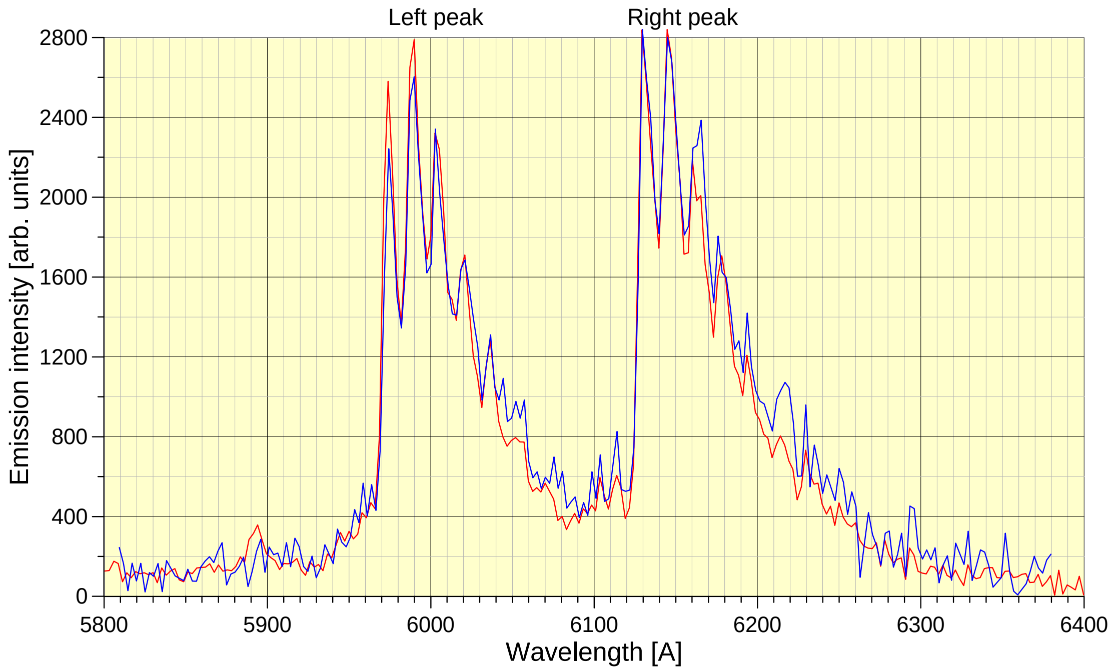

Fig.1.16. Optical spectrum obtained in red flame. CH2-radical generation

Conclusions to this Part 1

1. Fuel PAC completeness was measured in propane-airflow mixtures at the following parameters: M<1,2; P_{st}~ 1 Bar, T*<1200K; 0,2<φ<4
2. It was revealed that PAC completeness η of lean fuel mixture φ≤ 2 is high. The value η is about 90-100% in subsonic airflow (M~0.1). This value is decreased up to 30% in rich fuel mixtures.
3. High concentrations of the C2H2, CH4, C2H4, C3H6, C3H4-1, n-C4H10, iso- C4H10, C7+, C6H6 are measured in gas flow behind PAC zone in rich fuel-airflow mixtures
4. The value η is not high in lean fuel mixture (φ~ 2) in cold supersonic airflow (M~1,2; T*~300K) also. This value is about 30% in this regime.
5. Optical spectra in PAC zone in high-speed airflow at pre-heater operation (T*<1200K) are obtained and processed. Measured gas temperature in plasma zone is about T_{g1}~5500 K (CN (0,0); (1,0); (0,1); C2) and T_{g2}~3600 K (OH). Difference between T_{g1} and T_{g2} are studied now. Vibration temperature CN is about T_V ~6000-6500K.

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Part 2

Main results obtained in this Project Work

(ISTC Project #2127P)

There are three main Tasks in Work Plan of ISTC Project #2127P devoted to study of external and internal PAC in high-speed airflow:

Task #1 is devoted to continuation of our previous researches in the field of internal PAC in high-speed airflow with improved plasma generators. Fuel combustion completeness at plasma assistance in high-speed airflow was main sub-task in these researches.

Task #2 is devoted to study of local external PAC near aerodynamic model. The different types of aerodynamic models with on-board plasma generators were used in wind tunnel experiments. Supersonic flow around model with local PAC zone was studied and its aerodynamic characteristic (drag, lift, moment and others) were measured in this plasma-aerodynamic experiment.

Task #3 is devoted to study of supersonic airflow around spherical model with plasmoid created by combined discharge (DC discharge + electron beam). It is well known that combined discharge has some very important advantages. Main plasma parameters (electron concentration and electron temperature) could be changed independently in this discharge namely. Drag, pressure distribution, base pressure were measured in this plasma aerodynamic experiment.

Different wind tunnels, experimental set up and plasma generators are used in this Work. Modern diagnostic instrumentation was used to measure plasma and gas parameters.

2.1. Task 1. Internal PAC

Internal PAC was studied in experimental set up HWT-1, fig. 2.1. Hot wind tunnel HWT-1 was designed and manufactured to study PAC in a subsonic and supersonic airflow. Main technical characteristics of HWT-1 are the followings:

- Airflow parameters — $M<2$, $P_{st}< 1$ Bar
- Airflow mass flux — < 100 g/s,
- Propane mass flux — < 10 g/s.
- Gas temperature in arc heater — $T_o< 1000K$,
- HF power of the igniter — $N_d< 2$ kW
- Mean power of PG-jet — $N_d< 3$ kW

HWT-1 is consisted of two quartz tubes. This duct design helps us to use optical diagnostic instrumentation in PAC experiment.

Following diagnostic instrumentation was used in internal PAC experiment:

- Optical spectroscopy, spectrometer AvaSpec 2048, spectrometer STS-1 (λ= 180-900 nm)
- IR absorption spectroscopy, FTIR spectrometer (λ=0,8- 6μ),
- Chromatograph,
- Ion mass spectroscope,
- Electron microscope,
- Thermocouples,
- Pressure sensors, IKD, Honeywell
- Video camera and digital camera,
- PMA with optical filters,
- Optical pyrometer,
- Electrical probes,
- Microwave interferometer (λ= 2-8 mm),
- Current shunt (current coil) and resister divider

This instrumentation was calibrated by the well-known glow discharge in the test section (without gas flow) before PAC experiments.

Three types of the plasma generators (PGs) were designed, manufactured and tested in 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 (DC current discharge + high voltage pulses).

Mean power of each PG is about 2-3 kW. These PGs were tested in high-speed airflow M< 2; P_{st}< 1Bar. Mean plasma parameters created by these PGs are the followings:

- Electron concentration 10^{11}-10^{15}cm^3,
- Electron temperature 0,6- 10 eV
- Gas temperature 1000- 6000K.

1. 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 real hot wind tunnel experiment.
2. Stable volume streamer HF discharge was created in high-speed airflow (M< 2; P_{st}< 1 Bar), fig.2.2. Characteristic plasma parameters of a single HF streamer are the followings:

- Electron concentration $N_e < 10^{15}$ cm^3
- Electron temperature T_e=1-10 eV
- Gas temperature T_g=1000-2500K,
- Vibration temperature T_V~2500-7000K
- Specific energy storage ~1-10 J/cm^3
- HF streamer length $L_{str.exp}$~50 mm
- HF streamer characteristic lifetime T_{str}~50-100 mcs.
- Velocity of HF streamer propagation V_{str}~ 10^3- 10^5 m/s.

This plasma formation is non-equilibrium one. It has high specific energy storage. So, this plasma formation can stimulate plasma chemical reactions and radical generation in a fuel-air mixture.

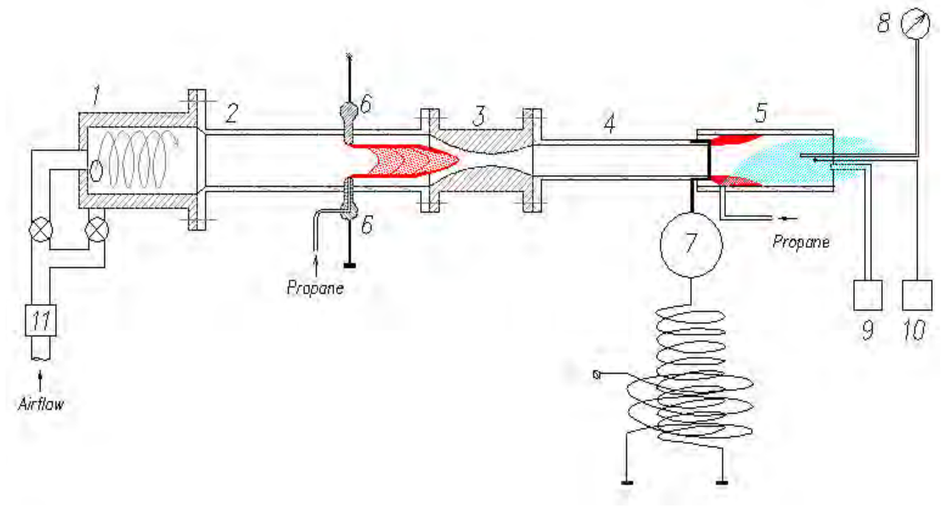

Fig.2.1. 1, 2- fore-chamber with electric arc pre-heater, 3- nozzle, 4, 5- test section, 6-arc electrodes, 7- HF electrode, 8- pressure sensor, 9-chemical probe, 10- thermocouple, 11- mass airflow

3. Stable external and internal PAC stimulated by streamer HF discharge and combined discharge (DC + pulse repetitive discharge) was created in a high-speed airflow (M< 2, P_{st}< 1 Bar), fig.2.2- 2.3.
4. 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:
   - HF discharge was ignited and burned near a mixing contact surface with high gas density gradient (near chemical flame front) as a rule, but never it burns inside chemical flame, fig.2.4
   - Modulated HF streamer discharge could disturb mixing contact surface considerably and stimulate propane- air mixing (advanced mixing),fig.2.5.

- Fuel can penetrate through a HF streamer in external airflow. Fuel transportation through HF streamer is very fast process. One can see propane transportation inside HF plasmoid towards incoming airflow and along its direction (typical red colour of the CH2 radical proves this conclusion). Mean velocity of fuel transportation inside a streamer channel is about $V_{fl}\sim 10^3$ m/s, and more. So, study of this transport property of single HF streamer is very important for advanced fuel mixing, fig.2.5.

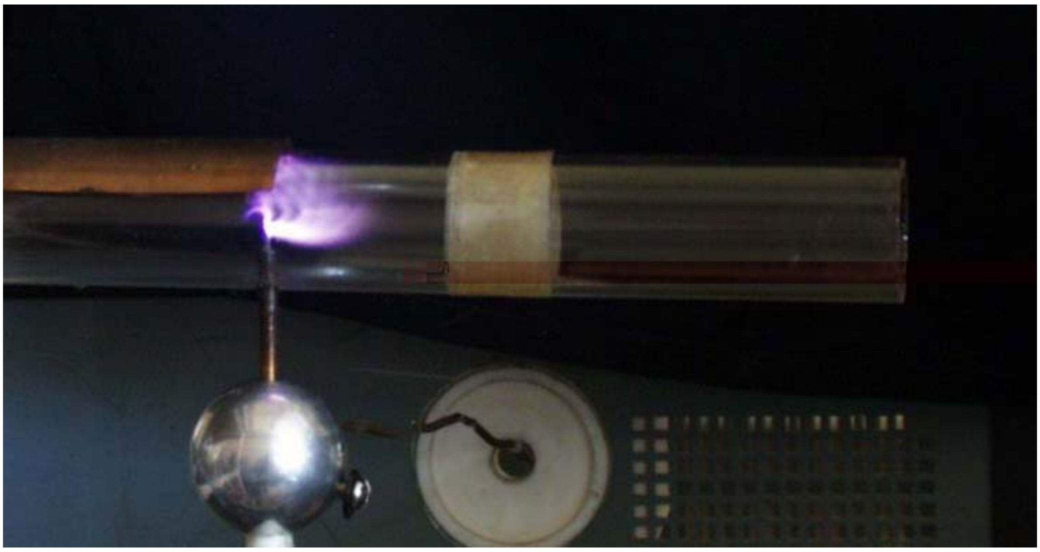

Fig.2.2. HF streamer modulated discharge in airflow (M~0,3; P_{st}=1 Bar)
F_{HF}= 13,6 MHz, F_i= 100 Hz; T_i=5 ms;

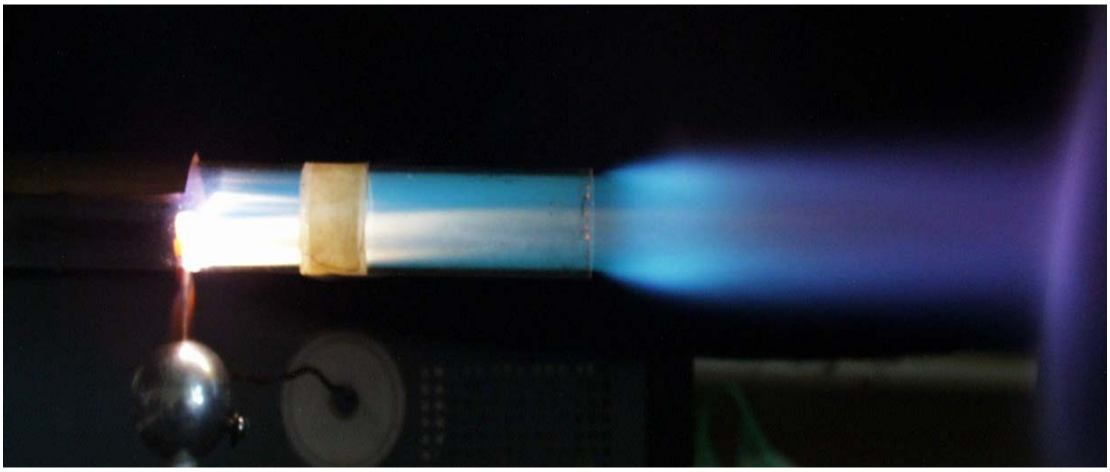

Fig.2.3. Stable plasma-assisted combustion in the set up HWT-1 in high-speed airflow (M=0.6; P_{st}=1 Bar), HF discharge (F_{HF}=13.6 MHz), modulation frequency F_i~ 100Hz

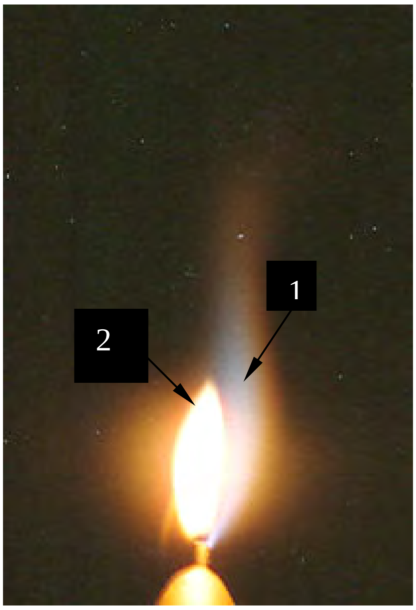

Fig.2.4. HF discharge (1) near chemical flame surface (2). Laminar propane flame in atmosphere,

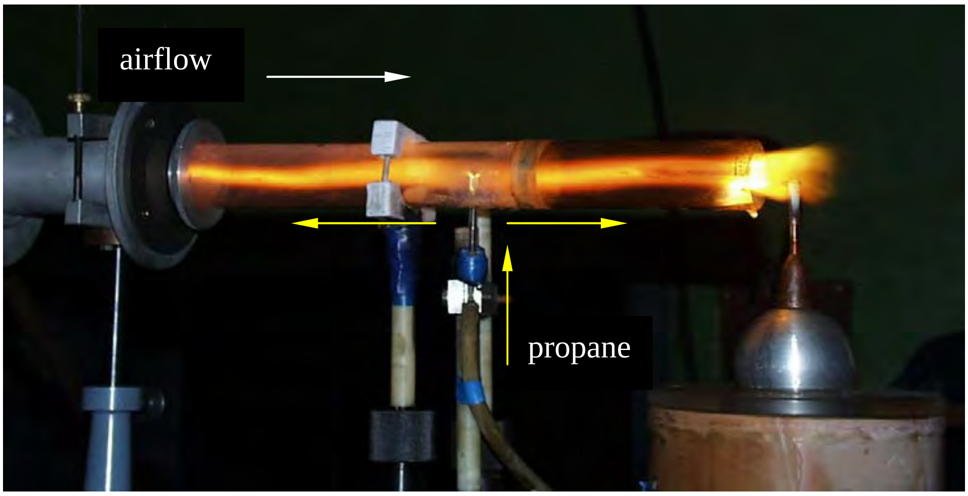

Fig.2.5. Propane transportation through HF filament discharge. Red colour is typical chemical flame colour in high-speed airflow in this regime (CH2 generation), M=1,2, P_{st}=1 Bar, ϕ=0,7

5. It was revealed that optimal location of a streamer HF discharge in the set up HWT-1 is a separation vortex zone behind pylon- electrode.
6. Very small characteristic ignition time τ_1 and combustion time τ_2 were measured during PAC experiment (M< 1,2 , P_{st}< 1Bar, T_o~300K), namely: τ_1~ 30-50 mcs, τ_2~ 100-150 mcs. These experimental values $\tau_{1,2}$ are more than 100-1000 times smaller than traditional chemical ones at plasma off (at the same other conditions).
7. Radical creation by electric discharge was measured in PAC experiment, such as: CH, CH_2, O, O_3, CN, and others. Maximal relative concentration of radicals in PAC experiment is ~10^{-2} (our estimations).

8. Final products of PAC are H_2O and CO_2 only in lean fuel-airflow mixtures (no toxic impurities and propane).
9. Additional small water vapour injection (propane: water ~ 100: 1) could intensify fuel combustion at plasma assistance.
10. It was revealed that small HF power (about ~100W) is needed for the propane- air ignition, radical generation for combustion stimulation.
11. *Estimations of plasma efficiency in PAC experiment.* Mean HF power used in this experiment was N_d~100-1000W. Total chemical power was about N_{ch}~16-17 kW, (it corresponds to propane mass flux m~0,4 g/s). So, ratio $\eta= (N_d / N_{ch})$ 100%= 1-6%.
15. Extension of fuel combustion concentration limits for rich and lean mixtures up to 2-4 times at plasma assistance.
16. Combustion temperature limit was decreased up to 2-3 times at plasma assistance.
17. Chemical analysis of the final PAC species is obtained by IR absorption method and chromatographic method. Partial pressures and concentrations of these species are measured.
18. Effective H2, CO, C2H2, CH4…. generation was obtained in rich propane-airflow mixtures at plasma assistance
19. It is revealed that that there is high fuel PAC completeness (80-100%) in lean fuel mixtures only, fig.2.6-2.7.
20. It was revealed that radical concentration in PAC zone is increased up to 2-3 times at non-intensive external UV radiation created by KrF laser.

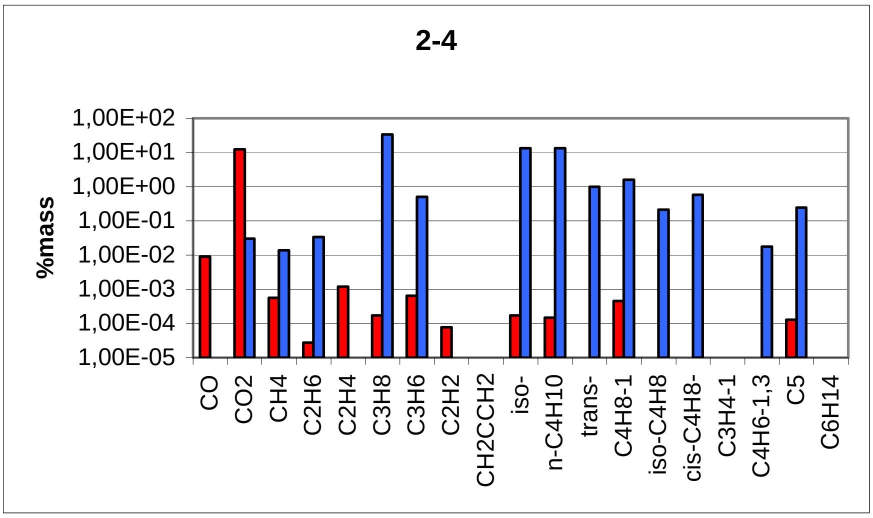

Fig.2.6. Chromatographic analysis of final PAC species, (log scale). Combined electric discharge (DC+ high voltage pulses), M=0,3; P_{st}=1 Bar, ϕ~1,5. Blue – initial airflow-fuel mixture, red- PAC

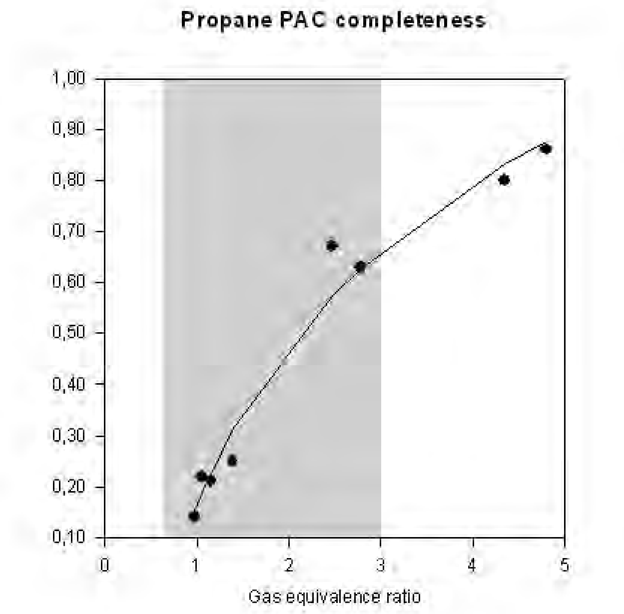

Fig.2.7. Fuel combustion completeness at plasma assistance in airflow. Combined electric discharge (DC+ high voltage pulses), I_{DC}=1 Amp, F_i=100 Hz, T_i=10 mcs, U_i=30 kV, M=0,3; P_{st}=1 Bar. Gray colour- fuel burning limit

2.2. Task 2. External PAC in high-speed airflow. Main results

1. Five modifications of model F were manufactured and tested in wind tunnel experiments. Different on-board plasma generators were arranged in these models and tested in supersonic airflow (M~2, P_{st}<1Bar), fig.2.8.
2. Stable local external PAC generation near aerodynamic model F was created at DC electric current I_d> 5Amp only, fig.2.9- 2.10.
3. Considerable bow shock wave modification near model F was recorded at local external PAC, fig.2.10,
4. Surface pressure decrease up to 30% at local external PAC generation
5. It is very simple to estimate typical value of the model F's drag power N_d (airflow mechanical power) in supersonic airflow. This value is about 70 kW in wind tunnel experiment with model F. Note that electrical discharge power (~3 kW) is much less than the value N. So, possible model drag change has to be small due to plasma generation. This conclusion was proved in plasma-aerodynamic experiment at plasma on. In other hand, chemical power ~40 kW (connected with propane combustion, M_{pr}~1G/s) is closed to value N. So, possible drag decrease by local external PAC has to be large one.
6. Measured model drag decrease is about 20-30% in real PAC experiment in wind tunnel.
7. External PAC near model F in supersonic airflow (M<2, P_{st}<100 Torr) was studied in wind tunnel HWT-2, fig.2.10. Electric DC discharge was used in this experiment.

8. Stable external PAC is created near model F in supersonic airflow at high electric current I_{DC}> 0,5 A only in this regime.
9. Preliminary experimental results on propane combustion completeness η at plasma assistance near model F in supersonic airflow (M_{af}~ 2, P_{st}~ 100 Torr) were obtained in wind tunnel experiment. This value η is about 10-30% at plasma on.

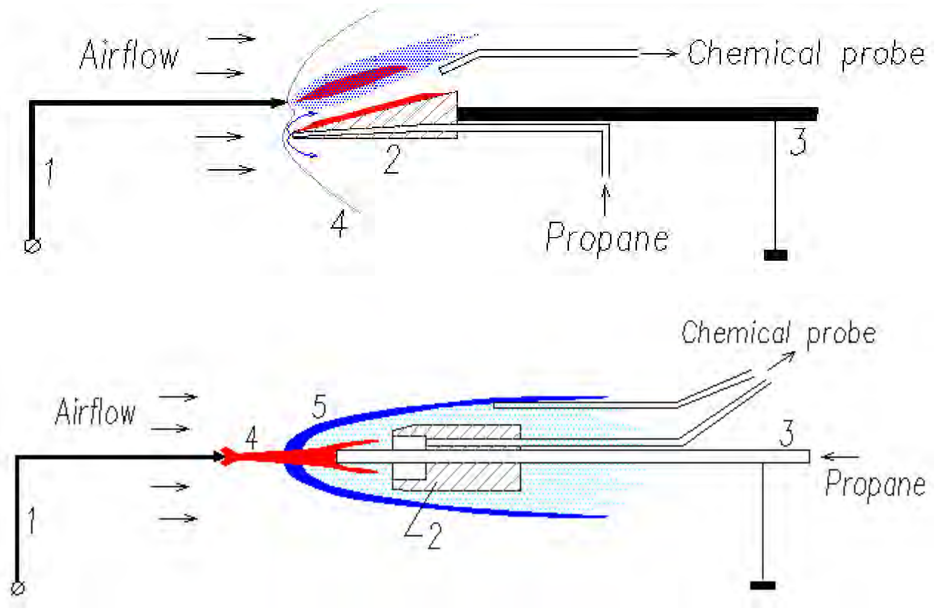

Fig.2.8. Schemes of wind tunnel experiment with model F. 1-hot electrode, 2-model (wedge, cylinder), 3-grounded electrode, 5-PAC zone

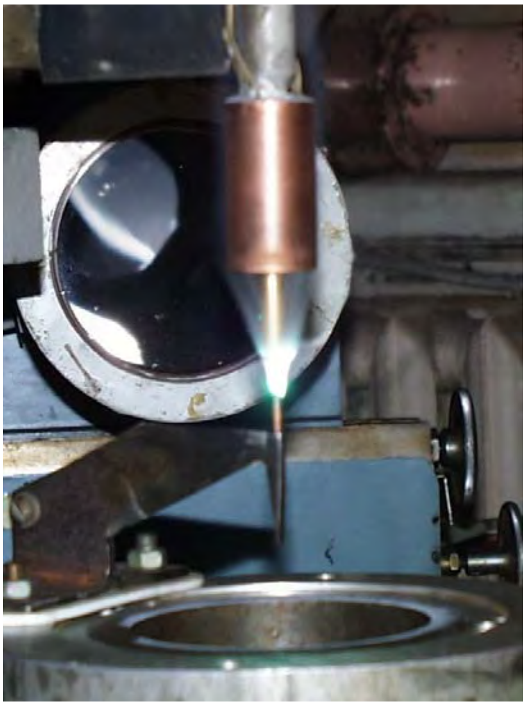

Fig.2.9. External PAC near model F in wind tunnel with open working section. M~2, P_{st}~1 Bar

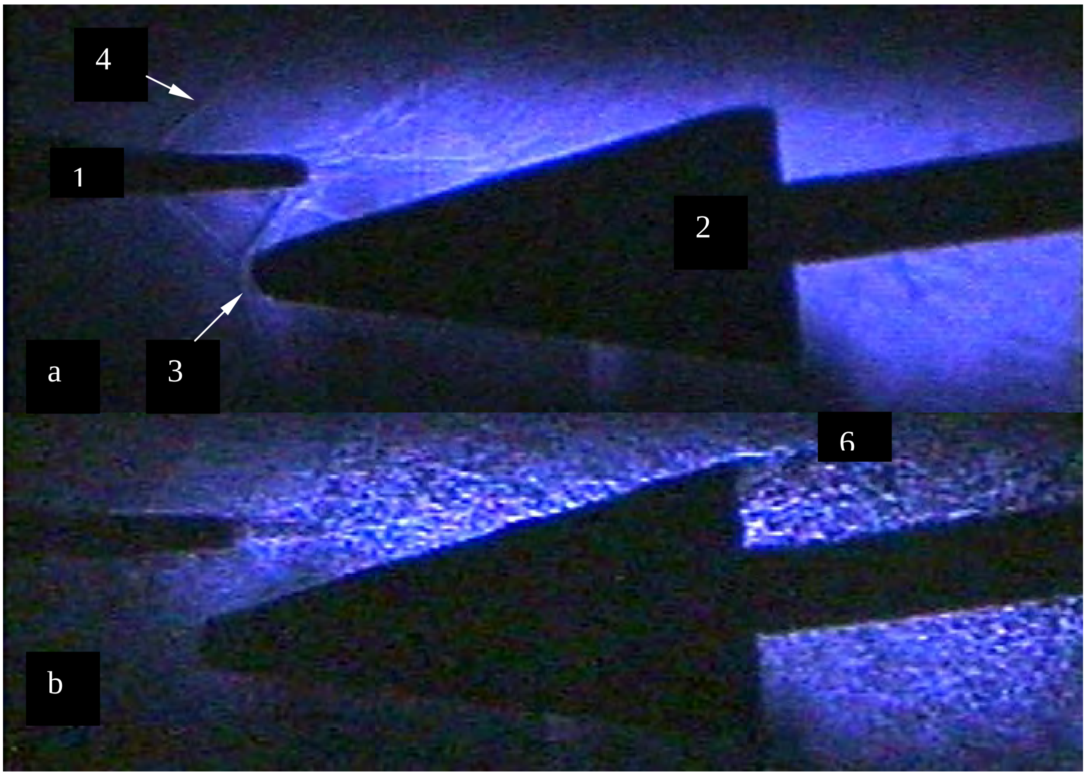

Fig.2.10. Shadow picture of supersonic airflow around wedge: a- plasma off, b- plasma on and local external PAC, 1 - external electrode, 2 – wedge, 3 – bow SW, 4 – local shock, 5 - hot gas wake, 6 - turbulent PAC; M~2; P_{st}~100 Torr

2.3. Task 3. Supersonic airflow around spherical model with plasmoid created by combined discharge. Main results

Modified experimental set up WT-3 is used in plasma-aerodynamic experiment. Airflow parameters in test section of this set up are measured by pressure sensors IKD, Honeywell; thermocouple; force sensor FSG15N1A; optical pyrometer. Combined electric discharge parameters are measured by resistance dividers and current shunts. Plasma parameters are measured by MW interferometer and electric probes, optic spectrometer and optic pyrometer.

Supersonic airflow created in this set up has the following parameters:

- Mach number M≤1,6
- Static pressure P_{st}< 100 Torr

Aerodynamic model E has the following characteristics:

- Type sphere, cylinder
- Diameter or width 10 and 18 mm
- Material steel, brass

Two pressure sensors IKD and thermocouple are arranged on model's surface. Stagnation pressure and base pressure are measured by these sensors. Surface model's temperature is measured by thermocouple and optical pyrometer. Drag force is measured by force sensor FSG15N1A

<u>Main experimental results obtained in this experiment:</u>

1. Stable homogeneous combined discharge (electric beam (EB) + DC discharge) near model E in supersonic airflow (M~1.6, P_{st}<100 Torr) was created at the first time.

   <u>EB accelerator</u> had the following parameters:

   - EB current < 30mA
   - Electron acceleration voltage < 30 kV

   <u>DC power supply</u> parameters were the followings:

   - Current I_d< 500mA
   - Voltage U_d< 2kV

2. It was revealed that there is a considerable spherical model heating by the electron beam in supersonic airflow (M~1,6, P_{st}~ 20 torr). Maximal model's temperature was about T_m~440K. Temperature T_m was measured by the thermocouple connected with model's surface. Drag model's force F_d is decreased about 10% at EB heating.
3. Model's drag force, stagnation pressure and base pressure were measured in supersonic airflow at combined discharge plasma on. It was revealed that model's drag is decreased up to 60- 80% at plasma on. Aerodynamic characteristics were measured in dependence on electric discharge parameter variation, fig.2.11. It was revealed that drag decrease was depended on model's electric potential (electric field direction). It was about 80% at model-cathode and 25% at model-anode, fig.2.12.
4. Volt-Ampere characteristics of the combined discharge in supersonic airflow were measured. It was revealed that total discharge current is controlled by electron beam at I_{DC}< 30mAmp~I_b only.
5. It was revealed that initial level of airflow turbulence was decreased by combined discharge at model-cathode.
6. Electron concentration in combined discharge was measured by the MW interferometer and electric probes. Its maximal value was about Ne~10^{12}cm^{-3} .
7. Local external propane combustion near model E in supersonic airflow is stimulated by combined electric discharge (EB+DC).

8. Stable local external PAC near model E was created at high electric current (I_{DC}>100 mA) and EB generation only.
9. It was revealed that there is excited propane luminescence near model E at small DC electric current (I_{DC}<100 mA) and small EB current (I_b<10mA) only, (regime without its external combustion). No model's aerodynamic characteristic change is measured in this experiment.
10. There is anomalous fuel transportation in combined discharge plasmoid in supersonic airflow. This anomalous transportation can be explained by fast ion drift at intensive electric field.
11. Considerable model's drag decrease up to 90% (and higher) was measured at local external PAC regime.

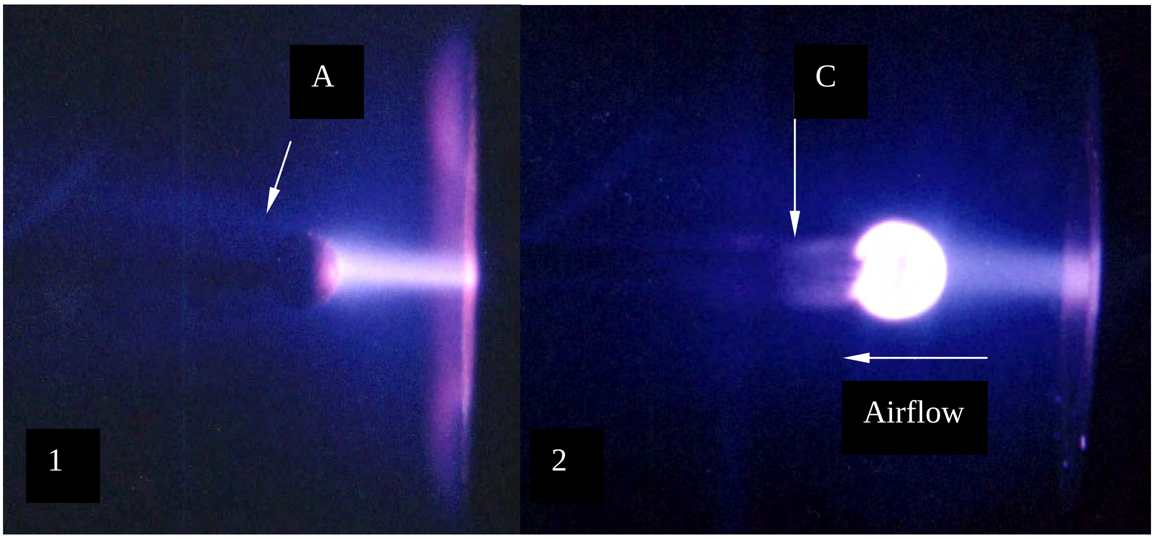

Fig. 2.11. Combined discharge plasma near model E in supersonic airflow,
M~1.6, P_{st}=16 Torr, I_b~8 mA, I_{DC}=200 mA,
1- positive model potential, (model-anode, A),
2- negative model potential, (model-cathode, C).
3- Arrows- gas flow separation point

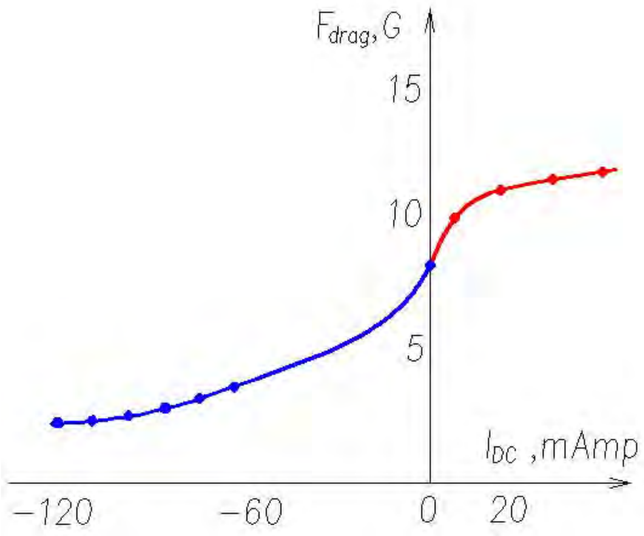

Fig.2.12. Dependence of model's drag force $F_d(I_{DC})$ on DC electric currents I_{DC}. Electron beam current I_b~8 mA, model E- sphere (diameter- 9,6 mm), distance from nozzle Z=15 mm, M=1.6, P_{st}=16 Torr. Red line- positive model's potential with EB, blue line- negative model's potential with EB, Violet point (I_d=0)- initial drag value $F_{d,o}$ (plasma off, EB-off)

2.4. Main papers and scientific presentations. Project #2127P

Main experimental and theoretical results were published in 10 papers and presented in 10 International Conferences:

1. Klimov A., Bityurin V., Kuznetsov A., Tolkunov B., Vystavkin N, Sukovatkin N, Serov Yu, Savischenko N, Yuriev A., External and Internal Plasma- Assisted Combustion AIAA Paper 2003-6240. Proc. 41st AIAA Aerospace Sciences Meeting & Exhibit, 6-9 January 2003, Reno, NV, P.9.
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10. Bityurin V., Bocharov A., Filimonova E., Klimov A., Study of Ignition of Fuel-Air Counter-Flow Jets by Electrical Discharge, XV International Conference on Gas Discharge and their Applications, Toulouse, France, 5-10 September, P.4.