Non-Equilibrium Plasma Igniters and Pilots for Aerospace Application

Igor Matveev[*] and Svetlana Matveeva**
Applied Plasma Technologies, Falls Church, Virginia, 22046

Alexander Gutsol[†] and Alexander Fridman[§]
Drexel Plasma Institute,
Drexel University, Philadelphia, Pennsylvania, 19104

Major results of development and experimental investigations of plasma igniters and pilots for gas turbine engine improvements are presented. Plasma igniters demonstrated reliable starts of real aircraft turbines at 12+ km altitude. Plasma pilots and plasma fuel nozzles realized simultaneous fuel atomization, ignition and partial fuel oxidation without lean flame outs and provided higher combustion performance in a smaller volume. Perspective subsonic and supersonic non-thermal plasma generators for the second generation of plasma assisted combustion systems were developed. Employment of high voltage DC arc in reverse vortex flow for such kind of plasmatrons demonstrated dramatically extended life time of the electrodes without their cooling and significantly wider range of operation parameters.

I. Introduction

Reliable high altitude ignition (9+ km) of fuel-air mixture in main combustor and after burner is still a problem for major aircraft gas turbine engines. Development of a pilot burner for combustion assistance and toxicity reduction from take-off to landing is also in a waiting list.

The idea to use plasma torch and active products of rich plasma-fuel mixture reactions for ignition and flame stabilization is not new [1-4]. Many researchers obtained positive results in the generation of active radicals, reduction of ignition time delay, extension of flammability limits, and flame stabilization at various fuel-air mixture flows (even supersonic) and fuel compositions (from coal to hydrogen) [1-7]. Recent high altitude tests of the plasma ignition system developed by Applied Plasma Technologies (APT) once again proved plasma advantages for aerospace applications in comparison with advanced spark plug systems even with oxygen support. Fig.1 shows flammability limit boarders (area to the left and up from the appropriate curve) for high energy spark plug with oxygen feeding into the discharge zone and plasma igniters with internal and external air systems. Internal air means air flow through the igniter due to combustor's resistance. External air means application of an additional air supply system.

Plasma torch and plasma-chemical reactions jet technology (Fig.2) has specific advantages for flame stabilization, for example: utilization as a pilot burner during missile launch, better engine control while maneuvering, cleaner environmental emissions, and immediate power level reduction (when needed). Plasma combustion technology also allows for jet engine design modifications including reductions of the combustion chamber volume, improvements in fuel and air mixing, and an increase of flame velocity.

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[*] President & CEO, 7231 Woodley Place, Falls Church, VA 22046

** General Designer, 7231 Woodley Place, Falls Church, VA 22046

[†] Research Professor, Department of Mechanical Engineering and Mechanics, Drexel University, 34th and Lancaster Avenue, Philadelphia, PA, 19104

[§] Professor, Department of Mechanical Engineering and Mechanics, Drexel University, 3141 Chestnut Street, Philadelphia, PA, 19104

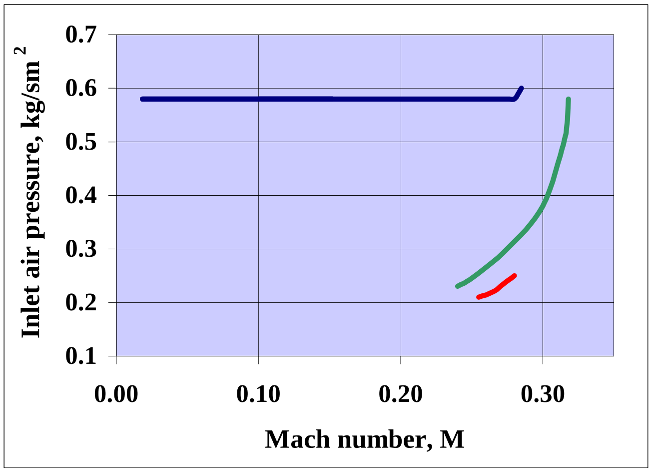

Figure 1. Aircraft gas turbine combustor flammability limits depending on inlet air barometric pressure and velocity.

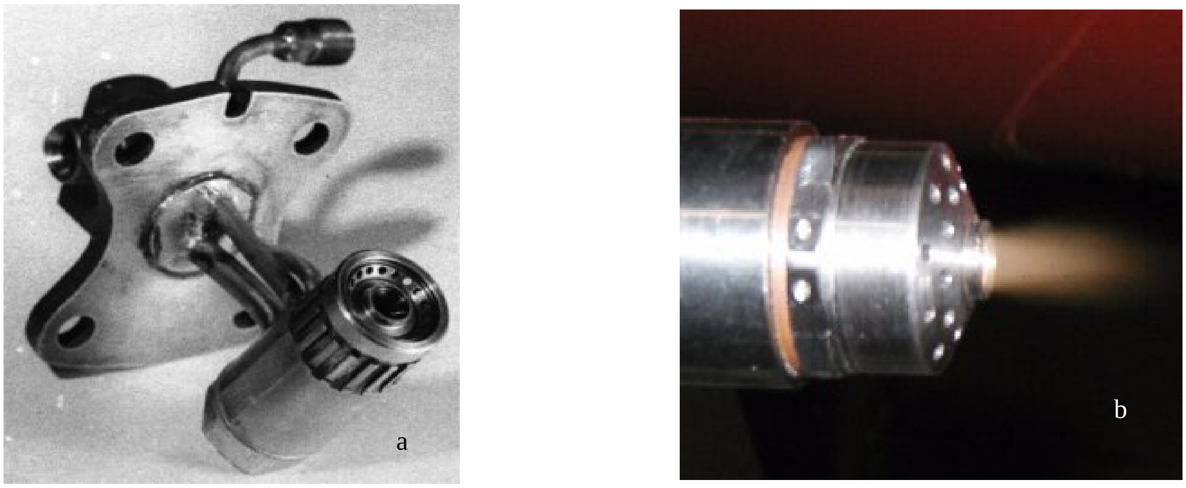

Figure 2. Plasma fuel nozzles for (a) liquid and (b) gaseous fuel burning in gas turbines.

So, plasma assisted combustion looks like ideal technology for aircraft gas turbine engine, but no one plasma system is available on the market till now. According to our understanding and two decades intensive expertise in this field, the major barrier on the way of plasma torch technology implementation for aerospace application is low performance of existing plasma generators, in particular:

- Narrow plasma formation gas flow operation range. This requires an additional air supply system to provide 6+ km starts (see Fig. 1);
- Limited life time of electrodes: sufficient for ignition but not enough for combustion assistance;
- Relatively high power consumption: up to 1.2 - 1.5 kW for 12 km altitude in case of pure plasma torch application.

This paper presents results of development and experimental investigations of different plasma assisted combustion systems based on thermal and non-thermal plasma generators, and reflects efforts to overcome above mentioned restrictions.

II. Results and discussion

Initially developed for marine and industrial gas turbines, plasma igniters were based on thermal micro plasma generators utilizing air as a plasma formation gas. The volt-current characteristics of such igniters depending on pressure inside the combustion chamber are shown on Fig. 3 [3]. Pressure drop on a combustion chamber wall usually served as a plasma gas source. It means that no additional air feeding for plasma systems installation was required. Igniters had major dimensions of existing spark plugs or igniters and could be installed at their places at the period of turbine's retrofit or maintenance. The pressure drop (combustor resistance) range at the starting period for major land based turbines is from 500 to 5,000 Pa (50 to 500 mm of water column). Plasma torch with power from 800 W to 1.2 kW and average plasma jet temperature from 1500 to 3000 C provides reliable ignition of fuel/air mixture with much lower rotor inlet temperature T_3 jump (Fig.4 [3]). With operation period up to 1 minute the igniter's life time is estimated from 1,000 to 4,000 starts depending mainly on flow parameters.

Conducted high altitude tests of the plasma ignition systems on contemporary aircraft turbines proved opportunity to reach 12 km level but also showed a real price of such achievement. For example, up to 6 km altitude, plasma system with the APT igniter VPL-8 could operate with an internal air source and power range 0.8 – 1 kW. For the higher altitude igniter VPL-12 could light fuel only with external air source and power level 1.2 -1.5 kW. Thus, plasma igniters with air plasma torch could be a great alternative for land based turbines, as far as for other heat engines, and middle altitude aircrafts. But for high altitude starts more powerful ignition system with affordable electrical energy consumption and power supply weight should be applied.

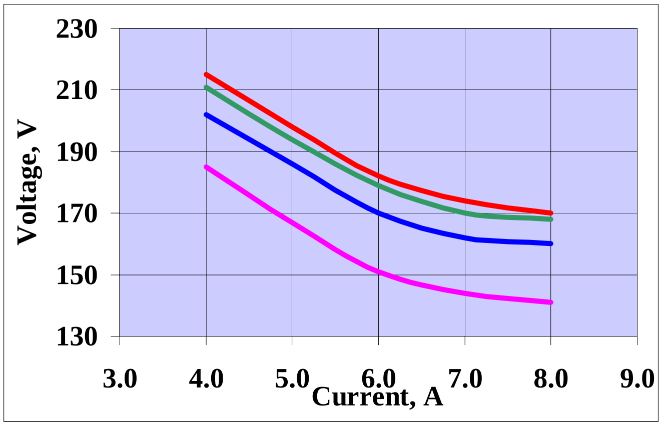

Figure 3. Voltage - Current characteristics depending on overpressure.

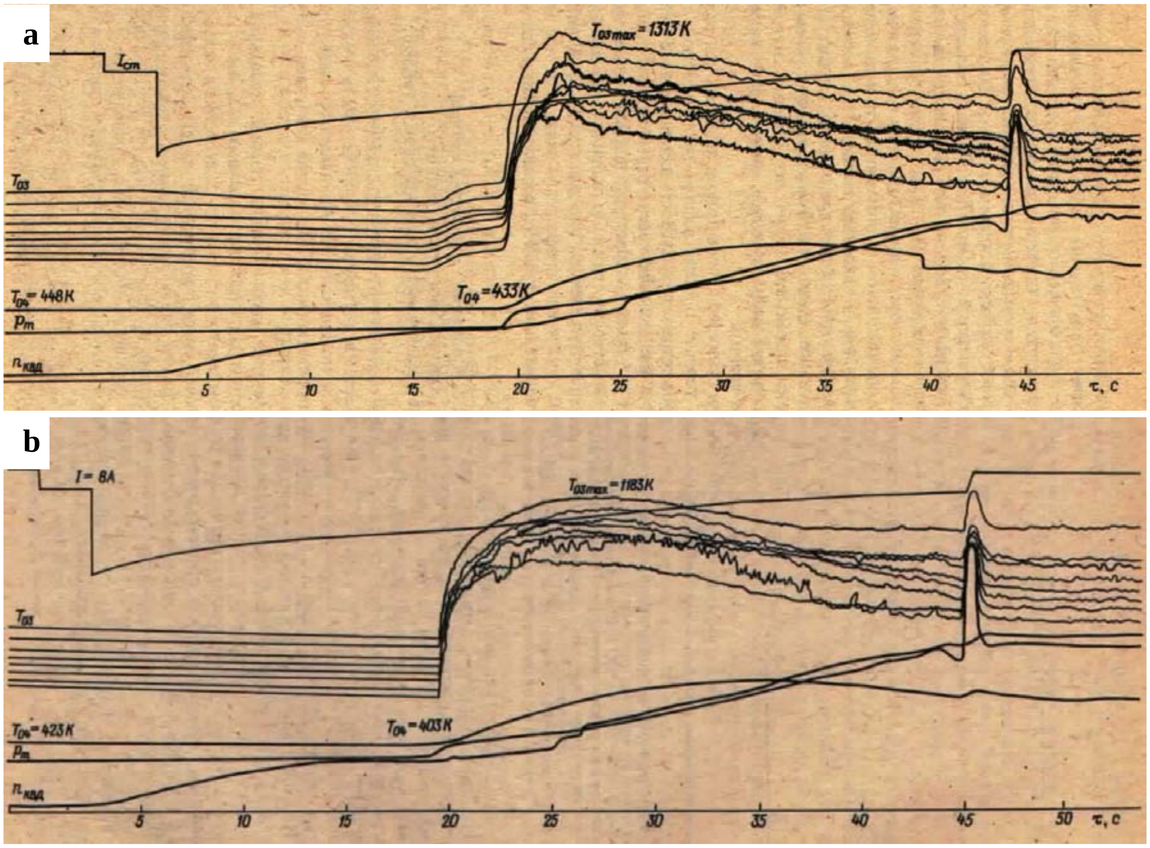

Figure 4. Start oscillograms: a – without plasma; b - with plasma.

For further improvement of ignition process, reduction of the plasma generator power and to provide continuous plasma assisted combustion modes such devices as plasma fuel nozzles and plasma chemical reactors were developed and tested. Fig. 5 shows design of an experimental plasma fuel nozzle for 2MW liquid fired gas turbine with additional air feeding for fuel atomization. Experimental investigations of such nozzles demonstrated that successful combination of plasma torch with partial fuel oxidation and further utilization of the plasma chemical reaction products for ignition, fuel atomization and combustion stabilization creates new quality device with significant advantages for gas turbines. These advantages are [11 -13]:

- Reliable ignition of any minimal and non-atomized portion of fuel at any investigated conditions;
- Much wider flammability limits with no lean flame outs at all;
- Significant decrease (up to 300 C) in T_3 jump at the point of fuel ignition.
- Opportunity for smooth increasing of T_3 from ambient to maximum;
- Utilization as a pilot burner;
- Utilization as a fuel reformer for hydrogen enriched gas generation;
- Reduction of combustion zone size (by 5-10%);
- Reduction of combustion chamber walls temperature (by 150 C);
- Increase of combustion efficiency (COP) by 5-10% on partial load;
- Reduction of exhaust gases toxicity;
- Ability of simultaneous burning of several fuels;
- Smooth regulation of the engine's power from almost 0 to 100%.

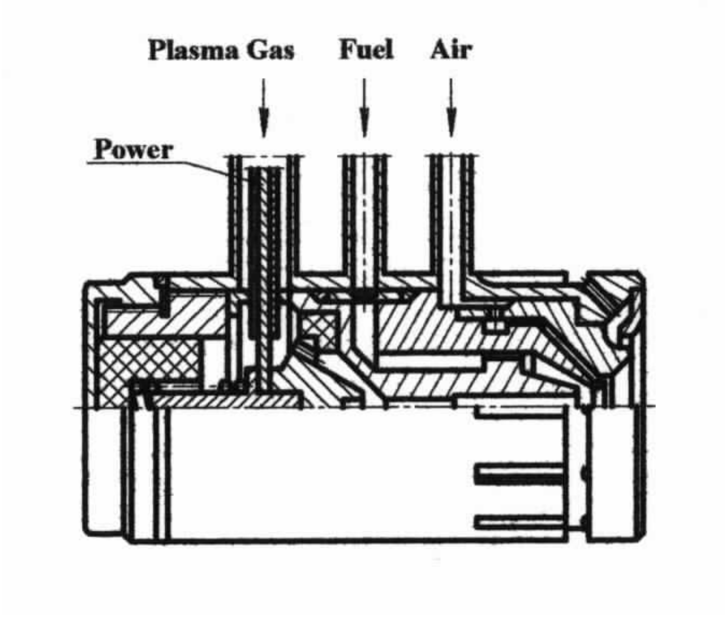

Figure 5. Plasma fuel nozzle schematic.

Such approach has a good potential for supersonic flows ignition and combustion support, as far as for power plants with low-Btu and multi-fuel consumption. Unfortunately plasma fuel nozzles and plasma chemical reactors have also limited life time of the cathodes. For continuous operation at 1kW electrical power level the lifetime was estimated as 50 hours. The reason of this limiting lifetime problem is extremely high temperature of plasma arcs. This also results in very high concentration of nitrogen oxides generated by thermal plasma torches, and restricts application of these torches for flame stabilization.

Figure 6. High voltage tornado plasmatron model.

It's clear that thermal plasma generators could satisfy major ignition requirements including 24V DC input power source weight limit (below 2.4 kg per igniter), but combustion assisted system needs low-NOx plasma generators with lifetime equal to thousands of running hours. That is why, to overcome the major problem we selected for further investigations a high voltage DC plasma generator with arc stabilization by reverse vortex (tornado) flow (Fig. 6) [9]. Plasma temperature in the low current high voltage arc system is on the level of 3,000K [8], in contrast with the usual thermal arc systems with plasma temperatures on the level of 8,000-10,000 K.

This type of non-equilibrium plasma generator is a perspective alternative to thermal plasmatrons with such advantages as:

- Generates relatively cold non-equilibrium plasma;
- Operates at various power levels (from a few Watts to tens of kilowatts) in continues and pulse modes;
- Promises much longer lifetime of electrodes (thousands of hours);
- More energy efficient;
- Does not require cooling of electrodes.

Prototypes of new non-equilibrium plasma generator with arc chamber inner diameter (ID) from 7 to 45 mm, plasma processing gas flow rates from 0.04 to 1.0 g/s, and power level from 10 W to 1.5 kW were developed and successfully tested on air and methane-air mixtures. Designed plasma generators demonstrated reliable operation at plasma gas pressure drop from 1 to 60 kPa or 100 to 6,000 mm of water column. That is equivalent to aerodynamic resistance of the aircraft combustion chambers (about 3% of pressure after compressor) from starting point to 100% power level. For comparison, one of the best thermal plasma igniters VPL-12 could be adjusted for operation from 1 to 15 kPa. Thus, new plasmatron makes possible to use the internal air as a plasma gas for the entire operation cycle of the aircraft engine from take-off to landing.

Continuous tests of the prototypes (Fig. 7) on methane-air plasma formation mixtures from lean to rich (air/fuel ratio from 6 to 0.5), for arc power from 100 to 700 W and air flow rate from 0.2 to 0.6 g/s demonstrated zero internal soot formation within the range of tested mixtures. Operation on air/fuel mixtures is impossible for existing thermal plasma igniters. Much higher temperature in their arc zone usually causes intensive soot formation which leads to short operation circle (a few seconds).

Preliminary 80-hour stage of a lifetime test conducted on a 500 W power level and 500 mm H2O pressure showed very low erosion of both electrodes [10] and maximum surface temperature of the tested sample below 70 C.

Voltage-current characteristics of the prototype in case of operation on air as a plasma gas with specially designed power supply are presented in Figure 8. If necessary for some applications, this prototype can be easily transformed into the supersonic plasma generator. Figure 9 presents characteristics of the same arc chamber dimensions plasmatron in supersonic mode (when overpressure is more than 0.1 MPa).

Figure 7. Non-equilibrium plasma generator.

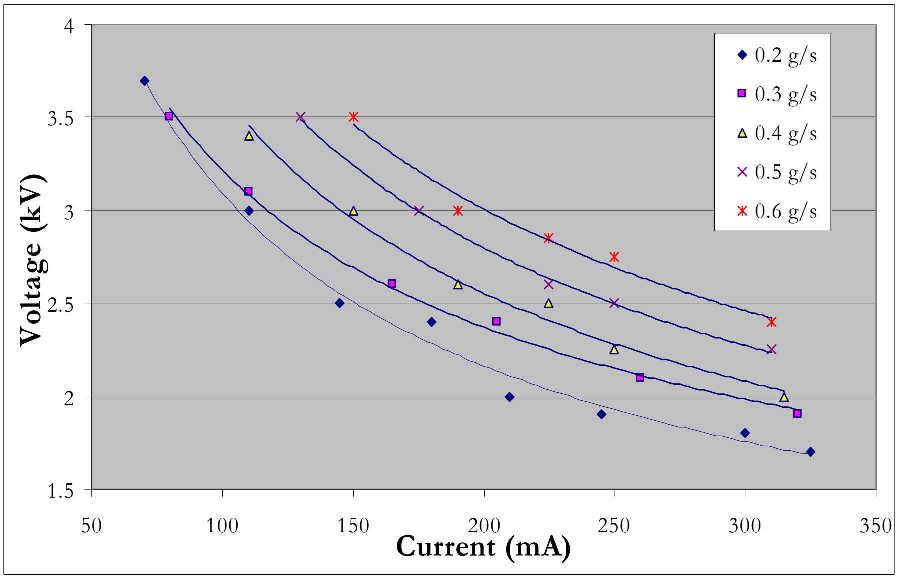

Figure 8. Voltage - Current characteristics of the non-equilibrium plasma generator.

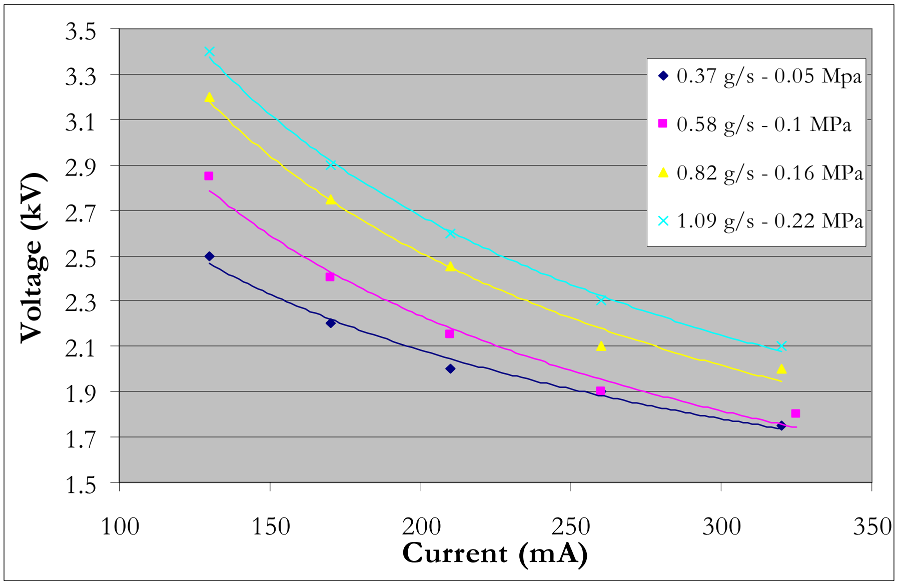

Figure 9. Voltage - Current characteristics of the supersonic plasma generator depending on overpressure and flow rate.

III. Conclusion

Plasma igniters and plasma-fuel nozzles developed on the basis of thermal plasma generators demonstrated high efficiency for ignition and combustion stabilization in marine, industrial and aircraft gas turbines. Positive results of performed investigations indicated significant advantages of selected non-equilibrium plasma generator in comparison with the thermal plasma sources. Obtained data created a solid basis for development and experimental validation of a new generation of plasma assisted combustion systems for aircraft and land based turbine engines.

Acknowledgments

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