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Plasma Assisted Combustion: A Review

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Abstract:
Plasma assisted combustion (PAC) is a newly growing field and a promising technology which has attracted many researchers to explore the effect of PAC on combustion control, combustion enhancement, flame stabilization and so on. This paper presents the history of PAC, its properties, types, effects and applications. In space propulsion, plasma thrusters are challenging the monopoly of chemical thrusters. Helicons is the highly efficient source of plasma and being used in plasma propulsion applications. In this paper we discussed why non-equilibrium plasma is preferred over equilibrium plasma. PAC is used for ignition enhancement in SCRamjet, IC and SI engines and PDE along with its several applications in gas turbine engines.

***Key Word**: Plasma Combustion; Ignition; Flame Stability; ScramJet*

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I. Introduction

Today, more than 80% of world energy is converted by combustion. Because of the high energy density of liquid fuels and the advantage in fast refueling, combustion has been playing a dominant role in air transportation. However, the energy conversion efficiency of existing combustion engines is still low, and the combustion of fossil fuels has become a major concern due to its influence on air pollution and climate change [1].

Plasma, which is the fourth state of matter, provides a unique opportunity for combustion and emission control because of its unique capability in producing active species and heat and modifying transport processes. To modify the fuel oxidation pathways considerably, New reaction pathways can be introduced into combustion systems such as atomic O production from the collisions between high energy electrons/ions and oxygen molecules.

Plasma has been demonstrated as a promising technique for enhancing combustion, reducing emissions, and improving fuel reforming, in the last two decades [2-9]. In high-speed propulsion such as scramjet engines, since the pioneering work of Kimura et al. [10] in 1980s, recent studies using plasma torch [7,11-16], filamentary discharge [8,17], microwave discharge [18], low frequency arc discharge [19], streamer high frequency (HF) discharge [20], surface discharge [21], and nanosecond pulsed discharge (NSD) [22] have showed that plasma can enhance flame stabilization, ignition, and fuel/air mixing via chemical, thermal, and plasma induced aerodynamic effects. Recent studies [23-28] have also shown that plasma discharge in pulsed detonation engines (PDE) can minimize the ignition delay time, and facilitate the transition from deflagration to detonation. In applications for gas turbine engines, pulsed and steady plasma jets [29], gliding arc [30], DC electric field [31], and HF streamer discharge [32,33] have been tested to increase flame stabilization. The results have demonstrated that plasma discharge has capability to extend lean flammability limit and lower lean blowout limit. For internal combustion engines, effective demonstrations of plasma assisted ignition and combustion have been achieved by using single and multi-spark discharges [38], radio frequency discharge [39], microwave discharge [34-37], laser ignition [40-44], and corona and nanosecond pulsed discharge [45-47].

In addition to combustion enhancement, plasma has also been used in emission control [48]. Studies have shown that NOx emission can be effectively reduced by using a pulsed corona discharge [50-52], gliding arcs [48], dielectric barrier discharge [53,54], and plasma jet [49]. Recent studies have extended plasma emission control to remove SOx [48,55,56] and unburned hydrocarbons (e.g., toluene and naphthalene) [57,58] in flue gas as well as soot formation in the exhausted gas of diesel engines [59-62]. Acetylene (C_2H_2), formaldehyde (CH_2O) , and high hydrogen syngas, can also be produced from methane (CH_4), large hydrocarbons, and biofuels by using low temperature plasma for accelerating the non-equilibrium kinetic process to maximize chemical yield. Plasma reformers have the advantages of high energy efficiency, fuel flexibility, lower cost, and being fast and compact as compared to conventional catalysts and steam reformers, [63]. Successful demonstrations of plasma assisted hydrogen production from hydrocarbons have been conducted by using a gliding arc [65-68], nanosecond pulsed discharge [72], thermal plasma [64], dielectric barrier discharge (DBD) [69,70], and microwave discharge [71]. Recently, low temperature cool flames have been successfully stabilized to reform large hydrocarbon fuels such as n-heptane ($\square\square_{7}\square_{16}$) and dimethyl ether (DME,$\square\square_{3}\square\square\square_{3}$) to $\square_{2}\square_{4}$, $\square\square_{2}\square$, $\square_{2}$ and CO [73,74] with no carbon deposit by using nanosecond pulsed discharge and DBD.

Although the above studies have demonstrated the effectiveness of plasma in fuel reforming, combustion as well as emission control, it remains unclear what kind of plasma is the best option for combustion enhancement in a given environment. Furthermore, detailed plasma-combustion chemistry is not well understood. Quantitative kinetic modeling remains difficult even in one-dimension. In addition, due to the large variation of plasma properties and complicated interactions between plasma, combustion chemistry, and transport processes and aerodynamics, it is even more difficult to know whether the observed enhancement is only because of the thermal effect or favorably by the kinetic effect. For instance, there has been a debate on whether a non-equilibrium plasma discharge can kinetically enhance flame speed and flammability limit or can only promote ignition. Many controversial results have been stated. It is not clear what are the important kinetic pathways, radicals, and excited intermediate species in plasma assisted combustion. There are many fundamental questions behind the plasma “magic” which are unanswered. For example, how does the kinetic pathway of plasma assisted combustion depend on plasma properties, temperature, and fuels? What is the role of plasma if a fuel has low temperature chemistry? How does plasma chemistry affect combustion chemistry, properties and so on? It is necessary to answer these questions for the fundamental understanding of plasma properties and plasma assisted combustion chemistry in well-defined physical and chemical conditions [75].

II. History Of PAC

Plasma-assisted combustion is the newly growing field and very limited research has been done on this particular concept. Using plasma in different forms for combustion and ignition is the main objective of this field. so, many scientists discovered various properties of plasma in various conditions in the past and till now the research has been going on.

In 1981, they showed that If the position of injection is appropriate then for flame stabilization and also for promotion combustion, the injection of plasma produced with the help of relatively small electrical power is highly effective. The wind tunnel they used had a very low heating capacity that’s why the experiment was restricted to low static temperature. [76]. As the reaction occurred in the probe that’s why they didn’t use a conventional total temperature probe [80]. In 1998, They scrutinized the breakdown of a high-voltage nanosecond in the form of a fast ionization wave (FIW) in large discharge volume fast ionization wave which offers great advantages over the other types of discharge. They showed that by using various shapes of electrodes, we can feasibly make non-equilibrium plasma in larger quantities [77]. In 2013, Low energy and high peak intensity (>100TW/$\square\square^{2}$) femtosecond laser pulses were inspected for directing and controlling sub-microsecond high voltage Discharge [78]. A weak ionized filament was formed at 120 femtosecond laser pulse where the breakdown was initiated in a high voltage electrode gap and likewise so many experiments were carried out for the study of lightning protection. The scale was the main difference between this work and previous work of lightning protection and filaments were initiated where the mechanism of leader breakdown was critical [81-85]. In the laser and high voltage pulses, the guiding effect of breakdown was observed for notably longer delay times than previously reported in another case study [81-84] [86-89]. In 2015: They used n-heptane by adding ozone to establish self-sustaining cool diffusion flames with well-defined boundary conditions [79]. Nearly 2 centuries ago cool flames were accidentally observed [90,91]. They also tested the most recent models of n-heptane [92,93], but no improvement in the $\square_{2}\square_{4}$ and $\square\square_{4}$ was noticed. Three different types of flame regimes were detected: (1) cool diffusion flames, (2) hot diffusion flames, and (3) unstable cool diffusion flames which were formed from the direct initiation by ozone, but are found unstable [79].

III. Properties Of Plasma Assisted Combustion

In understanding the mechanisms of plasma-assisted combustion in various forms including hydrocarbon-containing mixtures fair progress has been made over so many years [94].

The extremely non-equilibrium excitation of the gas in the discharge plasma is the main and variation between common combustion and plasma-assisted combustion [9]. Considerable progress has been made in understanding the mechanisms of plasma–chemistry interactions, energy redistribution, and the non-equilibrium initiation of combustion. Using different types of discharge plasmas so many different types of fuels have been examined [96].

Gas ionization is the main process occurring in plasma [102]. By performing experiments under controlled conditions and by comparing their results with numerical simulations of the discharge and combustion processes the mechanisms of plasma-assisted combustion were validated [102]. The excited level population rate in the discharge is completely dependent upon the electron energy. The lowest energy electrons are the major requirement of the excitation of rotational degrees of freedom [102]. The average electron energy in a gas discharge is determined by a reduced electric field, E/n, where E is the electric field and n is the gas density [101]. A non-equilibrium electron energy distribution function (EEDF) formation is nearly equal to E/n approximately 0.1 Td for atomic gases and E/n approximately 1 Td for molecular gases E/n approximately 1 Td (1 Td = 10−17 V □□^{2}). A non-equilibrium EEDF is the solution of the Boltzmann equation [101]. To initiate combustion or to stabilize a flame there are so many types of mechanisms that affect a gas when using discharge plasma [101]. There are two types of thermal mechanisms: the homogeneous heating is used for acceleration of the chemical reactions and inhomogeneous heating of the gas due to vibrational and electronic energy relaxation and also due to hot atom thermalization. The inhomogeneous heating produces flow perturbations, which assist in increased turbulence and mixing [95]. From the spectroscopic viewpoint, experimental plasmas are of two types. First, the plasmas whose main purpose is to proceed as a controlled source of radiation for the measurement of atomic parameters. Second, there are the plasmas which are controlled thermonuclear fusion devices [103]. In space propulsion plasma thrusters are challenging the monopoly of chemical thrusters, and also the space plasma thrusters are being proposed for non-propulsive applications. Real plasma thrusters ionize all the gas which is injected in them and the Plasma propulsion uses electric energy to ionize the propellant and transmit kinetic energy to the resulting plasma. Plasma thrusters are composed of a vast community of devices like commercial thrusters to under-development laboratory prototypes. There are so many devices that can produce thrust and also eject plasma, for an ample set of characteristics a competitive plasma thruster must bear good figures [104]. The highly efficient plasma source is Helicons and is being used for application in plasma propulsion [105]. To control ignition and flame stabilization in engines and high-speed propulsion systems plasma provides very promising solutions [106-108]. Many studies of plasma-assisted combustion focused on ignition and flames involving high-temperature chemistry (above 1100 K) [106–111, 112–114]. At atmospheric pressure, plasma discharge accelerates the cool flame chemistry and allows the initiation of self-sustained diffusion and premixed cool flames [115,116]. Recent experimental study reviews for non-equilibrium plasma-assisted ignition and combustion can be found in the literature [94-100].

Equilibrium Plasma

Thermally equilibrium plasma for combustion control has been used for more than 100 years for IC engines and spark ignition systems. But recently interest is increasing for the Use of non-equilibrium plasma for ignition and combustion control [117-119]. The electron temperature, rotational and vibrational temperatures of particles are in equilibrium and the neutral gas temperature and electron number density are very high in the equilibrium plasma [120]. non-equilibrium plasma has a higher electron temperature (1e100 eV) than equilibrium plasma, and non-equilibrium plasmas are more kinetically active due to the rapid production of active radicals and also the exciting species via electron impact dissociation, excitation, and subsequent energy relaxation [121,122]. spark and arc discharges are close to equilibrium plasmas between the different types of plasmas [120]. Both equilibrium and nonequilibrium plasmas both are potential sources of vacuum-ultraviolet radiation (VUV) [123].

Non-equilibrium Plasma

Non-equilibrium excitation of gas in the discharge plasma is the main dominant difference between simple combustion and plasma-assisted combustion [124].

For a wide range of applications, including aviation GTEs, piston engines, ramjets, scramjets and detonation initiation for pulsed detonation engines, nonequilibrium plasma shows an ability to control ultra-lean, ultra-fast, low-temperature flames and appears to be an extremely promising technology. To use nonequilibrium plasma for ignition and combustion in real energetic systems, then we have to know the mechanisms of plasma-assisted ignition and combustion and be able to numerically simulate the discharge and combustion processes under so many various conditions.

Radical generation by a nonequilibrium plasma in front of the flame can be divided into two different processes. Firstly, it involves the flow excitation by the plasma away from the flame front. In this phenomenon, only relatively stable radicals and intermediates can reach the region of intense reactions in the flame front, while the short-lived components, with lifetimes shorter than the transport time, are not directly involved in the process. The second process requires excitation of the gas directly at the flame front in which all active particles are produced directly in the region of the initiation of the chemical reactions in front of the flame.

In conjunction with the heating, 100e1000 ppm is the concentration of active particles in weakly ionized nonequilibrium plasma, acceleration of the flame propagation and forming of chemical chains ahead of the flame front is because of those active particles. We can get vacuum ultraviolet radiation (VUV) from equilibrium and non-equilibrium plasma in large amounts. We can stabilize ignition favourably at high altitudes and low dynamic pressures and temperatures by using nonequilibrium plasma [125]. So much work has been done recently to get the knowledge of the role of plasma-generated species on the ignition, flame stabilization, and also extinction. For further ignition studies, the reduction of ignition temperature was insured and examined in a counterflow burner with the activation by a magnetic gliding arc [126]. The catalytic effect of NOx on ignition boosting was examined quantitatively [130]. in Refs [127,128] The reduction of ignition delay time by a non-equilibrium plasma discharge was also measured.

We can decrease the ignition delay times by about an order of magnitude. They observed an increase in atomic oxygen concentration and was used as an explanation for the decrease of ignition delay times [130]. More than high-temperature combustion, non-equilibrium plasma can kinetically enhance low-temperature combustion. To accelerate low-temperature ignition and fuel oxidation, non-equilibrium plasma is an effective way, as a result allowing the establishment of stable cool flames at atmospheric pressure. Non-equilibrium plasma having a proper kinetic enhancement effect on ignition and flame stabilization also. The radical production process by electrons, ions, and electronically and vibrationally excited molecules in non-equilibrium plasma is faster than that of the key chain-branching processes of combustion particularly at low and intermediate temperature; thus, it can also dramatically shorten the ignition delay time [129].

IV. Effects Of Plasma On

1.Ignition

Thermal equilibrium plasma condition for combustion control originated hundred years ago with IC engines and spark ignition systems. These principles lead to high efficiency for various applications. Recently, scientific researchers have become interested in non-equilibrium plasma for ignition and combustion control [131,132] because of the new ways of approach for ignition and flame stabilization that are provided by the plasma-assisted approach.

Ignition control in quiescent gases: Ignition in methane air mixtures has been obtained by using low-energy seed-laser pulses and an overlapping subcritical microwave pulse [133]. There is a fact that Extremely weak ionization by a laser could localize the microwave heating pulse. This was observed using Schlieren and shadowgraph imaging to record the heating intensity, the scale of the interaction and to confirm ignition. In the paper [134] the efficiency of ignition by a high-voltage repetitively pulsed nanosecond discharge (up to 10 kV, 10 ns,30 kHz) for propane air mixtures of various compositions has been studied for stoichiometric and lean mixtures having pressure range 0.35 to 2.0 bar.

Development of predictive plasma-assisted ignition/combustion chemistry mechanism: Kinetic mechanisms of ‘conventional’ combustion [135,136] have been determined and validated for high temperature conditions and are not applicable at low temperatures typical for many plasmas assisted combustion environments. In low-temperature plasma-assisted ignition, these metrics are clearly insufficient as they have to be correlated with measurements of parameters controlling both plasma chemistry and conventional chemistry reactions, such as the number densities of key radical species and temperature in the plasma. The species number density measurements using laser diagnostics requires significant signal accumulation which requires the use of well-reproduced, repetitively pulsed plasma ignition cycles [137].

Plasma-assisted combustion above the self-ignition threshold: The kinetics above the self-ignition threshold is relatively better understood for hydrogen and small hydrocarbons. In the paper [138,139] the combined excitation of the combustible mixture by shock wave and fast ionization wave was proposed.

2. Flame Propagation

Some experiments reported that plasma boosted both the ignition and the lean burn limit. Other results showed that plasma had less impact on flame propagation speeds. Some experiments showed that the plasma enhancement was due to thermal effect, while others demonstrated enhancement effects via kinetics and transport (e.g., ionic wind). The experimental results of Wolk et al. [140] clearly showed that the use of microwaves had a better enhancement effect in oxygen rich operating conditions than that in fuel rich conditions and that plasma improved ignition kernel development but except flame speeds.

Dynamics and chemistry of plasma assisted ignition: At a critical temperature of the chain-branching limit, ignition occurs where both the concentration of radicals and the temperature of the reaction system increases exponentially. If we consider a diffusion-controlled system, once ignition occurs, a flame with higher temperature will be formed. If the fuel concentration decreases or the heat loss of the reaction system increases in a particular flame, the flame temperature decreases. Once the flame temperature decreases to a critical temperature, the chain-termination process becomes faster than the chain-branching process and thus the flame extinguishes. This is the called ignition to extinction S-curve [141,142].

Dynamics, chemistry, and transport of plasma assisted flame propagation: A flame is usually defined as an exothermic self-propagating, thermal diffusion driven auto-ignition front. The burning velocity of a premixed flame is a function of fuel oxidation, transport properties, adiabatic flame temperature, heat and mass losses. The theoretical and experimental determination of the limits have been conducted for several decades

[141,142,143,144]. It has been concluded that the radiation heat loss from the flame is the reason for the flammability limit [145,146].

3. Minimum Ignition Energy

In many unsteady combustion processes such as the internal combustion engines and PDE engines, a plasma-initiated ignition process involving unsteady transition from spark ignition to propagating flame is essential. It was shown that the minimum ignition energy (MIE) increased at both lean and rich sides and had its minimum near the stoichiometric condition. Moreover, the fuel molecule size and diluents also affected the MIE. However, recently the mechanism of the MIE has been understood theoretically and experimentally [147,148,149,150]. These studies have shown that a successful flame initiation depends on critical flame initiation radius, which means only the spark which can drive the flame kernel to a size greater than this critical flame initiation radius, can cause successful ignition. Recently, the critical flame initiation radius was measured for hydrogen and other hydrocarbon fuels [149,150]. It is seen that similar to the theoretical results in the flame kernel speed decreases first then reaches a minimum, and finally increases back to the adiabatic flame speed as it propagates outside. Fortunately, at fuel rich conditions, the critical radius decreases significantly due to the decrease in the mixture Lewis number for large hydrocarbon fuels. In addition to this the critical radius decreases with the increase in pressure. These conclusions explain that the ignition enhancement decreases both in fuel rich conditions. It is seen that the minimum ignition energy depends monotonically on the mixture Lewis number. The larger the Lewis number, the larger the minimum ignition energy.

V. PAC Application Specially On SCRAMJET Engine

The major challenges faced in supersonic ramjet engines for hypersonic propulsion are fuel/air mixing, ignition, flame stabilization, and cooling [151,152]. At a high Mach number, the flow residence time in the engine is even shorter than the typical auto-ignition time of jet fuels at 900 K [153]. Moreover, even when the fuel is ignited, the flow residence time may still be shorter than the time for the fuel to be completely combusted (tc). Therefore, both the ignition and combustion are less than unity. The earliest attempt to use a plasma torch to enhance ignition in a supersonic flow was attempted by Kimura et al. [154]. Since then, a large number of experimental studies have been carried out to control ignition in a supersonic flow by using different plasma torches [155,156,157,158]. Recently, Matsubara et al. [159] extended the plasma torch ignition by combining it with a Dielectric Barrier Discharge (DBD) in a supersonic flow.

VI. Applications

Ignition enhancement by plasma in internal combustion engines: Over the last decade, plasma assisted combustion has attracted increasing attention for applications in internal combustion engines such as gasoline and diesel engines [160,161]. In spark ignition (SI) engines, the development of the initial spark ignition kernel size strongly depends on the lean burn limit and emission characteristics. In order to improve the ignition of SI engines, different plasmas such as microwave [160,162] NSD [161], and gliding arc [163] have been used to integrate with a conventional spark plug.

Plasma assisted combustion for pulse detonation engines: Since plasma can boost ignition, non-equilibrium plasma has also been tested to accelerate deflagration to detonation transition in pulse detonation engines (PDE) [164]. Cathey et al.[165] summarized the collaborative work between USC and Naval Postgraduate School (NPS), Stanford University, and AFRL at Wright Patterson AFB on TPI to accelerate ignition in pulse detonation engines. It was demonstrated that at high flow rates where spark-initiated flames were normally extinguished, the transient plasma was able to ignite and effectively create a detonation wave in the PDE experiment at NPS. Recently, Lefkowitz et al. [166] studied the effect of high-frequency nanosecond pulsed discharges on PDEs.

Plasma assisted combustion for flame stabilization in gas turbine engines: Lean blowout limit, flame stabilization and instability are the main issues of gas turbine engines. Plasma is used as a new technology to increase the flame stability and achieve ultra-lean combustion. Serbin et al. [167] claimed that a gas turbine combustor with piloted flame stabilization by non-equilibrium plasma can provide better performance, wider turndown ratios, and lower emissions of carbon and nitrogen oxides. However, details were not discussed in the paper. Moeck et al. [168] studied the effect of nanosecond pulsed discharge on combustion instabilities at 1 atm.

Emission control and fuel reforming by plasma: Plasma has been widely studied for reduction of soot and NOx emissions as well as fuel reforming [169,170]. Since the focus is on plasma assisted combustion, the applications of plasma on soot/NOx/hydrocarbon emissions and fuel reforming are being reviewed. For soot emission control, Cha et al. [171] studied a dielectric barrier discharge (DBD) in coflow jet C3H8 diffusion flames. The plasma reactor had wire-cylinder type electrodes with AC power supply operated at 400 Hz.

VII. Conclusion

Plasma Assisted Combustion has a long history and so much progress has been made since a long time. The advantage of Non-equilibrium plasma over equilibrium plasma is dominant. That's why researchers have become interested in non-equilibrium plasma for ignition - combustion control, ignition boosting and for flame stabilization. We explored an approach towards its applications like (PDE), where plasma discharge was used to lower the delay time in the ignition, plasma is used to stabilize the flame and to achieve ultra-lean combustion. to improve the ignition of Spark ignition engines. This study reviews the effectiveness of plasma in combustion enhancement, combustion control and fuel reforming but there are still many unanswered questions such as what kind of plasma is the best option for combustion enhancement in a given environment? How PAC depends on plasma properties, temperature and fuel? How plasma chemistry affects combustion chemistry and properties?

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