

# Plasma Assisted Combustion Technologies

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## Abstract

This paper provides an overview, classification, and analyzes of the most advanced plasma based technologies developed mainly to improve ignition reliability, avoid flame instabilities, reduce emissions in a wide variety of applications, including aerospace propulsion systems, land based power generation units, technological boilers, furnaces, incinerators, heaters, dryers, etc. The fuel reformation, coal gasification, and waste-into-energy plasma processing technologies have been also analyzed. The paper shows the most recent and advanced efforts in the field of plasma assisted combustion and perspective directions for further investigations.

## Introduction

Recent progress in research and development of the plasma based technologies for ignition and combustion enhancement in propulsion and power generation systems has led to formation of a new field of science well known as the plasma assisted combustion (PAC). With the first known practical efforts in early 60s of the 20th century the PAC technologies developers and investigators became already a well organized community with both annual conference named International Workshop and Exhibition on Plasma Assisted Combustion (<http://www.plasmacombustion.com/iwepac.html>) and special annual issue under the IEEE Transactions on Plasma Science umbrella (<http://www.ieee.org/portal/site/iportals>).

At the moment a list of technologies in the field of PAC could be divided onto several groups, including the follows:

- Plasma igniters;
- Plasma pilots and flame sustainers;
- Plasma fuel nozzles;
- Spatial arc;
- Fuel reformers and coal gasifiers;
- Waste-into-energy processing.

## Discussion

**Plasma igniters** are the most developed units for short term operation (up to several minutes) mainly based on thermal DC torches, RF and MW initiators [1-12] for sub- and supersonic flows. Over 1,200 plasma ignition systems are in operation worldwide, including land-based gas turbines and furnaces. They normally replace spark plugs and have power consumption from 500W to 1 kW, plasma gas flow rate up to 1 g/s and lifetime up to 4,000 operating cycles. The main advantage of a plasma igniter in comparison to conventional spark plug is in much higher plasma plume volume and velocity. That allows deeper penetration of the high reactive plasma plume into the combustion zone for more reliable ignition. One of the plasma igniters for industrial gas turbine in operation is demonstrated in Fig.1.

There are several known approaches for ignition in high-speed cross flows specifically for the aerospace propulsion systems and scramjets [1, 7-9,

11-12]. Among perspective solutions are radiofrequency (RF) and microwave (MW) discharges, as far as non-thermal torches with a fuel feeding into the arc chamber. Recently developed by



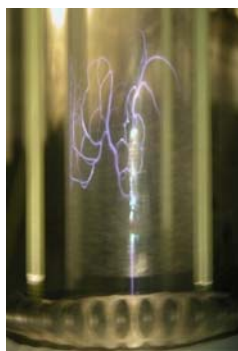
**Figure 1.**  
**Plasma Igniter**  
**in operation.**

Applied Plasma Technologies (APT) supersonic torch based on transient glow to spark discharge is shown in Fig.2 [9].



**Figure 2. Supersonic Plasma Igniter.**

**Plasma pilots and flame sustainers** are in the



**Figure 3.**  
**Subcritical**  
**streamer MW**  
**discharge in a**  
**reverse vortex**  
**combustor.**

second group of the plasma devices with two main functions – ignition and continuous flame control [13-28]. The market needs of continuously operating in a high temperature environment with variable pressure pilots and flame holders have moved researches to development of a non-thermal plasma sources with significantly extended lifetime and less power consumption, pulse power devices, direct arc initiators, and MW initiators. Known plasma pilots operate within the averaged power

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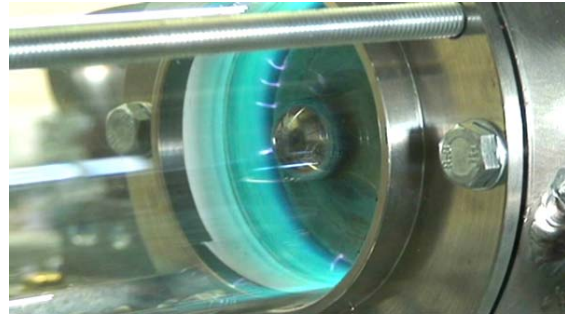
range up to 300-500 W, at pressure by 10-15 bar, and provide continuous operation by 1,000 running hours. One of the most perspective MW systems for ignition and flame control in a reverse vortex combustors has been developed by Moscow Radio Technical Institute [27] and is presented in Fig.3.

**Plasma fuel nozzle** as a combination of plasma generator and fuel atomizer with simultaneous fuel atomizing, ignition and flame control in one unit is the most complicated and advanced plasma assisted combustion solution. Several experimental nozzles for gaseous and liquid fuels with a flexi-fuel operation and steam feeding are under development in APT. The main advantages of these nozzles are: (a) dramatically increased ignition reliability, (b) much wider equivalence ratio or lambda range, (c) significant decrease in  $T_4$  (RIT) jump at the point of fuel ignition, (d) utilization as a pilot burner, (e) utilization for hydrogen enriched gas generation, (f) reduction of a combustion zone geometry, (g) reduction of the combustion chamber walls temperature, (h) increase of a combustion efficiency (COP), (i) achieving smokeless operation, (j) simultaneous burning of several fuels, (k) smooth regulation in a wider turn down ratio. One of a plasma nozzle samples for gaseous fuel burning in a gas turbine is provided in Fig.4.



**Figure 4. Plasma fuel nozzle for gaseous fuels appearance.**

**Spatial arc** is one of the recently patented by APT [38] applications of a non-thermal high voltage discharge in a form of orbiting inside a combustion chamber source of ignition and flame control. Employing the combustor walls as the electrodes, this arc with averaged power consumption from 10W to 1 kW provides simple and energy efficient solution for gas fired furnaces and combustors, particularly lean-burned ones [29, 30]. One of the lab-scale combustor prototypes with low power spatial arc is provided in Fig. 5.



**Figure 5. Reverse vortex combustor with 10W spatial arc.**

#### **Fuel reformers and coal gasifiers.**

There are numerous publications devoted to fuel reformation [31-44] and coal gasification [45-55]. The authors have provided just a portion of the recent ones, which disclose the most marketable approaches and solutions. It could be seen from the published manuscripts analyzes that the main obstacle on the way of the full-scale gasification technologies development and implementation is absence of the energy efficient plasma sources with affordable lifetime and operation costs. For example, existing coal ignition and partial gasification technology [46, 51] employs 100-200 kW DC torches with limited by 200 running hours cathode lifetime. Similar situation is with all other plasma torches on the market. It means that any progress in this direction will be caused by development of a new generation of high power atmospheric pressure plasma sources and power supplies. Based on known plasma generation solutions analyzes the authors have selected for further development and implementation a hybrid type (RF + DC) plasma torch with reverse vortex flow [30-32], which could provide the atmospheric pressure plasma reactors operation in combination with the solid state power supplies. Such a solution allows unlimited lifetime of both electrical and plasma generation modules and high caloric value of a syngas as a final product based on oxygen gasification process also based on recently developed air separation technology. The maximum achieved power level per unit is 1.8MW and expected 10MW.

**Waste-into-energy processing** is vital for developed countries, but still not feasible for many of them due to high cost of ownership and operation expenses for existing plants and absence of the high productivity ones with capacity over 250 tons per day. Significant reduction of the operation costs could be achieved by: (1) application of a hybrid (RF + DC) torches with dramatically extended lifetimes, (2) introduction of a plasma gasification in the oxygen or oxygen-rich environment, (3) syngas treatment in a steam catalyst converter to increase a hydrogen yield, and (4) multi-feedstock operation to process any waste from scrap tires and MSW to coal and electronic waste [31, 32, 40, 41, 55]. Possible integration of the MSW modules

with the coal fired utility power plants will help in cost of the ownership reduction and minimizing emissions, including dioxins and furans.

Performed by APT feasibility study of such a waste-into-energy technology implementation in a city of Austin, Texas with population about 775,000 residents, annual amount of generated waste of 594,220 tones, tipping fee per household \$25 per month, and cost of waste processing facilities \$350 million has shown expected return on investment from 4 to 5 years, depending on the generated electricity export price.

In case of all annually generated by the USA MSW processing net power output could be up to 326 million MW. That could cover over 6% of the U.S. power demand. Existing landfills recycling will give additional 1 to 5%. The estimated program cost based on equipment ownership price is about \$90 billion dollars.

## Conclusion

Progress in plasma generation, industrial and societal demand have led to development and worldwide implementation of a variety of plasma based technologies, including that ones for combustion enhancement, fuel reformation, and gasification.

Plasma Assisted Combustion is a new fast growing field of science, from one hand side stimulates progress in such areas as plasma physics, electronics, material science, and from the other side provides extraordinary opportunities to make a progress in propulsion, power generation, environment protection, etc.

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