Guest Editorial
Classification of Plasma Systems for Plasma-Assisted Combustion

I. Introduction

RECENT progress in the research and development of plasma-based technologies for combustion enhancement in power generation and propulsion systems has led to the further development of an emerging field of plasma science and technology which is now well known as plasma-assisted combustion (PAC). This field has historical roots dating back to the 19th century in terms of the observed phenomenon that an electric field can influence a candle flame [1]. However, the realization of this phenomenon first became a practical reality in the 20th century for heating enhancement via electrically augmented burners, extending the blowout limit of flames, flame ignition, combustion stabilization, and fuel conversion. For a historical background and further descriptions of these subjects, the reader is referred to the books by Lawton and Weinberg [2] and Weinberg [3] and the book chapter by Rosocha [4].

When the electric field strength is sufficient to cause an electrical breakdown of a fuel or fuel/air mixture, plasma effects will dominate. Plasma effects can increase electron and ion temperatures and promote combustion through the formation of "active" species (such as free radicals) or the dissociation of fuel molecules into smaller more easily combusted fragments. Presently, the most mature PAC applications are combustion ignition and flame stabilization. The latter application is expected to help reduce pollution (mainly oxides of nitrogen—NO_x) through ultralean-burn combustion. In addition, PAC can potentially improve the efficiency of combustion, the conversion of fuels into other forms [5], [6], the gasification of coal and municipal solid waste (MSW) into synthesis gas (syngas—$H_2 + O_2$) [7]–[9], and the conversion of low-grade fuels into higher grade fuels (although such work is less developed than for ignition and stabilization) [10].

This is the fifth issue in a series of special issues on PAC, following on the success of the first IEEE-TPS Special Issue on Plasma-Assisted Combustion (December 2006).

PAC is a cross-disciplinary field of plasma science and technology. Because of a greater concern about global climate change and the need for more energy-efficient and less polluting combustion techniques, it is currently receiving even greater interest and, through progress in the past few years, has established this Special Issue forum for scientists and researchers to disseminate and review the current research and applications in the field.

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The intention of this Special Issue is to continue the aim of the first special issue—namely to provide an integrated forum for reporting on timely research in the field and to promote further interest and exchange of technical information in this exciting and technologically practical area of plasma science. Contributions were solicited in the primary topic areas of the physics/chemistry of the effects of plasmas on flames and deflagration-to-detonation transitions, the use of plasmas to promote and/or improve efficiency in engines (automotive, aircraft, etc.), flames and/or burners and plasma sources (e.g., jets) for improved ignition, applications to aircraft pulse detonation engines, applications to pollution reduction through enhanced combustion, and applications to fuel reformation/conversion (e.g., fossil fuel to hydrogen) and the conversion of municipal waste to energy.

In addition, this Special Issue includes additional technical information on building a common framework for the field, particularly in formulating descriptions and background material on how various PAC systems can be classified, so a common nomenclature is provided for the discipline.

This Special Issue contains nine papers. Basic investigations on combustion dynamics in plasma-enhanced flames, propane–air combustion with dielectric-barrier discharges (DBDs), the effects of electrical discharges on liquid droplets, and combustion considerations in plasma fireballs are represented in the papers by Rao *et al.* Tang *et al.*, Deng *et al.*, and Bychkov *et al.*, respectively. PAC applications for methane/CO_2 reformation and plasma-based fuel nozzles and modeling and experimental investigations for PAC and fuel reformation systems are represented in the papers by Cha *et al.* and Serbin *et al.* The theory of a plasma-based coal gasification system is covered in the paper by Serbin *et al.* In addition, the vitrification of waste residues from air pollution control systems is covered in the paper by Tu *et al.*

The guest editors would like to thank the authors for the excellent papers in this Special Issue and also the reviewers who offered their assistance in improving the individual papers and the issue as a whole. We hope that this Special Issue will stimulate the submission of similar high-quality papers in future issues of the IEEE TPS. In addition, the guest editors would like to thank the Editor-in-Chief, Dr. Steven Gitomer, and the IEEE editorial and production staff for the encouragement and assistance in preparing this Special Issue.

In the future, a special issue slated for December 2011 will contain selected papers from the 6th International Workshop and Exhibition on Plasma Assisted Combustion that was held in September 2010 in Heilbronn, Germany. It had over

40 attendees from 10 countries: Brazil, Canada, the Czech Republic, Germany, France, Japan, The Netherlands, Russia, Ukraine, and the U.S. Thirty-five papers were presented in six sessions: 1) plasma ignition and flame control; 2) plasma generation, diagnostics, and modeling; 3) plasma flow dynamics; 4) fuel reformation and activation; 5) new plasma effects and prospective applications; and 6) waste into energy. Six roundtable sessions facilitated discussions on prospective directions of activity and created several international research collaborations for joint project development and implementation.

II. Equilibrium and Nonequilibrium Plasmas

As a reminder, there are essentially two types of plasmas commonly employed for plasma-chemical processing: equilibrium plasmas (also called *thermal* or *hot* plasmas) and nonequilibrium plasmas (also called *nonthermal* or *cold* plasmas). One major difference between the two is that thermal plasmas are characterized by nearly equal electron, ion, and neutral-species temperatures (average energies), while nonthermal plasmas (NTPs) are characterized by having much more energetic electrons, with ions and neutrals being of low temperature (frequently very close to ambient). This nonequilibrium situation frequently allows more efficient direction of energetic-electron energy into favorable chemistry (into molecular decomposition or excitation), without high enthalpy (heat) in the process medium/gas. Heat energy loss is commonly gas heating, resulting from a transition from glowlike or transient streamer discharges into sparks or arcs. Another major difference between these plasmas is the degree of ionization (thermal plasmas are usually fully ionized, whereas NTPs are of low degree of ionization, like $\sim 10^{-5}$). The common automotive spark plug is an example of an equilibrium plasma device—a spark or an arc.

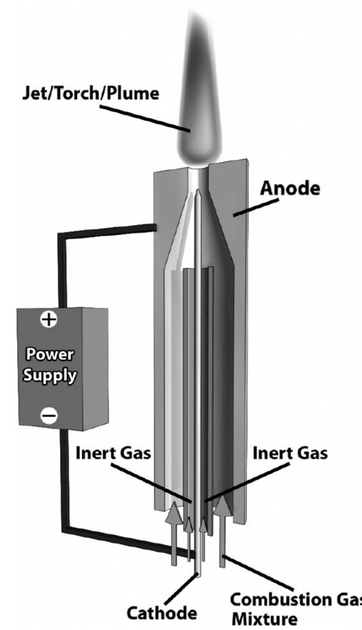

Fig. 1. Early plasma torch/jet (after Weinberg [3]).

Fig. 2. Plasma igniter in operation [6].

III. Applications

The primary applications of plasmas to combustion enhancement are discussed in this section. This is not an exclusive list but includes the major focus areas of present research and development in the field. The key applications are as follows: 1) igniters; 2) flame sustainers; 3) fuel nozzles; 4) vortex-flow combustors; 5) fuel reformers and gasifiers; and 6) waste processors/converters.

A. Igniters

The common automotive or aircraft spark plug is the best known example of a plasma-based igniter. In a typical spark plug, an electric-discharge arc (a thermal plasma) is drawn between two electrodes, thereby ionizing and decomposing molecules of the fuel/air mixture and heating the mixture locally such that ignition (local burning) takes place and a flame (combustion wave) propagates through a combustion chamber. Newer types of plasma-based igniters are the most well-developed devices for combustion enhancement. Such units are typically employed for replacing spark plugs and operating for relatively short periods of time (e.g., several minutes). The most common devices are based on dc thermal plasma torches for application to gas turbine engines, like those employed for industrial equipment, aircraft, and watercraft (with airflow conditions considerably less than supersonic). Historically, the device (ca. 1960) shown in Fig. 1, described by Weinberg [3], is an early embodiment of a dc plasma torch, whereby a plasma is established by an arc in an inert stabilization gas stream. Heat and some active species are then transferred and mixed with the combustion gas mixture.

The main advantage of a plasma-based igniter, in comparison to conventional spark plugs, is its much higher plasma plume volume and velocity. This allows deeper penetration of a highly reactive plasma plume (see Fig. 2) into the combustion zone of an engine and, therefore, more reliable ignition. DC plasma torches typically consume electrical power in the range of 500–1000 W, require a plasma-supply-gas flow rate of up to 1 g/s, and have an operational lifetime of up to 4000 h [6].

For ignition at other subsonic and supersonic flow conditions, such as the high-speed airflows required of aerospace propulsion engines and scramjets, the radio frequency (RF), microwave (MW), and transient glow-to-spark discharge plasma

Fig. 3. Supersonic plasma igniter [6].

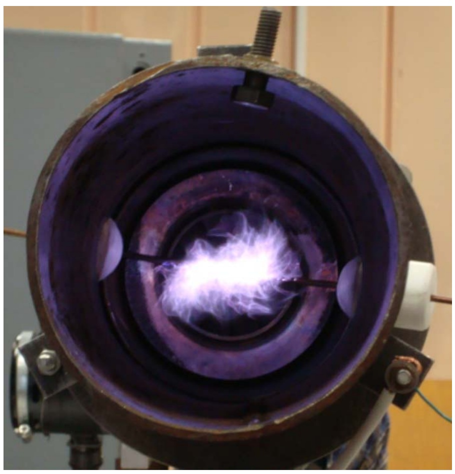

Fig. 4. RF igniter in operation (after [17]).

torches (see Fig. 3) are employed [6], as well as very short-pulse (10–100 ns) electrical discharge devices [11]–[14].

RF and MW plasma torches, igniters (see Fig. 4), and other devices are less well developed at present, so their operating-parameter ranges are not so well defined [15]–[17].

In the past roughly two decades, plasma-ignition research has focused on the use of short-pulse electrical discharges (e.g., pulsed corona and other extremely fast-pulse discharges, with voltage rise times of $\sim$10 kV/ns) applied to improve the transition from ignition to combustion-wave/flame propagation. The discharges produce a nonequilibrium plasma in their vicinity and generate active species that can promote chemical reactions. Most recently, such NTP plasma applications have been focused on the aerospace field (e.g., ramjets, scramjets, and supersonic combustion) [18]). Pulsed plasma-based ignition has proven to be effective in supporting the development of chain oxidation mechanisms (i.e., fuel burning) that contribute to the decreases in ignition delay time and a more uniform spatial distribution of combustion. A technique, reported by Wang *et al.* [11], for applying pulsed corona to an aerospace combustion chamber (e.g., a pulse detonation engine) is shown in Fig. 5.

In this technique, the ignition delay time and ignition pressure rise time are significantly reduced, compared to traditional spark-ignition methods. Other studies on the application of short (30–40 ns) and fast rise-time pulses ($\sim$10 kV/ns) to combustion processes, particularly aviation, aerospace, and supersonic applications, which create a more spatially uniform and fast volume ignition have been recently reported by Starikovskaia *et al.* [13], Starikovskii [18], and Do *et al.* [19]. Fast-pulse discharge ignition has also been applied to

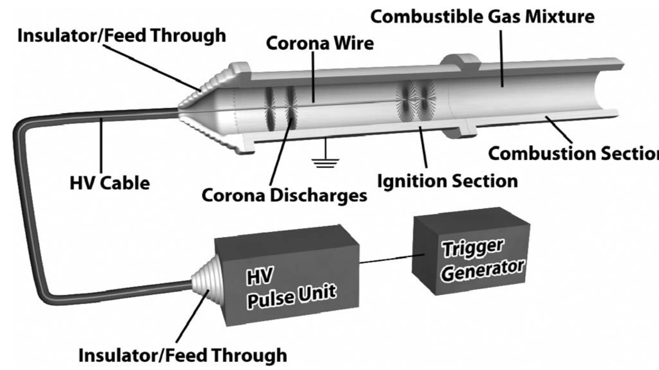

Fig. 5. Artist's conception of pulsed corona ignition scheme for aerospace (pulse detonation) engine [11]).

automotive applications for improving engine stability and fuel mileage [20], [21].

B. Flame Stabilizers

Flame stabilization can be accomplished by grossly heating a combustible gas mixture, by aerodynamic effects (e.g., turbulent and vortex mixing), or by chemical effects (modification of the fuel or combustion gas to produce more chemically active species). It is these desirable chemical effects that can be realized using plasmas, with stabilization, particularly involving the seeding of a combustion volume with active species which tends to initiate more spatially uniform combustion that then propagates through the entire combustion volume.

Example applications are high-altitude aircraft reignition and lean-burn combustion for reduced pollution emissions. Ignition and stabilization sometimes overlap, e.g., better ignition can seed better more uniform volume combustion. Therefore, work on ignition can, in some aspects, fall into both stabilization and ignition categories.

IV. Plasma Jets/Torches for Combustion Stabilization

Two general types of plasma torches are of interest: continuous and pulsed. Historically, the continuous form (as illustrated in Fig. 1) was developed first, and it normally functioned by heating flowing gas streams to very high temperatures (beyond that achieved by normal combustion). They were usually applied to stabilize flames in regimes where it is desired to considerably increase the fuel mass flow or to operate in very lean-burn regimes, which are conditions under which the flames normally tend to blow out. Continuous plasma torches have also been shown to be useful in reducing the generation of soot in flames and in removing oxides of nitrogen. In the last three decades of the 20th century, the pulsed type has become the preferred form of plasma torch. Because of it, the plasma functions to inject free radicals that promote better combustion and, using nitrogen, generates nitrogen-atom radicals that can remove nitric oxide (NO) by converting it to N_2, thus reversing the rate-limiting chemical reaction by which NO is produced in high-temperature combustion—the well-known Zeldovich mechanism.

Matveev *et al.* [22] developed continuous torches for ignition and flame control in gas turbines for natural gas pumping stations in 1980–1985. A proven application of newer continuous plasma torches is a pilot (igniter and burner) device for the stabilization of lean-burning flames (see [6] and the citations therein) because the plasma-chemical effects dominate aerodynamic effects. Weinberg *et al.* (see [2] and [3] and the references therein) have shown an electrical power input of only ∼2% of the combustion chemical-power release. Such plasma devices can be simply introduced into burners or ducts to improve the stability and/or prevent blowouts.

Pulsed plasma torches display some of the same advantages as continuous torches but have lighter weight power supplies (because of high frequency and/or pulsed operation). These devices can cold-start diesel engines and are also beneficial for the cold-start phases of internal combustion (IC) engines (both gasoline and diesel) to curb NO_x and unburned-hydrocarbon emissions. Cold start is where most IC-engine pollution emissions occur. Burners and furnaces also benefit from quick ignition (from the point of view of safety and efficiency). Relighting flamed-out gas turbine engines on aircraft is also a very useful and important application.

V. Nonequilibrium Plasma Flame Stabilization

To provide two illustrative examples of nonequilibrium plasma-enhanced combustion, the influence of dc corona and DBDs on the flame stability will be discussed in this section.

A. Corona-Based Flame Stabilization

Into the early 1970s, Bradley *et al.* had studied the exchange of electron energy with other species in flames subjected to external electric fields. This work concluded that ohmic gas heating and selective excitation of some molecular energy levels would occur, thus leading to increased rates of chemical combustion. In the early 1980s, these researchers applied this concept to a flame burner, operating with a methane–air mixture [23]. They used metal points (much like sharpened triangles) at the exit of the metal-tube burner to enhance the electric field in the flame region (see Fig. 6).

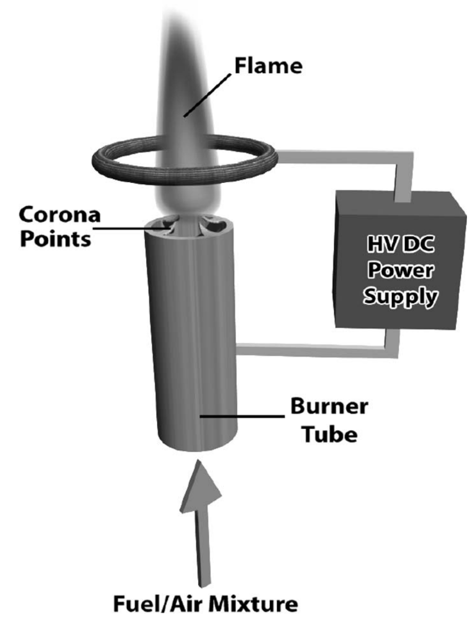

Fig. 6. Corona-influenced burner (after [23]).

They found that, with negative corona at the points, an increased gas flow rate could be achieved before the flame experienced a blowout. Without the presence of corona (no appreciable plasma), blowout flow rates were realized with the electric field alone, but they were lower than those achieved with a corona plasma. This experiment clearly demonstrated the effect of a nonequilibrium plasma on flame stabilization.

Rosocha *et al.* [24]–[26] have carried out tests on the cracking of hydrocarbon fuel gases, flame stabilization under lean-burn conditions, and flame propagation speed. Fig. 7 shows a setup for determining the influence of an NTP on the blowout limit of an activated propane–air flame (i.e., ultralean-burn conditions), using a DBD. Coflow air (the center tube of a reactor) was mixed with the plasma-activated propane at ∼1.5 cm from the top of the plasma region, and this mixture was ignited. The applied ac frequency was about 450 Hz. Blowout tests were conducted by holding the propane flow constant

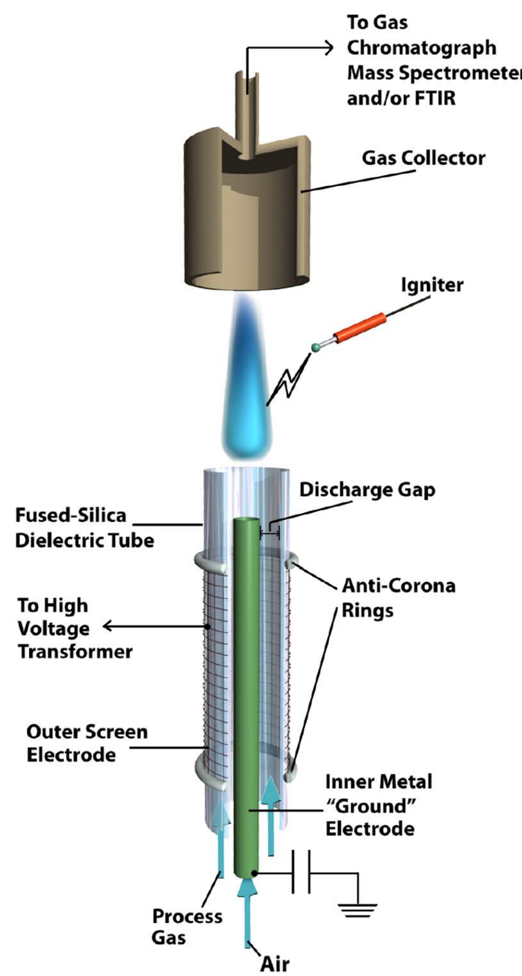

Fig. 7. Illustration of DBD device for lean-burn experiments.

and increasing the airflow rate until the flame blew out. The blowout airflow rate is an indicator of the flame stability, and the high blowout airflow rate achieved in these tests shows that combustion continues to occur under very lean-burn conditions (equivalence ratio < 0.2).

VI. Hybrid Plasma Devices for Combustion Stabilization

Hybrid plasma devices, such as certain types of plasma pilots (i.e., "pilot" in the sense of a pilot light on a stove) and flame sustainers, have two main functions—ignition and continuous flame control [6]. The application-focused needs of continuously operating in a high-temperature environment with variable pressure pilots and flame sustainers have moved research to develop NTP sources with significantly extended lifetime and lower power consumption—characterized by pulse power devices, direct arc initiators, and MW initiators. Known plasma pilots operate within an average power range of 50–500 W and pressures of 10–15 bar and provide continuous operation for approximately 1000 running hours. Hybrid devices are frequently based on systems that combine aspects of both equilibrium and nonequilibrium plasmas.

VII. "Glid-Arc" Discharges

This discharge, historically called Jacob's ladder, has been known for over a century. It was used in plasma chemistry for fertilizer production around the beginning of the 20th century, was named the "glid-arc," and was further developed for flame-heating enhancement, removal of air pollutants, and hydrocarbon conversion into syngas by Czernichowski [27]. A glid-arc usually consists of two or more metal electrodes, with a diverging space, which are connected to a dc power supply. A gas to be processed is quickly flowed upward through the space between the electrodes, where upward-moving electrical discharges process the gas. Because the arc is constantly moving over the electrode surfaces, electrode wear can be ameliorated at high plasma power levels.

By changing the gas flow to a swirl, "tornado"-like discharges can be established in configurations similar to a glid-arc (plasma tornado trapped in a gliding discharge using a spiral electrode), as discussed in the book by Fridman and Kennedy [28]. A modification of this idea and application to combustion is discussed hereinafter.

VIII. "Plasma Tornado"/Vortex Combustors

The diverging electrodes in the approach previously mentioned can be eliminated if reverse-vortex stabilization of the plasma is effected by introducing a swirl airflow through ports arranged tangentially in a combustion chamber to which an electric field longitudinal to the fuel-gas flow is applied. This device has been described and modeled by Matveev and Serbin [29], [30] for the purpose of gaseous-fuel combustion. Initial experiments and modeling indicate that such a combustor can increase the fuel efficiency and reduce CO_2 emissions [30]. The inherent stabilization of the plasma by the tornado-swirl effect (vortex) serves to insulate the tornado plasma from the combustor walls, thereby allowing the contained gas to be heated by the plasma and preventing excessive heat loss and damage to the walls. Fig. 8 shows a photograph of a reverse-vortex plasma-assisted combustor.

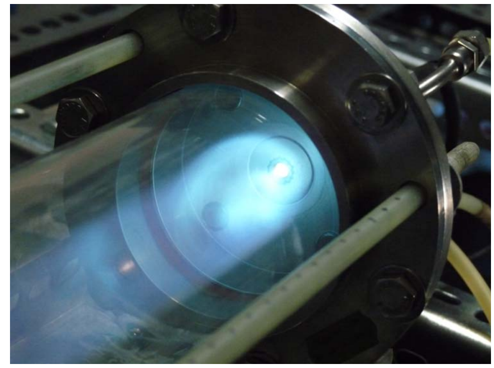

Fig. 8. Reverse-vortex combustor with plasma assistance.

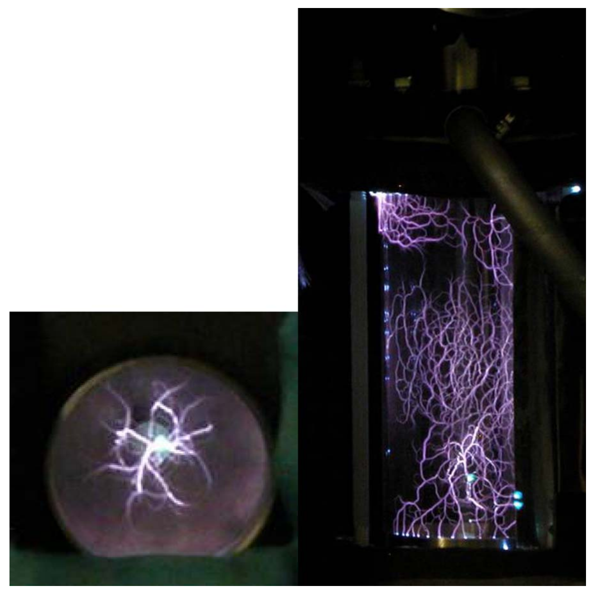

Fig. 9. Subcritical MW discharge in reverse-vortex combustor.

A. Plasma Tornado/Reverse-Vortex Combustor Incorporating MWs

One attractive prospective MW system for ignition and flame control in a reverse-vortex combustor has been developed by Applied Plasma Technologies and the Moscow Radio Technical Institute [29]. Discharge photos are shown in Fig. 9. A volumetric MW discharge on the fuel-nozzle tip of the combustor was developed.

B. Fuel Nozzles

A plasma fuel nozzle is a combination of a plasma generator and a fuel atomizer, which provides simultaneous fuel atomization, ignition, and flame control in one unit [6], [31]. It is the most complicated and advanced solution for many PAC applications. Several experimental nozzles for gaseous and liquid fuels with flexible-fuel operation and the incorporation of steam are currently under development. The main advantages of these nozzles are as follows: 1) dramatically increased

Fig. 10. Plasma fuel nozzles.

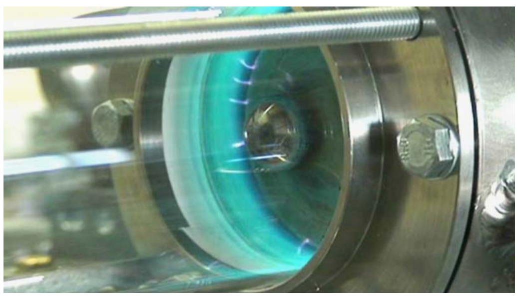

Fig. 11. Reverse-vortex combustor with 10-W spatial arc.

ignition reliability; 2) much wider equivalence ratio—φ, λ range; 3) significant decrease in rotor inlet temperature jump at the time of fuel ignition in gas turbines; 4) the ability to serve as a pilot burner; 5) application to hydrogen-enriched gas generation; 6) reduction in combustion zone space; 7) reduction of the temperature at combustion chamber walls; 8) increase in combustion efficiency; 9) achievement of smokeless operation; 10) simultaneous burning of several fuels; and 11) smooth regulation in a wider turndown ratio. An example plasma fuel nozzle for gaseous fuel burning in a gas turbine is shown in Fig. 10.

C. Spatial-Arc Devices

The so-called spatial arc is an example of recently patented applications [6] of a nonthermal high-voltage discharge that orbits inside a combustion chamber and serves as an ignition source and a flame controller. Employing the combustor walls as the electrodes, this arc, with an average power consumption from 10 W to 1 kW, provides a simple and energy-efficient solution for gas-fired furnaces and combustors, particularly in lean-burn modes [32]. A laboratory-scale combustor prototype incorporating a low-power spatial arc is shown in Fig. 11.

D. Fuel Reformers and Gasifiers

There are numerous publications devoted to fuel reformation [5], [6], [10] and coal gasification [6], [7], [10], [33]. Here, we provide just a few examples of recently developed systems, which disclose the most practical approaches to fuel reformation and gasification using plasmas. It can be seen from analyses presented in published manuscripts that the main obstacles confronting full-scale gasification technology development and implementation are the lack of energy-efficient plasma sources with affordable lifetimes and operational costs. For example, existing coal ignition and partial gasification technologies [6] employ 100–200-kW dc torches with very limited cathode lifetimes of approximately 200 running hours. Similar situations apply to all other plasma torches on the market. This means that any significant progress in this direction will result from the development of new generations of high-power atmospheric pressure plasma sources and power supplies. Based on known plasma generation solutions analyses, one of the authors has selected for further development and implementation a hybrid type (RF + dc) plasma torch with reverse-vortex flow [33], [34]. Such a device could provide for atmospheric pressure plasma reactor operation in combination with more efficient solid state power supplies. Such a solution allows virtually unlimited lifetimes for both electrical and plasma generation modules and also high caloric value of produced syngas, based on an oxygen gasification process incorporating recently developed air separation technology. The maximum achieved power level per unit is currently 1.8 MW and is expected to increase to 10 MW (Fig. 12).

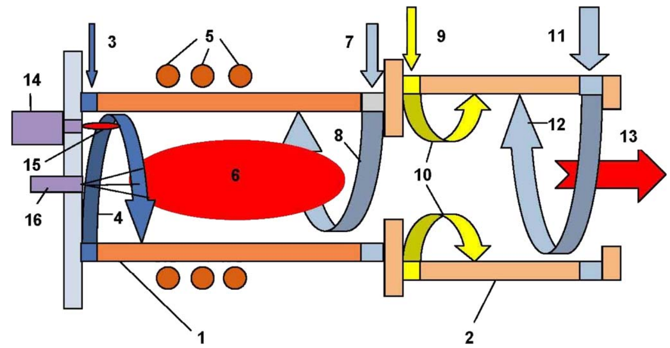

Fig. 12. Plasma-based gasifier for coal [33], [34], [U.S. Patent 7 452 513 B2].

E. Waste Processors and Converters

Waste-into-energy conversion is vital for both developed and developing countries but still not feasible for many of them due to high capital and operational costs for existing plants and the cost of implementing high productivity plants with capacity over 250 tons/d. Significant reduction of the operational costs could be achieved by the following: 1) application of hybrid (RF + dc) torches with dramatically extended lifetimes; 2) introduction of a plasma gasification stage in an oxygen-rich combustion environment; 3) syngas treatment in a steam catalyst converter to increase hydrogen yield; and 4) multifeedstock operation to process waste from scrap tires, MSW, coal, and electronic waste [6]. The possible integration of the MSW modules with coal-fired utility power plants will help reduce the cost of the ownership and minimize emissions, including dioxins and furans.

A feasibility study for implementing such a waste-into-energy technology for the city of Austin, Texas, has been carried out by one of the authors. Austin has a population of about 775 000 residents, a generated waste of 594 220 tons/year, and a tipping fee per household of \$25/mo. The expected cost of a waste-to-energy conversion facility is \$350 million, and the expected return on investment ranges from four to five years, depending on the export price of the generated electricity.

For the case of converting all annually generated MSW in the U.S., the net power output could be up to 326 million MW. That could cover over 6% of the U.S. power demand. Existing landfill recycling could supply additional 1% to 5%. The estimated program cost, based on equipment ownership prices, is about $115 billion.

IX. Outlook and Conclusion

Progress in plasma sources, coupled with industrial and societal demands for cleaner and more energy-efficient combustion and waste processing methods, has led to the development and worldwide implementation of a variety of plasma-based technologies for combustion enhancement, fuel reformation, and gasification.

PAC is now a quickly growing field of science: on the one hand, stimulating progress in such areas as plasma physics, electronics, and material science and, on the other hand, providing extraordinary opportunities to make progress in propulsion, power generation, and environment protection.

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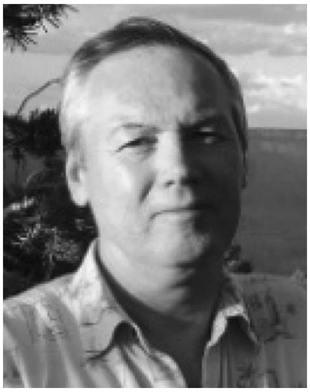

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