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Introduction.

Plasma assisted combustion (PAC) in a cold subsonic and supersonic airflow was studied in our previous works [1-3]. Present work is devoted to continuation of PAC study in a ***hot*** airflow. The experimental studies were carried out in a hot wind tunnel (HWT). The comparative analysis of the different types of plasma formations (PF) used in PAC experiment is considered in this work, namely

- HF streamer plasmoid,
- PF created by pulse repetitive discharge,
- PF created by combined discharge.

The PF's characteristics in a ***hot*** airflow are studied. The dependencies of the PF parameters on airflow parameters, gas temperature, types of testing gases were obtained. Some of the new experimental results obtained in this HWT are considered in this work, namely:

- Stimulation of propane- air mixing by a streamer HF discharge, (advanced air-fuel mixing).
- Small characteristic ignition and combustion times ($\tau_{1,2}$) in HF plasma assisted combustion experiment.
- Parameters of a single HF streamer in a hot airflow.

Combined discharge. HF+HF. PAC stimulated by a streamer HF discharge was studied in [1-3]. In the present experiments it was revealed that Tesla's coil generator could create a number of HF plasmoids simultaneously, fig.1. Note that only one Tesla's coil was active and has galvanic connection with the power supply. Other PGs were passive ones and had the capacity connection with active PG. Maximal number of HF plasmoids was 8 in our experiment. Simultaneous operation of two HF PGs is shown in fig.1. One of them is active command PG and second PG is passive one. It was revealed that these PGs could operate consecutively. The operation time of the separate PG was about 100 mcs (repetitive operation frequency F* was about 5 kHz).

The scheme of the experimental set up (Hot Wind Tunnel, HWT) is shown in Fig.2. This installation consists of

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

This 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.

First HF PG was used for airflow heating and excitation (radical generation in airflow). Second HF PG was used for ignition and combustion control. The possible propane injection locations are the followings:

- Through the thin tube in the HWT between small and large tubes (9) and near the nozzle (3, main injection location),
- Through the thin tube inside of the HF hot electrodes (additional injection location).

Namely utilization of the quartz tubes in our experiment helps us to use optical diagnostic instrumentation to study plasma- assisted combustion.

Main technical characteristics of the HWT are shown in Tabl.1.
The airflow rotated in the nozzle in some experiments. The homogeneous arc discharge was created in the nozzle in this case.

Main experimental results.

1. The single HF streamer parameters were measured by the different diagnostic methods. The characteristic plasma parameters of a single HF streamer are shown in tabl.2, [1-3]. One can conclude that the HF streamer is the non-equilibrium plasma formation. It has a very high-energy storage. So, it can stimulate the plasma chemical reactions and radical generation in a fuel-air mixture.
2. There is the optimal location of two HF PGs in HWT. The optimal distance L between two HF electrodes is determined by the HF plasmoid transit time $T^* = (F^*)^{-1} \sim L/V_d$ (where V_d- transit plasmoid velocity). The PAC near second HF electrode started with first plasmoid arriving (generated by first HF PG) simultaneously in this case. This regime was named resonance one. The optimal value L was about 10÷30 cm in our experiment.
3. Small fuel mass injection into airflow through the first electrode (very poor air- fuel mixture) increases the airflow pre-heating considerably. The maximal gas temperature T_g of gas flow near the first electrode was about T_g = 800÷900K in this case (M= 0,6; P_{st}= 1 Bar).
4. Very active PAC was recorded near the second HF electrode at previous gas pre- heating and excitation near the first HF electrode, fig.4. The flame color was very bright blue in this regime. Note that the flame color was yellow-red at single HF PG operation (M= 0,6; P_{st}= 1 Bar) only. In the combined HF discharge the flame length was two times less than it was in the case with the single HF PG. The characteristic ignition time τ_i and combustion τ_c time were less than $\tau_{i,c}\sim$ 20 mcs in the combined HF discharge.
5. The gas temperature T_g was about T_g = 1200÷1400K in the combustion region in a combined HF discharge. Note that the gas temperature was about $T_g \sim$ 900K in the combustion region in the single HF discharge.
   Note that the mean HF power was the same one (about 2 kW) in these two considered variants. So, the combined discharge created by two HF PGs is more effective one than the single HF discharge for plasma-assisted combustion.
6. HF plasmoid with very large streamers (50÷100 cm length) was created in airflow (M~ 0,4÷1,2) by a new powerful HF generator (mean power about 18 kW), fig.2. This longitudinal HF streamer discharge (about 100 cm) was created in supersonic and subsonic airflows in a quartz tube and a metal channel also. We hope that the PAC of a hydrocarbon fuel (such as benzene, oil and others) stimulated by this longitudinal HF discharge will be possible in a supersonic airflow at the parameters closed to the scram jet ones (due to large HF streamer length, high gas temperature and high excitation level in this discharge).
7. It was revealed that fuel could penetrate deeply in airflow through HF streamer channels [1-3]. One can see that the longitudinal HF streamer rotates in airflow, fig.2. Estimation gives the rotation velocity about $10^4 \div 10^5$ c^{-1}. It was revealed that fuel is transported through this curved HF streamer, fig.2. Rotation acceleration of this fuel is very high, more than

$10^4 \div 10^5$ g. So, this plasma rotation motion could stimulate airflow-fuel mixing.

8. Theoretical estimation of the plasma rotation and its acceleration stimulated by HF electric current gives the value closed to the experimental ones:
   $a = j_{HF} B/\rho \sim V_e \alpha \omega_i \sim 10^4 g$
   where V_e- electron velocity, $\alpha = N_e/N$, ω_i- ion resonance frequency. So, plasma convection stimulated by electric current can explain fast fuel propagation through HF streamer channel.

Combined discharge created by pulse repetitive discharge PG (PG PRD) and HF PG in the HWT is shown in fig.5. The transverse PR discharge was created in a small quartz tube (5, fig.3). Small propane injection through PRD electrode was used for pre-heating and excitation of airflow.

Characteristic parameters of PRD are shown in Tabl.3

Main experimental results obtained in this PAC experiment:

1. The stable PAC was obtained in subsonic airflow ($M<0.8$, $P_{st} \sim 1$ Bar, $T_o = 300K$).
2. The selective radical generation was obtained at the different PRD operation parameters. One can see the different luminescence color of the excited fuel-airflow mixing in PAC experiment, fig.5. Note that the selective radical generation (in the wide species range) was possible in this combined discharge namely.
3. Very homogeneous PAC was created in this combined discharge (HF+ PRD).
4. There is the critical pulse power (more than 10 kW) of the thermal blocking of airflow in a quartz tube.
5. There is the negative electromagnetic interference between HF PG and PRD PG. So, it is need to overcome these difficulties by the careful shielding of these PGs

Main conclusion of this work. The combined discharge is the optimal one for plasma- assisted combustion namely. The optimal radical generation in a fuel-airflow mixture was obtained by this discharge namely.

Acknowledgements.

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References.

1. Klimov A., Brovkin V., Bityurin V., et. al., Plasma Assisted Combustion, Paper AIAA 2001-0491, 39th AIAA Aerospaces Meeting& Exibit, 8-11 January 2001/ Reno, NV, P.9.
2. Bityurin V.A., Klimov A.I., Lebedev P.D. et.al. Study of ignition and burning of fuel-air mixture in supersonic flow stimulated by HF streamer discharge. Report IVTAN, 1998, P.45.
3. Klimov A., Brovkin V., Bityurin V., et. al., Plasma Assisted Combustion in airflow, Paper AIAA 2001- 0491, 3rd Workshop on MPA, 24-26 April 2001/ Moscow, IVTAN, P.11.

Tabl.1. Technical parameters of the HWT

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

Tabl.2. HF streamer parameters

Electron concentration	
Inside streamer	$N_e\sim 10^{15}$ cm^3
Between streamer	$N_e\sim 10^{12}$- 10^{13}cm^3
Estimated electron temperature	$T_e\sim$ 1-10 eV
Gas temperature	$T_g\sim$ 1000-1500K,
Experimental streamer length	$L_{str.exp}\sim$50 mm.
Velocity of HF streamer propagation	$V_{str}\sim 10^3$- 10^5 m/s.
Generation frequency	2-20 kHz
Life time	$T_{str}\sim$50-100 mcs.
Specific energy storage	~1-10 J/cm^3

Tabl.3. PRD PG parameters.

Pulse duration	1-4ms
Current amplitude	<100Amp
Repetitive frequency	<100Hz
Pulse power	<100 kW

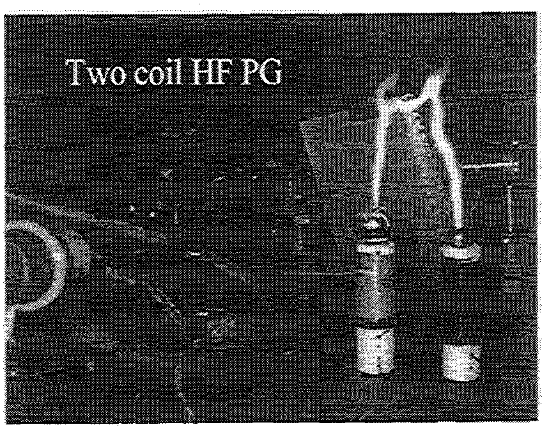


Fig.1. Simultaneous operation of the active Tesla's coil and passive one.

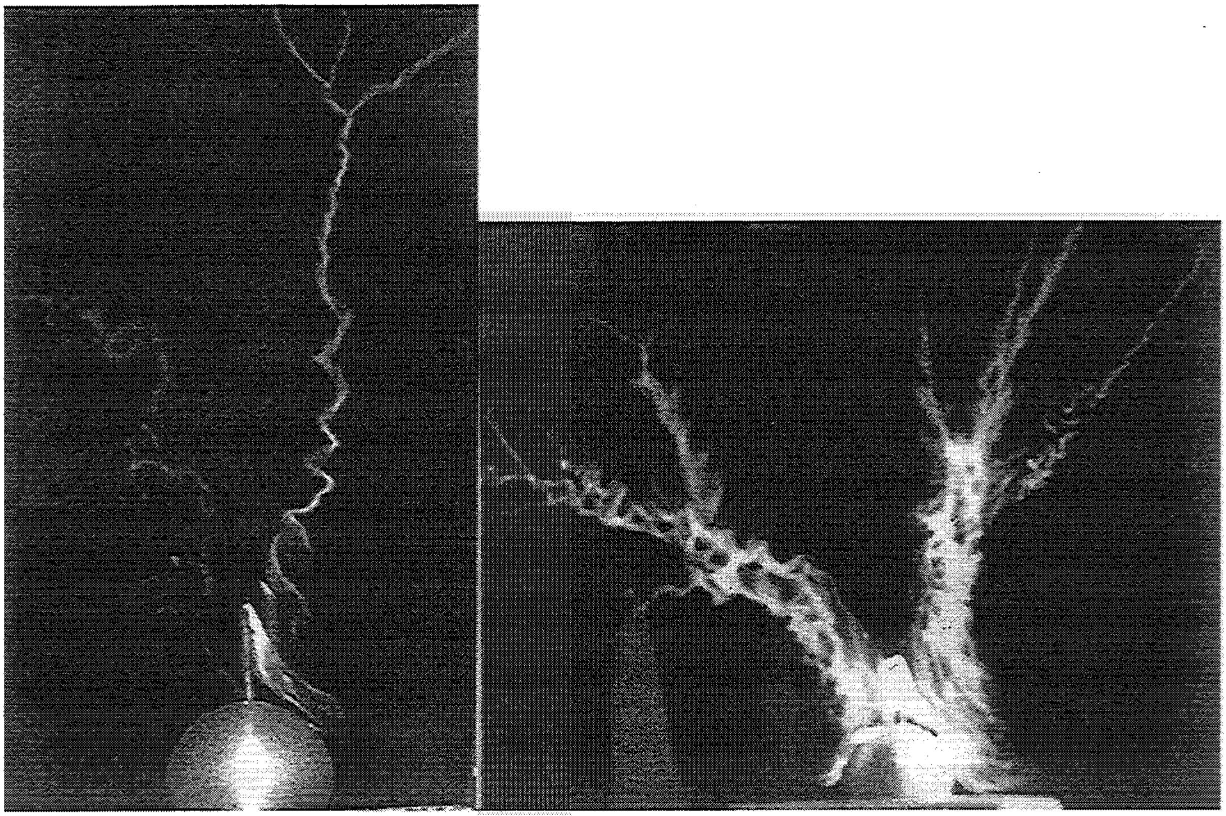
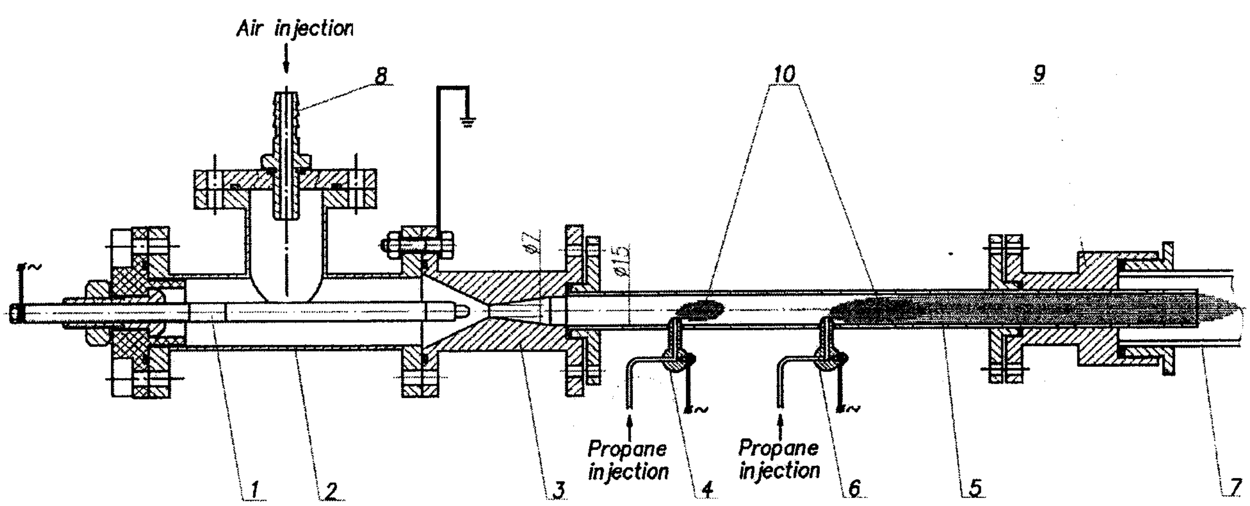


Fig.2. Rotation of large HF streamer in subsonic airflow (M~0,4, P_{st}= 1 Bar). Sphere diameter – 5 cm. N_i ~10 kW



Chematic diagram of experimental set up (hot wind tunnel) with combined HF discharge:

1– arc electrode of heater,
2– forechamber,
3– nozzle,
4,6– HF electrode,
5,7– quartz tube,
8– air injection input,
9– connecting unit,
10– HF plasma.

Fig.3. Experimental set up HWT with two HF PG.

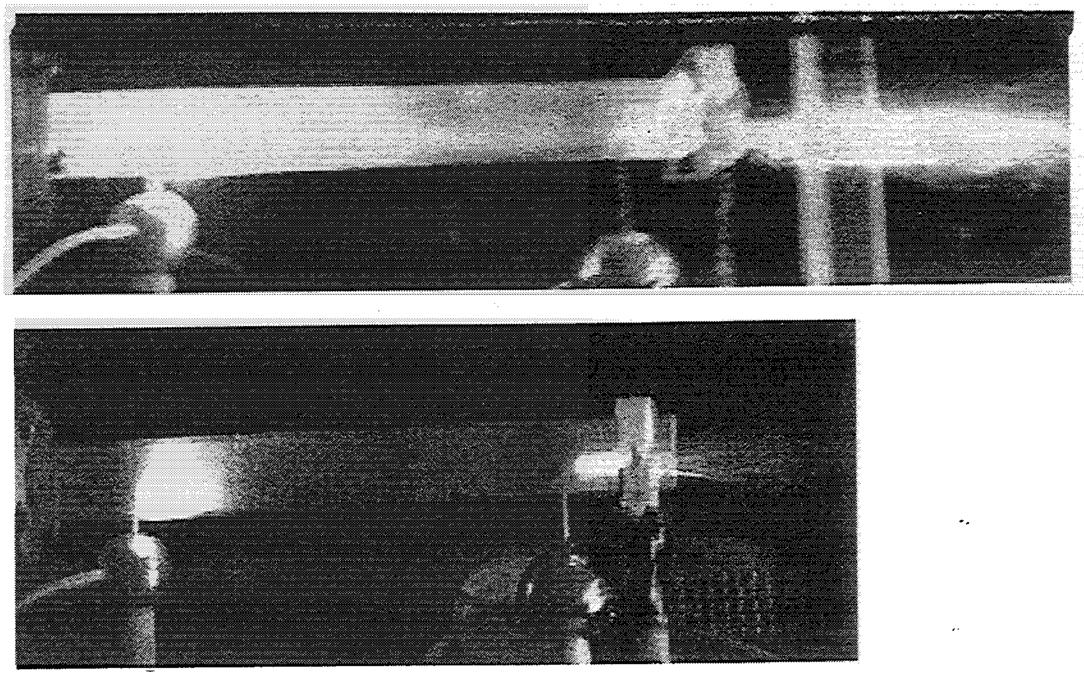


Fig.4. Simultaneous operation of two HF PG in HWT (M=0,6, Pst~ 1 Bar). Left PG – active one, right PG- passive one

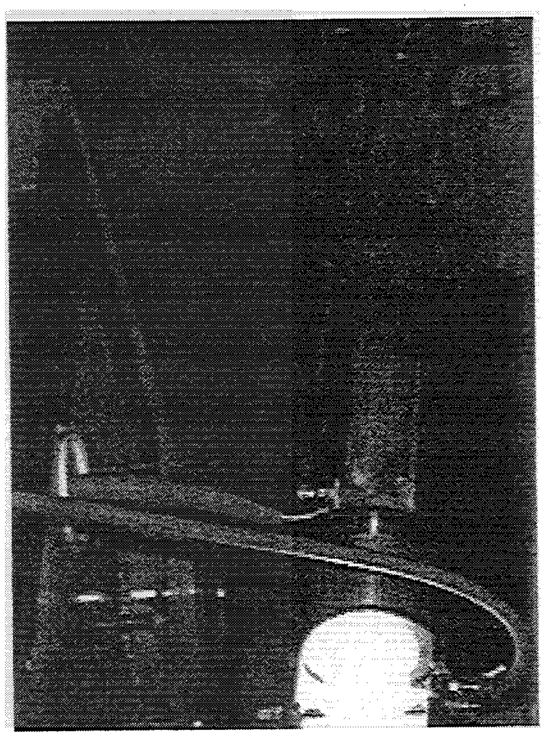


Fig.5. Combined discharge (PRD+ HF) in the HWT.