International Plasma Technology Center

PLASMA ASSISTED COMBUSTION, GASIFICATION, AND POLLUTION CONTROL

Volume I. Methods of plasma generation for PAC

Chief Editor
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PREFACE

Dear Reader,

Thank you very much for your interest in this book, whose appearance is a logical development of the research activity in a relatively new field named Plasma Assisted Combustion (PAC) and is the first attempt to collect the most valuable contributions to the field from different research groups all over the globe.

The first practical applications of different plasma sources for ignition and combustion enhancement date back to the 1960s and 1970s. The first PAC conference was organized by the Editor in 1989 in the former Soviet Union. At this time, the PAC community is relatively well organized with an annual International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC), now converted into the International Conference on Plasma Assisted Technologies or ICPAT starting in 2012, and special issues in the IEEE Transactions on Plasma Science on the topic of on Plasma Assisted Combustion.

This two-volume work is one of the first projects of the newly established International Plasma Technology Center (IPTC) intended to provide, in Volume 1, a description of different plasma sources especially designed for PAC and, in Volume 2, to describe PAC processes that are under development or used industrially. If successful, we plan to publish new editions every two-three years depending on progress in this field.

This book is intended to be used as a textbook at the senior or first-year graduate level by students from all engineering and physical science disciplines, by PhD students, researchers, and as a reference source by in-service engineers and other researchers

Basic information on plasma physics and the accompanying physical processes important in PAC are contained in Volume 1. Devices, technologies, current state, and future works are placed in Volume 2.

This book does not contain derivations from first principles of some of the more advanced material from plasma physics, electrical engineering, or materials science. Such material can be found in graduate texts. This is also not an encyclopedia.

I would like to express my appreciation to all contributing authors (over 30 from 7 countries), whose support, suggestions, and hard work have contributed to the book in its present form.

I especially would like to thank Dr. Louis Rosocha for his very thorough and helpful scientific editing of the final manuscript.

Finally, I am especially desirous of establishing contact with the university professors who teach or plan to develop courses on PAC, students, PAC researches, in-service professionals, and potential investors who use this book, in order to improve it, correct it, and answer any questions. Please feel free to contact me with any corrections or comments at (703) 560-9569 voice, (703) 849-8417 fax or by e-mail at i.matveev@att.net.

Best regards,
The Editor,

Igor Matveev, Ph.D.
McLean, Virginia, USA
January 20, 2013

FROM THE TECHNICAL EDITOR

This book, which is privately produced, is a unique addition to the scientific and technical literature which is focused on the expanding field of plasma applications in the context of combustion, energy, and the environment. This book is different from ones on similar topics in that its philosophy is focused on practical applications in its subject fields and to make use of the key and current expertise of many authors from around the world.

The book has been produced under the auspices of the International Plasma Technology Center (IPTC), a non-profit corporation located in McLean, Virginia, USA (see plasmacombustion.org for more information). In spite of the IPTC umbrella, the expenses for the book have been covered by the personal financing of Dr. Igor Matveev of the IPTC and the mostly-volunteer editing and production efforts of the Technical Editor and the private citizens Matthew Chandler, Larry A. Moody, Cyril A. Moody, and Svetlana Matveyeva.

The basic mission of the IPTC is to promote scientific, educational, and charitable activities. This book is an example of organizing an international team of authors to promote education in the focus areas of the disciplines addressed. There are over 30 authors for Volume 1, who hail from five countries: Czech Republic, Netherlands, Russia, Ukraine, and the United States. A second volume will be produced in the future. The IPTC will gratefully welcome new authors in this endeavor to aid our mission of keeping abreast of new developments in the field of plasma assisted combustion, gasification, and pollution control and to update the literature to include new information through additional or revised volumes.

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INTRODUCTION

PLASMA ASSISTED COMBUSTION HISTORY, APPLICATIONS, AND CLASSIFICATION OF SYSTEMS

Louis A. Rosocha and Igor B. Matveev

ABSTRACT

The application of electric fields to flames has been studied at least as far back as the early 19th Century, was applied to flame combustion in the 1920's, was further developed into several applications in the last half of the 20th Century, and continues to be explored in the 21st Century. When the electric field strength is sufficient to cause electrical breakdown (i.e., ionization) of a fuel or fuel/air mixture, plasma effects will dominate. This plasma is simply described as an 'electrical gas', consisting of neutral gas molecules, ions, atoms, and energetically-excited atoms and molecules. 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. Plasma-assisted combustion (PAC) is now a timely and growing worldwide field of research.

Plasma-based techniques can enhance combustion in terms of improving ignition reliability (and consequent reduction in induction time), ameliorating flame instabilities, and reducing environmentally-pertinent emissions. Such plasma systems apply to a wide variety of combustion applications, including burners, incinerators, heaters, dryers, boilers, furnaces, land-based power generators, aircraft, watercraft, aerospace propulsion systems, and coal and waste gasification/conversion systems.

This chapter will present a description of plasma assisted combustion (PAC) systems, including a brief historical overview of the subject and the motivation for employing plasmas in combustion, as well as some information on classifying various plasma systems and adopting a common terminology for the field.

I. Introduction

Research and development of plasma-based technologies for combustion enhancement has shown significant progress in the recent past, as mainly applied to combustion-based devices (e.g., heaters, furnaces, incinerators), power generation, vehicles (autos, aircraft, watercraft), aerospace propulsion systems, and coal/waste gasification systems. This has led to the further development and recognition of a growing field of plasma science and technology 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.

The basis of PAC is the application of an electric field to a fuel gas or fuel-oxidizer mixture. When the applied electric field strength is sufficient to cause electrical breakdown (i.e., ionization) of a fuel or fuel/air mixture, plasma effects will dominate. As a reminder to the reader, a plasma is simply described as an ‘electrical gas’, consisting of neutral gas molecules, ions, atoms, and energetically-excited atoms and molecules. Plasma effects can increase electron and ion temperatures and promote combustion through heating effects and the formation of ‘active’ species (such as free radicals), or the dissociation of fuel molecules into smaller, more-easily combusted fragments. Resultant combustion enhancements consist of, for example, an increase in the blow off velocity of premixed flames or increases in blowout and liftoff velocity of jet flames, extension of lean flame flammability limits, and a decrease in ignition delay time.

In this chapter, we will present a description of PAC systems, including a brief historical overview of the subject and the motivation for employing plasmas in combustion. This chapter is intended to show the most relevant applications for PAC technology and prospective directions for future investigations and applications. In addition, we include additional technical information on building a common framework for the field – especially in terms of how various plasma assisted combustion systems can be classified, so a common nomenclature is provided for the discipline.

Historical Background

Work published the early- and mid-20th Century by Southgate [2], Lewis and Kreutz [3], Calcote and Pease [4], and Katz et al [5] have described the effects of electric fields on flames and associated practical applications (like electrically-augmented burners for influencing blow-out limits and gas heating). Later, for the time period 1960’s – 1980’s, background and state-of-the-art research and techniques for influencing flames and improving combustion ignition, stability, and flammability limits were described by Lawton and Weinberg [6]. Overlapping with the last-mentioned work, increases in flame reaction rates and velocities, under the influence of DC, AC, and high-frequency electric fields, were reported in a 1971 publication by Jaggers and von Engel [7] and references contained therein.

During the last two decades of the 20th Century, further research on the effects of electric fields on flames was reported by Gulyaev et al [8], Shebeko [9], Yagodnikov and Voronetskii [10], and Panteleev et al [11]. Some of their experimental setups most likely produced electrical-discharge plasmas. The use of non-equilibrium plasma sources, using various kinds of electric fields, during the last three decades of the 20th Century, in modifying the combustion properties of flames is described by Bradley, Gupta, and Nasser [12-14], Inomata et al 1983 [15], and Shebeko [9]. More recently, Lee et al [16] and Vincent-Randonnier et al [17] have shown that AC electric fields, and associated plasmas, can decrease flame liftoff from turbulent propane and methane flames in air, thus increasing the range of flame stability.

The first book documenting practical applications of engineered, industrial type PAC devices was published in 1992 by Matveev et al [18], in Russian. Starting from 1979, he and his team members performed a series of pioneering works on the development and practical application of plasma systems for different types of power plants. They offered an approach to combustion intensification by comprehensive plasma influence on combustible mixtures to achieve reliable ignition, high combustion performance of different fuels (including heavy oils), and low emissions. The team also performed theoretical and experimental investigations on a variety of

PAC devices operating at elevated pressures, utilizing both gaseous and liquid fuels, for both test facilities and real heat engines. As a result, a line of PAC devices, such as plasma igniters, plasma chemical reactors, plasma fuel nozzles, and plasma gasifiers were developed [18-22]. Mass production of these devices started in the former Soviet Union under Dr. Matveev's supervision from 1985 and, by the end of the 1990s, over 600 gas turbines from 100 kW power to 25 MW power and over 20 steam and water boilers were equipped with different PAC systems. That was the world's first large scale and commercially successful demonstration of PAC system development and implementation.

As we know, many PAC processes generally involve the decomposition/fragmentation of fuel molecules. During the 1970's – 1980's, investigations into the plasma-aided decomposition of hydrocarbons were reported in a 1974 book edited by Hollahan and Bell [23]; the publications of Jensen et al [24]; and several publications of Romanovsky, Matveev, Serbin, and others [25-28] (in Russian), focused mainly on heavy liquid fuel decomposition and clean combustion in boilers, turbines, and IC engines. The conversion of methane into higher-order hydrocarbons (mainly for combustion fuel) by non-equilibrium plasmas has also been investigated. For further information on that subject, the reader is referred to the works of Yang [29] and Supat et al [30] from 2003.

One particular device and its variants (e.g., the *plasma tornado*) is certainly worthy of mention here – the plasmatron (basically a rotating thermal-plasma arc) for the conversion of hydrocarbon fuels, including liquids, into synthesis gas (syngas, or H_2 + CO) was initially investigated and invented by Rudiak, Rabinovich, and Tul, as patented in Russia in 1979 [31] Such a device was adapted for vehicular and decentralized fuel-cell applications by Bromberg, Cohn, Rabinovich, and others about one or two decades later [32, 33].

Plasmatrons or modified plasmatrons also have application in combustion ignition and stabilization. An application involving the use of a plasmatron for combustion enhancement is shown in schematic form in Fig. 1 below. Here, a primary unit for combustion sustainment is a low-current nonsteady-state plasmatron with low-level electric power. The plasmatron activates an air/hydrocarbon mixture and sustains the oxidation processes in the plasma torch. In turn, the heat power of the torch sustains the main burning process in the torch flame. Further practical uses of plasmatrons (ignition, flame sustainment, etc.) are described further below in the Applications section.

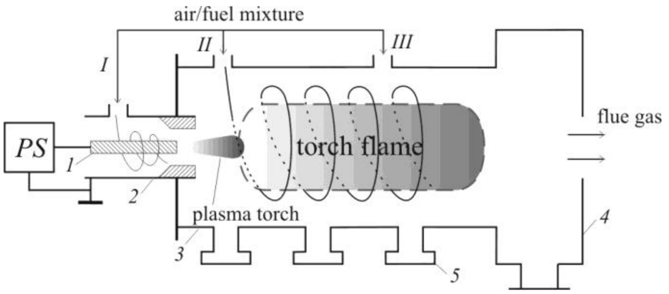

Fig. 1. Schematic arrangement of a plasmatron-based, plasma-assisted combustion system and. *1* – inner electrode of a nonsteady-state plasmatron (cathode); *2* –grounded outer electrode of plasmatron (anode); *3* – combustion chamber; *4* – pyrolysis chamber; *5* – auxiliary windows. After Korolev et al 2012 [34].

So-named plasma chemical reactors for combustion enhancement in gas turbines, boilers, and IC engines were investigated, starting in 1979, in Ukraine by Matveev and Serbin. They were based on micro-thermal torches with vortex arc stabilization, but due to unique designs, they allowed long term operation at high pressures without cooling and also featured simple integration into existing combustors and engines [22, 26, 35, 36].

Such devices continue to be investigated for fuel conversion [37, 38], combustion enhancement [39], and carbon dioxide decomposition [40, 41].

The works of Bradley et al [42-43] very well described the connection between flames and plasmas (and the associated field of gaseous electronics) in terms of how external applied electric fields can affect the energy transfer from electrons to neutral gas species and ions in flame gases. The above-referenced works from Bradley et al, coupled with the works described in the book of Hollahan and Bell [23] and in the work of Jensen et al [24], describe the effects of electric fields on flames and the decomposition of hydrocarbons in the framework of gaseous electronics and plasma chemistry (e.g., the reduced electric field strength E/N – magnitude of electric field divided by gas density – which is directly related to the average electron energy or electron temperature in an electric gas-discharge). At least one of the authors of this section (LAR) has been urging practitioners of PAC to adopt the language and descriptions of gaseous electronics to clarify communication and the comparison of research results in the field.

For additional historical background and further descriptions of the above subjects, the reader is referred to the citations in the above sections, the books by Lawton and Weinberg [6] and Weinberg [44], the publication of Starikovskii [45], the book chapter by Rosocha [46], and the paper of Matveev and Rosocha [47].

As mentioned before, when the strength of an electric field applied to a fuel or fuel-oxidizer (air, oxygen) mixture is sufficient to cause electrical breakdown (viz. ionization) of the 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. At present, the most mature PAC applications are combustion ignition and flame stabilization. This last-mentioned application is expected to help reduce pollution (mainly oxides of nitrogen – NO_x) through ultra-lean burn combustion. In addition, PAC can potentially improve the efficiency of combustion, the conversion of fuels into other forms [22], the gasification of coal and municipal and industrial solid wastes into synthesis gas (syngas – a mixture of mainly H_2 and CO) [48-54], and the conversion of low-grade hydrocarbon fuels into higher-grade fuels (although such progress is less developed than that for ignition and stabilization).

PAC encompasses cross-disciplinary studies 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, this field is currently receiving additional interest.

This chapter draws on knowledge extracted from the following primary topic areas for PAC applications: 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.) or flames and/or burners, plasma sources (e.g., jets) for improved ignition, applications to aircraft pulsed detonation engines, applications to pollution reduction through enhanced combustion, and applications to fuel reforming/conversion (e.g., fossil fuel to hydrogen) and the conversion of industrial and municipal wastes to energy (e.g., syngas production and it’s associated combustion). Selected primary applications for PAC will be discussed in this work.

II. Equilibrium and Non-Equilibrium Plasmas

As a reminder to the reader, there are essentially two types of plasmas commonly employed for plasma-chemical processing: equilibrium plasmas (also called *thermal* or *hot* plasmas) and non-equilibrium plasmas (also called *non-thermal* 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 non-thermal plasmas (NTPs) are characterized by having much more energetic electrons, with ions and neutrals being of low temperature (frequently very close to ambient). This particular situation frequently allows the achievement of more efficient direction of energetic-electron energy into favorable chemistry (into molecular decomposition or excitation), without high enthalpy (heating and associated energy loss) in the process medium/gas. Heat energy loss is commonly gas heating, resulting from a transition from glow-like 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 ~ 10^{-5}). The common automotive spark plug is an example of an equilibrium plasma device – a spark or arc.

For non-equilibrium plasmas, most of the electron energy is channeled into the dissociation of molecules and the production of radicals [56]. That is, most of the discharge-plasma energy is converted to chemical energy, while with DC discharges, arcs, and sparks; the major portion of the deposited energy is converted to heat.

III. Applications

Selected applications for plasmas to combustion enhancement are discussed in this section. What is covered is not an exclusive list but includes the major focus areas of present research and development in the PAC field. The key applications are: 1) Igniters, 2) Flame sustainers, 3) Fuel nozzles, 4) Vortex-flow combustors, 5) Fuel reformers and gasifiers, 6) Waste processors or converters.

A. Igniters

The common spark plug, either automotive or aircraft, 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 in an engine. 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 are usually based on a modified spark plug and a fast-pulse (10's ns duration voltage pulse) or a DC thermal plasma torch. The fast-pulse devices are typically for automotive and aerospace applications, whereas the DC torches are more suitable for gas turbine engines, like those employed for industrial equipment, aircraft and watercraft (with air flow conditions considerably less than supersonic), and where they operate for relatively short periods of time (e.g., several minutes). Historically, the device (ca. 1960) shown in Fig. 1, described by Weinberg [44], is an early embodiment of a DC plasma torch whereby a plasma is established by an arc in an inert, stabilization gas stream. Some active species and heat are then transferred and mixed with the combustion gas mixture.

Theoretical considerations of pulsed discharge igniters have been described by Starikovskii [57] Laboratory experiments and modeling analysis of fast-pulse igniters have been reported by

Starikovskii [45] and and Starikovskaia et al [58]. Actual devices for transient-plasma-based jet flame ignition and IC engine ignition are described by Do et al [59] and Cathey et al [60], respectively. Experimental data, accompanied by numerical modeling, of a comparison between a spark-ignition system and a nanosecond-discharge-based ignition system in IC engines is shown in the publication of Tropina et al in 2009 [61].

Fig. 2. Photograph of a DC plasma igniter in operation, after Matveev et al [48, 62].

The key advantage of a plasma-torch-based igniter, in comparison with conventional spark plugs, is a much higher plasma plume volume and velocity. This allows deeper penetration of a highly-reactive plasma plume (see Fig. 6) into the combustion zone of an engine and, thus, more reliable ignition.

Commercially-practical and successful DC plasma torches for actual gas turbines were developed by Matveev et al [18]. These typically consume electrical power in the range 500 – 1,000 W, require an external plasma-supply-gas flow rate of up to 1 g/s, and have an operational lifetime of up to 4,000 hours.

Plasma-based devices can also be applied to ignition at other sub-sonic and supersonic flow conditions, such as the high-speed airflows required of aerospace propulsion engines and scramjets. Such devices are based on radiofrequency (RF), microwave (MW), and transient glow-to-spark discharge plasma torches (see Fig. 3) are employed [48, 62-64], as well as very short voltage pulse (10’s – 100 ns) electrical discharge devices [11-14].

Fig. 3. Photograph of a DC supersonic plasma igniter, after Matveev [88].

RF and MW plasma torches, igniters (see Fig. 4), and other related devices are less well developed at present, so their operating-parameter ranges are not so well defined [65-67].

During, approximately, the past two decades, plasma-based ignition research has focused on the use of short-pulse electrical discharges (e.g., pulsed corona and other extremely fast-pulsed discharges, with voltage rise times of ~ 10 kV/ns) applied to improve the transition from ignition to combustion-wave and flame propagation. The discharges produce a non-equilibrium plasma in their vicinity and generate active species that can promote chemical reactions. Such NTP plasma applications have, in most recent times, been focused on the aerospace field (e.g., RAM jets, SCRAM jets, supersonic combustion). Pulsed plasma-based ignition has proven to be effective in supporting the development of chain oxidation mechanisms (i.e., fuel-burning and flame propagation) that contribute to decreases in ignition delay-time and a more-uniform spatial distribution of combustion. A technique, reported by Wang et al [68], for applying pulsed corona to an aerospace combustion chamber (e.g., a pulse-detonation engine) is shown in Fig. 5.

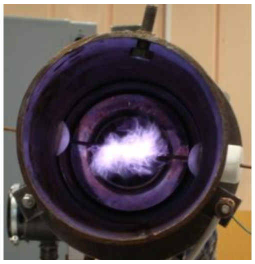

Fig. 4. Photograph of an RF igniter in operation (~ 1 mHz), after Klimov et al [67].

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), fast rise-time pulses (~ 10 kV/ns) to combustion processes, particularly aviation, aerospace and supersonic applications, that create a more spatially-uniform and fast volume ignition have been reported by Starikovskaia et al [58] and Starikovskii et al [45], and Do et al [59]. Fast-pulse discharge ignition has also been applied to automotive applications for improving engine stability and fuel mileage [60, 61].

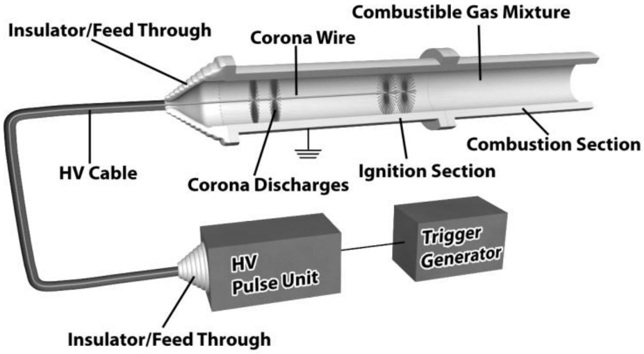

Fig. 5. Artist's conception of pulsed corona ignition scheme for an aerospace (pulsed detonation) engine, after Wang et al [68].

B. Flame Stabilizers

Flame stabilization can be accomplished by grossly heating a combustible gas mixture, aerodynamic effects (e.g., turbulent, 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 especially 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 re-ignition and lean-burn combustion for reduced pollution emissions. Ignition and stabilization sometimes overlap, e.g., better ignition can seed better, more-uniform volume combustion. So work on ignition can, in some aspects, fall into both stabilization and ignition categories.

Criner et al [69] have presented evidence that the stabilization of a turbulent partially premixed flame of more than 10 kW can be enhanced by pulsed high-voltage, DBD discharges with power consumption less than 0.1% of the power of the flame.

Other researchers have also demonstrated the benefits of pulsed discharge ignition and flame stabilization. Kim [69] compared three types of discharges for flame stability improvement. These included a single-electrode corona discharge, an asymmetric dielectric-barrier discharge (DBD), and a repetitive ultrashort-pulsed discharge. The degree of non-equilibrium of the pulsed discharge was found to be higher than that for the DBD. The pulsed discharge caused the most significant improvement in flame stability. In [69], it is also mentioned that the stability limit of a swirl-stabilized methane/air-premixed flame could be extended with a repetitive ultrashort-pulsed discharge beyond the thermochemical lean flammability limit of a methane-air mixture.

Galley and Pilla et al [71] also observed a stability-limit extension using a repetitive ultrashort-pulsed discharge for a bluff body-stabilized premixed V-shaped flame [72]. As described by Pancheshnyi and Anikin et al [73], applied a repetitive ultrashort-pulsed discharge toimprove the ignition of a propane/air mixture at high pressure [74]. Lou et al [75, 76] showed evidence for a significant preflame oxidization of methane/air and ethylene/air mixtures when ignited with an ultrashort repetitive pulsed discharge.

C. Plasma Jets/Torches for Combustion Stabilization

Plasma torches of interest to us can be classified into two general types: continuous and pulsed. Historically, the continuous form (as illustrated in Fig. 1) was developed first and 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 operate in very lean burn regimes, conditions under which the flames normally tend to extinguish. Continuous plasma torches have also been shown to be useful in reducing the generation of soot in flames and in reducing emissions of oxides of nitrogen (NO_x). In roughly the past forty years, the pulsed type has become the preferred form of plasma torch. For 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, the well-known Zeldovich mechanism [77], by which NO is produced in high-temperature combustion.

One author of this chapter (IBM) developed continuous-operation torches for ignition and flame control in gas turbines for natural gas pumping stations in 1980-1985 [18, 78]. A proven application of newer, continuous, plasma torches is a pilot (igniter, burner) device for the stabilization of lean-burning flames [47, 48 and citations therein], because the plasma-chemical effects dominate aerodynamic effects. Weinberg et al, and references therein [6, 44], have shown a required 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 stability and/or prevent flame/combustion blow-outs.

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 engines (both gasoline and diesel) to curb NO_x and unburned-hydrocarbon emissions. Cold start is where most IC-engine pollution emissions occur. Burners, furnaces, and incinerators also benefit from quick ignition (from the point of view of safety and efficiency). The relighting of flamed-out gas turbine engines on aircraft is also a very useful and important application for these devices.

D. Non-Equilibrium Plasma Flame Stabilization

In this section, we provide two illustrative examples of non-equilibrium plasma-enhanced combustion, namely the influence of DC corona and dielectric barrier discharges on flame stability (particularly lean-burn conditions).

Into the early 1970’s, Bradley et al had published results concerning research on the exchange of electron energy with other species in flames subjected to external electric fields. These studies concluded that ohmic gas heating and selective excitation of some molecular energy levels would occur under energetic-electron conditions, thus leading to increased rates of chemical combustion. In the early 1980’s, these researchers applied this concept to a methane-air flame burner [79]. To enhance the electric field in the flame region, they used metal points (much like sharpened triangles) at the exit of the metal-tube burner (see Fig. 6).

It was found that with negative corona at the points, an increased gas flow rate could be achieved before the flame experienced 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 the presence of a corona plasma. This experiment clearly demonstrated the effect of non-equilibrium plasma on flame stabilization.

One of the authors of this chapter (LAR) and his collaborators have carried out tests on the cracking of hydrocarbon fuel gases, flame stabilization under lean-burn conditions, and flame propagation speed using a non-thermal plasma source [80-82]. Fig. 7 shows a setup for determining the influence of dielectric-barrier-discharge (DBD) generated plasma on the blowout limit of an activated-propane-air flame (i.e., ultra lean-burn conditions). Co-flow air, going through the center tube of the reactor, was mixed with plasma-activated propane at ~ 1.5 cm from the top of the plasma region – and this mixture was then ignited. The applied voltage AC frequency was about 450 Hz. Blowout tests were conducted by holding the propane flow constant and increasing the air flow rate until the flame was extinguished. The blowout air flow rate is a primary indicator of flame stability, and the high blowout air flow rates achieved in these tests shows that combustion continues to occur under very lean-burn conditions (equivalence ratio $\varphi < 0.2$).

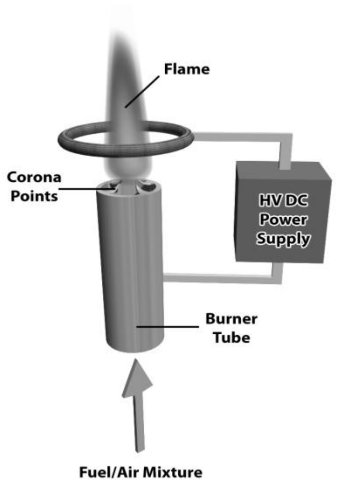

Fig. 6. Corona-influenced burner, after Bradley & Nasser 1984 [79].

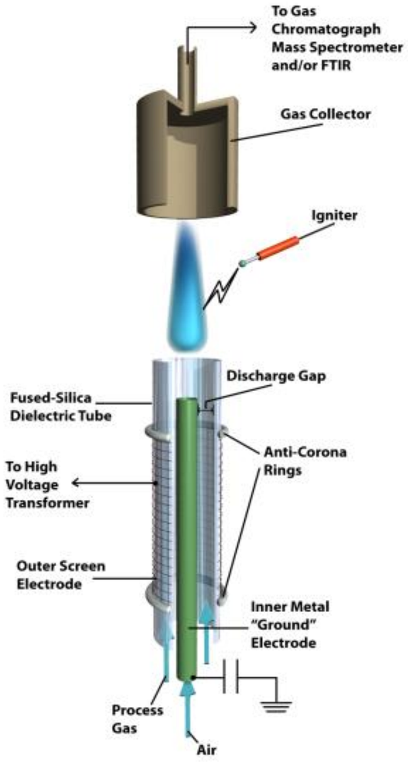

Fig 7. Illustration of a DBD device for lean-burn experiments, after Rosocha et al [80-82].

Y. Kim et al [83] carried out experiments that separated the physical electrical effects of an electric field (e.g., ionic wind) from the plasma-chemical effects on a flame, using apparatus similar to that shown in Fig. 7. This work showed that the plasma was responsible for extending the lean-burn limits of a propane-air flame, where propane was activated by the plasma before being mixed with air and ignited; i.e., combustion occurred away from the plasma and electric field regions. Flame flashback images were recorded as a function of the separation distance between the propane plasma termination and the point of injected air, and the mixing length of the activated propane-air mixture. The effective lifetime of activated propane (i.e., the time when it has a significant effect on the flame) was found to be about 150 ms, while the lifetime of activated propane mixed with air was measured to be about 300 ms. Using a gas-chromatograph diagnostic, stable H_2, CH_4, C_2H_2, C_2H_4, and C_2H_6 were identified as the principal propane-discharge fragments; however, these did not appear to be the dominant species causing flame flashback behavior because their measured concentrations depended very weakly on the distance from the plasma region termination to the point where the activated propane was mixed with air. Because of this, the presence of reactive radical species was suggested to be a main factor governing flame flashback. In particular, because the effective lifetime of plasma-activated propane which is subsequently mixed with air has a larger value (300 ms), it was surmised that reactions between hydrocarbon radicals and molecular oxygen is a driving factor in the observed combustion enhancement.

Using a DBD applied to a premixed methane diffusion flame, Vincent-Randonnier et al [17] investigated the effects of such a discharge on flame structure and detachment height, the height being reduced with the plasma.

E. Hybrid Plasma Devices for Combustion Stabilization

Certain types of plasma pilots (i.e., ‘pilot’ in the sense of a pilot light on a stove) and flame sustainers – hybrid plasma devices - have two main functions – ignition and continuous flame control [47, 48]. The application-specific needs of continuously operating in a high temperature environment with variable pressure pilots and flame sustainers have motivated PAC research to develop non-thermal plasma sources with significantly extended lifetime and lower power consumption – characterized by pulse power devices, direct arc initiators, and microwave (MW) initiators. Presently known plasma pilots operate with an average power range of 50-500 W, pressures of 10-15 bar, and provide continuous operation for approximately 1,000 running hours. Hybrid devices are frequently based on systems that combine aspects of both equilibrium and non-equilibrium plasmas, in which a few cases will be discussed below.

F. ‘Glid-Arc’ Discharges

This type of electrical discharge, historically called the ‘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 further developed and reported for flame-heating enhancement, removal of air pollutants, and hydrocarbon conversion into synthesis gas by Czernichowski [84]. A glid-arc device usually consists of two or more diverging-gap metal electrodes connected to a DC power supply. A gas to be processed is quickly flowed upward through the space between electrodes, whereby upward-moving electrical discharges process the gas. Because the arc is constantly moving over the electrode surfaces, electrode wear can be much reduced at high plasma power levels.

By changing the linear, upward 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 [85]. A modification of this idea and its application to combustion enhancement is discussed below.

G. ‘Plasma Tornado’/Vortex Combustors

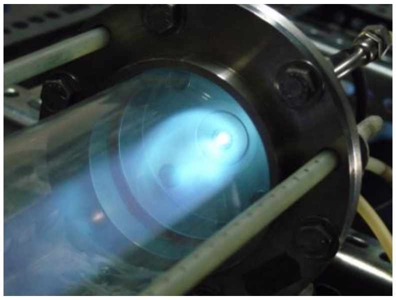

Fig. 8. Photograph of a working reverse vortex combustor with plasma assistance, after Matveev & Serbin [86].

Diverging electrodes in the approach mentioned above are used to stabilize the electrical discharge (i.e. prevent a fixed hot arc between single electrode points). These electrodes 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. Such a device has been described and modeled by Matveev and Serbin for the purpose of exploring improved gaseous-fuel combustion [86, 87]. Modeling and initial experiments indicate that such a combustor can increase fuel efficiency and reduce CO_2 emissions [87]. 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 combustor walls. Fig. 8 shows a photograph of a reverse-vortex plasma-assisted combustor.

H. Plasma Tornado/Reverse-Vortex Combustor Incorporating Microwaves

An attractive, prospective MW system for ignition and flame control in a reverse vortex combustor has been developed by one of the authors (IBM) and the Moscow Radio Technical Institute [88]. Photos of the electrical discharges inside such a device are presented in Fig. 9. A volumetric MW discharge on the fuel-nozzle tip of the combustor was formed, as shown by the photos.

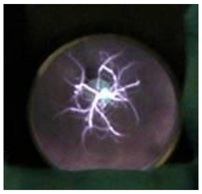

Fig. 9. Photos of subcritical MW discharges in a reverse vortex combustor, [81].

I. Plasma Fuel Nozzles

A plasma fuel nozzle is a combination of a plasma source and a fuel atomizer, such a combination providing simultaneous fuel atomization, ignition and flame control in one unit [48, 89, 90]. It is one of the most complicated and advanced solutions for many plasma assisted combustion applications, ranging from gas-turbine ignition/re-ignition and combustion stabilization to boilers and furnaces for heavy and contaminated fuel burning. Several experimental nozzles for gaseous and liquid fuels with flexible-fuel operation and the incorporation of steam are currently under development in one of the authors (IBM) laboratory. The main advantages of these nozzles are: (a) dramatically increased ignition reliability, (b) much wider equivalence ratio - φ, λ stable operational range, (c) significant decrease in gas turbine rotor inlet temperature jump at the time of fuel ignition, (d) the ability to serve as a pilot/sustainer burner, (e) application to hydrogen-enriched gas generation, (f) reduction in combustion zone volume, (g) reduction of the combustion chamber wall temperature, (h) increase in combustion efficiency, (i) achievement of smokeless operation, (j) simultaneous burning of several fuels, (k) smooth regulation in a wider power turn-down ratio. An example plasma fuel nozzle for gaseous fuel combustion in a gas turbine is shown in Fig. 10.

Fig. 10. Photograph of DC-excited plasma fuel nozzles, after Matveev et al [48, 89, 90].

J. Spatial-Arc Devices

A device invented by one of the authors (IBM), the so-named *spatial arc* is an example of recently patented applications [48, 91-93] of a non-thermal, high voltage discharge that orbits inside a combustion chamber and serves as an ignition source and a flame controller/stabilizer. This arc employs the combustor walls as electrodes and has average power consumption from 10 W to 1 kW. It provides a simple and energy-efficient solution for gas-fired furnaces and combustors, particularly in lean-burn modes [91, 92]. A lab-scale combustor prototype incorporating a low-power spatial arc is shown in Fig. 11.

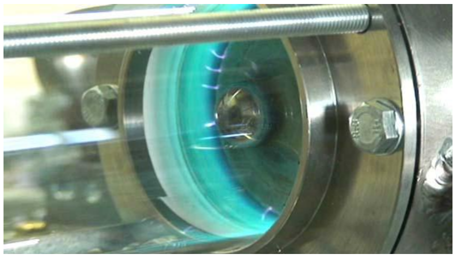

Fig 11. Photograph of a DC-excited reverse vortex combustor with 10 W spatial arc, after Matveev et al [91-94].

K. Fuel Reformers and Gasifiers

In the literature, one can find many publications devoted to fuel reformation [32, 33, 48, 55] and coal gasification [48, 51]. In this section, we present a few selected 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 the literature that the main obstacles confronting full-scale gasification technology development and implementation are the lack of energy efficient plasma sources with reasonably long lifetimes and affordable operational costs. For example, existing coal ignition and partial gasification technologies [48] employ 100-200 kW DC torches with very limited cathode lifetimes of approximately 200 operating hours. At this time, similar situations apply to all other commercial plasma torches. This means that any significant improvements in lifetime and cost will result from the development of new generations of high power atmospheric pressure plasma sources and power supplies. Based on known plasma generation analyses, one of the authors (IBM) has selected for further development and implementation an type RF plasma torch with reverse vortex flow [49, 53, 93, 94]. Such a device could provide for atmospheric and even above-pressure plasma reactor operation. This type of solution allows virtually unlimited lifetimes for both the electrical and plasma generation modules and also high caloric value of produced syngas, based on an oxygen or steam gasification process. The maximum achieved power level per RF plasma unit is currently 1.8 MW and is expected to increase to 10 MW.

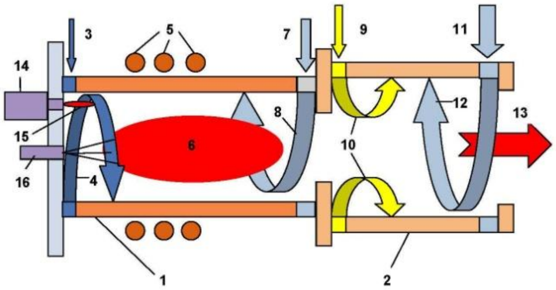

Fig. 12. Plasma-based gasifier for liquid and solid feedstock, after Matveev et al [93, 94], US Patents 7,452,513 B2, 8,252,243 B2.

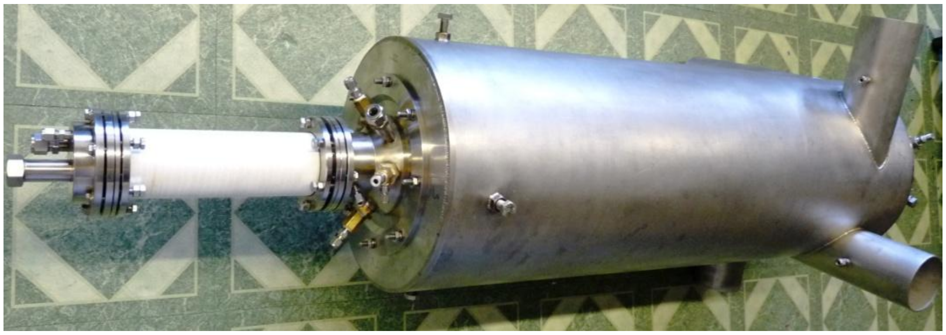

Fig.13. Photograph of a plasma-assisted gasifier for contaminated liquid hydrocarbon destruction.

One of the gasifiers recently developed by one of the authors (IBM) is shown in the scheme in Fig.12. An actual system for 100 liters per hour contaminated liquid hydrocarbons plasma gasification and further combustion is demonstrated in Fig. 13. It combines a 50 kW plasma RF torch with feedstock delivered into the plasma plume at a gasification stage with further syngas clean combustion in a two-stage burner with reverse vortex flow.

L. Waste Processors and Converters

The conversion of waste into energy is vital for both developed and developing countries, but still not feasible for many because of the high capital and operational costs for existing plants and the cost of implementing high productivity plants with capacity over 250 tons per day. Significant reductions in the operational costs could be achieved by: (1) application of RF 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) multi-feedstock operation to process waste from scrap tires, municipal solid waste (MSW), industrial wastes, coal and electronic waste [48, 50]. One can consider the possible integration of the MSW modules with coal-fired utility power plants, which is expected to reduce the cost of ownership and the minimization of emissions, including dioxins and furans.

Here, we provide some background economic information on the above-mentioned systems. A feasibility study for implementing such a waste-into-energy conversion technology for the city of Austin, Texas has been carried out by one of the authors (IBM). Austin has a population of about 775,000 residents, 594,220 tones per year of generated waste, and a tipping fee (waste disposal fee) per household of $25 per month. The expected cost of a waste-to-energy conversion facility is $350 million and the expected return on investment ranges from 4 to 5 years, depending on the sale price of the generated electricity. For the case of converting all annually generated MSW in the US into energy, the net power output could be up to 326 million MW. That could amount to over 6% of the US power demand. Existing landfill recycling could supply an additional 1 to 5% over the above figures. The estimated cost of a single waste-to-energy facility, based on equipment ownership prices, is about $115 billion.

IV. Outlook and Conclusions

Progress in plasma sources over the past two decades, coupled with industrial and societal demands for more energy-efficient and cleaner combustion and waste processing methods, has led to the development and implementation of a variety of plasma based techniques for combustion enhancement, fuel reformation, and gasification. Plasma Assisted Combustion is now a quickly growing field of science with an annual forum – the International Conference on Plasma Assisted Technologies (ICPAT), a Special Issue on Plasma Assisted Combustion under the IEEE umbrella; and the International Plasma Technology Center; on one hand stimulating and coordinating progress in such areas as plasma physics, electronics, and materials science; and on the other hand providing extraordinary opportunities to make progress in power generation, propulsion (autos, aircraft, watercraft), new material sintering, surface modifications, and environmental protection (air, water, soil).

An anecdote provides some information to the reader about how international and cross-disciplinary cooperation can strengthen the PAC field. In January 2005, one of the two authors of this chapter (IBM) demonstrated plasma igniters that were recently developed around that time [95] to a group of Russian scientists in his laboratory in Virginia. Interest was raised by the very low power consumption of the device. One of the attendees, Professor Yuri Korolev (Institute of High Current Electronics – Tomsk, Russia), suggested examining the igniter discharge behavior by means of oscillograms. This marked the day of the so-named glow-to-spark transition discharge discovery in these types of igniters. That was followed by several years of successful joint investigations. Later on due to the efforts of the authors of this chapter (IBM and LAR) and the efforts and programmatic support provided through Ms. Olga Martin from the Los Alamos National Laboratory (US Department of Energy Program on Proliferation Prevention), Professor Korolev and his Institute of High Current Electronics of the Russian Academy of Sciences were granted a three year US government, financially-supported project to develop a range of power supplies for PAC devices based on such a discharge.

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