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Effects of Nanosecond Repetitively Pulsed Discharges Timing for Aeroengines Ignition at Low Temperature Conditions by Needle-Ring Plasma Actuator

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Abstract: These days, various national and international research organizations are working on the development of low NO_x combustors. The present work describes the experimental and numerical characterization of flow dynamics and combustion characteristics in a rectangular burner. A ring-needle type plasma actuator was developed and driven by a high voltage nanosecond pulsed generator under atmospheric conditions. Smoke flow visualizations and Proper Orthogonal Decomposition (POD) were carried out to identify the relevant flow structures. Electrical characterization of the non-reactive flow was carried out to predict the electrical power and the optimum value of the reduced electric field (E_N), which is useful for the implementation of a numerical model for the study of plasma-assisted ignition. A detailed plasma kinetic mechanism integrated with all excited species was considered and validated with experimental studies. Numerical modeling of plasma ignition has been performed by coupling ZDPlasKin with CHEMKIN. Energy and power consumption for methane/air plasma actuation is higher than the air plasma actuation. This could be due to the excitation and ionization of methane that required more energy deposition and power. The mole fraction of O atoms and ozone was higher in the air than the methane/air actuation. However, O atoms were produced in a very short time interval of 10^{-7} to 10^{-6} s; in contrast, the concentration of ozone was gradually increased with the time interval and the peak was observed around 10^{-1} s. Plasma discharges on the methane/air mixture also produced radicals that played a key role to enhance the combustion process. It was noticed that the concentration of H species was high among all radicals with a concentration of nearly 10^{-1} . The concentration peak of CH₃ and OH was almost the same in the order of 10^{-2} . Finally, the mixture ignition characteristics under different low inlet temperatures were analyzed for both air and methane/air plasma actuation in the presence of different plasma discharges pulses numbers. Results showed that it is possible to reach flame ignition at inlet temperature lower than the minimum required in the absence of plasma actuation, which means ignition is possible in cold flow, which could be essential to address the re-ignition problems of aeroengines at high altitudes. At $T_i = 700$ K, the ignition was reached only with plasma discharges; ignition time was in the order of 0.01 s for plasma discharges on methane/air, lower than in case of plasma in air, which permitted ignition at 0.018 s. Besides this, in the methane/air case, 12 pulses were required to achieve successful ignition; however, in air, 19 pulses were needed to ignite.

Keywords: ignition timings; smoke flow visualization; electrical characterization; ZDPlasKin; CHEMKIN

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1. Introduction

In recent years, numerous research organizations are working on the advancement of low NO_x combustors and aeronautical engines to fulfill the regulations of international organizations. Lean fuel burning is one of the encouraging methods in order to achieve the low temperature combustion but as a result, strong flame instabilities are produced in the form of flame quenching which ultimately reduce the overall efficiency of the combustion

process [1–3]. Furthermore, high-altitude aircraft engines operate in conditions of low inlet temperature, and under such conditions, the flow, atomization, and combustion characteristics are different from those at sea level. A low ambient temperature makes both ignition and combustion difficult as it slows down the rate of fuel evaporation and requires more spark energy for fuel evaporation.

This reduces ignition and flame extinction limits in high-altitude conditions, making ignition unstable and in a narrow range of fuel/air ratio. To improve ignition and flame stability both in lean fuel and low temperature conditions, various passive control technologies are commonly used to improve the flame stabilization by modifying the injector geometry or flame holders in a permanent way, which could help to promote combustion stability by creating large vortices [4].

In addition to this, active control technologies could control flow and combustion parameters as operating conditions change in real time without altering the combustor design. Non-thermal plasma (NTP) is the established technology that actively controls the combustion characteristics of coaxial burners and axisymmetric air jets [5–8]. The basic principle of NTP is to produce plasmas in which electrical energy is used to ionize the fuel, air, or mixture without overheating the gas. It not only increases the efficiency of burners by increasing flame stabilization, improving oxidation at low temperature and extending the limits of lean blow out, but at the same time, also reduces the significant amount of exhaust emissions, i.e., nitrogen oxides (NO_x) [9–11].

Among all NTPs dielectric barrier discharge (DBD), plasma actuators gained great attraction for aeronautical applications because of low power consumption, ease to handle, no movement of mechanical parts, being lightweight, and being cheap to build, implement, and maintain high-frequency response, permitting real-time operating conditions [12]. Usually, DBD is functioning with two electrical modes; the first one is the AC in which a high voltage (HV) waveform with a frequency in the range of kHz is used with or without the pulsation form. In the second mode, HV is applied in the form of nanosecond repetitive pulses (NRP), usually operating in a wide range from a few hundred Hz to a few hundred kHz. Particularly, nanosecond pulsed discharge has been drawing much attention due to the wide and efficient aptitude of producing excited states and free radicals by dissociation, ionization and electron impacted excitation reactions by subjecting to a high reduced electric field (E_N) which kinetically improves the combustion process [13,14]. Furthermore, nanosecond plasma discharge produced fast gas heating via thermal pathways, which also helped in accelerating the combustion process [15]. However, during the nanosecond pulse discharge, plasma chemistry (electron impact reactions) has different time scales than the combustion chemistry (gas-phase reactions) [16–18].

Xu et al. [19] in 2015 studied the flame properties in a co-axial burner by using AC-DBDPA; the outer tube, carrying a CH_4 jet, was connected with a HV electrode and the inner tube, carrying an air jet, was used as a grounded electrode. They noticed that flame behavior was significantly influenced by the reduced electric field strength (E_N). Furthermore, they also observed that pre-mixing performance was improved, which results in the combustion enhancement.

Bernard et al. [20,21] in 2007–2008 carried out experimental studies to investigate the effects of AC-DBDPA by operating with or without the pulsation mode of the HV sinusoidal generator. Velocity profiles, turbulent kinetic energy (TKE), and turbulent spectra were characterized. The authors described that the mixing performance of the jet was heavily improved with plasma actuation.

Our research group also performed some experimental and numerical studies [22–24] focused on the impacts of plasma discharge on the flame behavior of the methane/air mixture by using a coaxial dielectric barrier discharge (DBD) in the Bunsen burner. It was noticed that the plasma excitation improved the production of OH radicals and changed flame luminosity. Moreover, the impact of plasma discharge with two different configurations of burners, normal diffusive flame (NDF) and inverse diffusive flame (IDF), was analyzed by considering lean non-premixed methane–air flame. It was found that

plasma effects greatly depend on the burner and DBD configurations. Finally, a study about the impacts of plasma discharge on methane decomposition was carried out to improve combustion. It was observed that in the presence of a plasma discharge, the flame speed was increased by about 10% as compared with the clean case at stoichiometric conditions.

Rosocha et al. [25] in 2007 investigated the effects of AC-DBDPA on the flame in a burner. The authors analyzed the fragmentation process of hydrocarbons in the presence of plasma discharges and they also highlighted the basic ideas of the fuel plasma activation. Owing to this, increased flame speed, reduction in fuel consumption, and flame stability were examined.

Zhang et al. [26,27] in 2013–2014 investigated fuel reforming by DBDPA by considering two cases: partial oxidation and dry reforming. It was observed that fuel reforming was improved with the oxidation case. Furthermore, the overall conversion of methane and oxygen was increased with the plasma power, E_N values, and the initial temperature. It was shown that by increasing the temperature, concentrations of neutral radicals such as O, H, CH, and OH are increased, which leads to improving the conversion efficiency of the fuel and oxidizer. However, because they used a low number of electrons impacted reactions in their model, no quantitative comparison of produced species was performed which ultimately limited the plasma-based analysis of fuel and oxidizer conversion processes.

Haibao et al. [28] in 2015 studied the effects of AC-DBDPA on $\text{CH}_4/\text{O}_2/\text{He}$ mixture. They noticed that AC-DBDPA enhanced the flame speed from 17% to 35% under equivalence ratios ranging from 0.85 to 1.10. They also analyzed the decomposition of CH_4 into intermediate radicals (CH, CH_3 , and H). The H and CH_3 reacted very quickly with O_2 to produce OH radicals. Owing to this, O atoms were generated through the dissociation of O_2 molecules.

In the literature, it was found that plasma assisted combustion (PAC) effects are broadly explained in three different ways: thermal or temperature effects (slow and fast gas heating processes from vibrational and electronic state relaxation), kinetic effects (formation of charged species, electrons, excited species, neutral radicals, and fuel fragments) and via transport effect (fuel decomposition and oxidation at low temperatures) [29,30]. However, the accurate and detailed mechanism that could improve combustion is not well understood yet.

Therefore, the big challenge is a deep knowledge of the effects of DBD plasma actuation on combustion enhancement, which could help to optimize and identify the role of each specific process involved in the plasma induced combustion. Several assumptions were considered in previous studies by aiming to classify the plasma effects.

In this context, the main aim of this study is to examine the key challenges involved in plasma combustion such as fluid effects and the effects of produced species and radicals due to the plasma actuation on the ignition characteristics at low temperature conditions by varying the number of HV nanosecond plasma pulses in order to address the problems produced during cold ignition. The experimental characterizations of flow dynamic characteristics in a rectangular burner were investigated. A ring-needle type plasma actuator was developed and driven by a high voltage nanosecond pulsed generator at atmospheric conditions. Electrical characterization of non-reactive flow was performed to predict the optimum value of reduced electric field E_N that could be supportive to correlate it with numerical simulations.

Generally, the nanosecond repetitively pulsed plasma actuators in combustor have been characterized in terms of the thermal effects and species decompositions. However, the present plasma needle-disk plasma actuator configuration could also influence the fluid dynamics such as induced flow with an impact on the recirculation zone near the corners of the combustor, improving the mixing performance of the mixture, ultimately resulting in the reduction of ignition delay timings.

Hence, in order to decouple the fluid, dynamic effects of the plasma actuation on the flow were investigated by means of a non-reacting flow characterization (absence of combustion), where the air was used as both fuel and oxidizer. The flow pattern and

turbulence in both the presence and absence of actuation were studied by CCD flow visualization coupled with POD analysis and PIV analysis.

Then, the same experimental E_N and voltage were used for the numerical analysis on the flame ignition, and smoke flow visualizations were performed by using a high-resolution camera. Proper orthogonal decomposition analyses were carried out to recognize the relevant flow structures. Electrical characterization has been also performed to estimate the power consumption and the reduced electrical field to be used in the numerical simulations. In order to understand the kinetic plasma effects, a detailed plasma kinetic mechanism integrated with all excited species was considered and validated with experimental studies by comparing the mole fraction of O atoms. Plasma ignition numerical modeling has been performed by coupling ZDPlasKin with CHEMKIN. A detailed description of numerical models is available in Section 3. The comparative analysis of species production and ignition characteristics at low inlet temperatures for different nanosecond plasma pulses numbers were considered for air and methane/air mixture that could be essential to address the re-ignition problems of aeroengines at high altitudes.

2. Materials and Methods

The experimental setup has been implemented to investigate the effects of plasma discharges on the flow and to measure the electrical properties in the case of a plasma actuator installed in a closed rectangular cross-sectional burner having the following dimensions: height $H = 305$ mm, width $W = 104$ mm, and wall thickness $T = 2$ mm. The burner was equipped with a ring-needle type plasma actuator. The actuator consisted of two copper electrodes; the disk electrode has inner and outer diameters equal to 32 mm and 52 mm, respectively, and relates to high voltage. This electrode was installed in the center of a Teflon plate that was the bottom part of the rectangular burner. A needle copper electrode with a diameter of 1 mm, the length equal to 330 mm and a blunt tip angle of 90° , was axially placed at the center of disk type electrode with standoff distance $s = 0$ mm, and it acted as the grounded electrode, as shown in Figure 1. The standoff distance indicated the positioning of the grounded electrode with reference to the upper edge of the HV disk.

Figure 1. A disk and needle type plasma actuator configuration: (a) sketch of the plasma actuator electrodes connections; (b) picture of the experimental plasma actuator device.

All tests were conducted at a laboratory ambient temperature and pressure of 298 K and 1 bar, respectively, by considering non-reactive flow (absence of flame). Different plasma actuation conditions were considered by using a nanosecond pulsed generator. A Faraday cage was used to shield the acquisition system from the electromagnetic interference caused by the high electric field required to generate the plasma discharge. Table 1 shows the experimental actuator operating conditions, in terms of the amplitude and repetition frequency of the nanosecond repetitive pulsed discharges and needle position.

The amplitude and frequency values are reported in terms of percentage value with respect to the maximum given by the HV generator.

Table 1. Experimental conditions (amplitude and frequency are expressed as the % value with respect to the maximum of the HV generator).

Test Case	Actuator Configuration		Actuation Conditions			Standoff Distance (mm)
No.	High Voltage	Ground	Generator	Amplitude (% V _{max})	Frequency (% F _{max})	
1.	Disk	Needle	Nanopulsed Generator	40%	30%	00
2.				20%	20%	00
3.				30%	20%	00
4.				20%	30%	00
5.				30%	30%	00
6.				40%	20%	00
7.				40%	30%	40

The electrical setup consisted of the HV nanosecond pulse generator (NPG-18/3500), the HV probe (Tektronix P6015A), the current transformer (Bergoz Current Transformer CT-D1.0-B), the oscilloscope (R&S-RTM3004), and a dedicated personal computer. To obtain the characteristic voltage-current curves as a function of time (t) and electrical power dissipation, both the HV probe and the current transformer were connected to the oscilloscope, and the corresponding signals were recorded with an accuracy given by Equation (1).

$$\text{Measurement Accuracy} = \pm \text{DC gain Accuracy} + |\text{reading-net offset}| + \text{offset accuracy} \quad (1)$$

where DC gain Accuracy was: 1.5% for the input sensitivity $> 5 \text{ V/div}$ (Voltage case) and 2% for the input sensitivity $\leq 5 \text{ mV/div}$ to $\geq 1 \text{ mV/div}$ (Current case); Reading is the value of voltage or current measured by oscilloscope; Net offset is the offset value set in each test.

$$\text{Offset accuracy} = \pm 0.5\% * |\text{offset}| + 0.1 \text{ div} * \text{input sensitivity} + 0.5 \text{ mV} \quad (2)$$

where: Input sensitivity is in the range 0.5 mV/div to 10 V/div at $1 \text{ M}\Omega$.

In particular, the HV probe was placed on the HV connector side and the current transformer was located on the grounded side, allowing simultaneous measurement of the applied voltage and current due to the plasma discharge; a single oscilloscope's acquisition was characterized by a sampling rate of 25 MHz, equivalent to two periods (T) for each signal; 128 individual acquisitions were recorded and averaged in order to obtain the average values of the applied voltage signal ($V(t)$) and current signal ($I(t)$).

The electrical power dissipation P was calculated by Equation (3):

$$P = \frac{1}{n} \sum_1^n \left(\frac{1}{2T} \int_0^{2T} I(t) \times V(t) dt \right) \quad (3)$$

where $2T$ is the period of the applied voltage and $I(t)$ and $V(t)$ are the acquired current and the voltage signals, respectively.

For the power calculation, a numerical integration was performed using the trapezoidal rule and the corresponding uncertainty of each power measurement was estimated by standard uncertainty analysis methodology [29,30]. A detailed sketch of electrical characterization is shown in Figure 2.

Figure 2. A complete sketch of electrical characterization.

3. Numerical Procedure

Numerical modeling has been performed by coupling a zero-dimensional plasma kinetic model (ZDPlasKin) [31] and the chemical kinetic model (CHEMKIN) [32]. A detailed description of coupling ZDPlasKin and CHEMKIN with their governing equations is available in [33,34]. ZDPlasKin was used to analyze the thermal and kinetic effects of nanosecond repetitive pulsed discharges on the air and methane/air mixture. A simulation model of plasma kinetics was developed to investigate the temporal evolution of time-dependent species. In this model, the 0-D plasma kinetic model (ZDPlasKin) was integrated with the Boltzmann equation solver (BOLSIG+) to predict the time-dependent evolution of species. CHEMKIN was considered to predict the ignition characteristic timings, particularly at low temperature ranges. The complete numerical procedure is described in Figure 3. Step 1: a detailed literature review carried out by aiming to generate the comprehensive plasma kinetic mechanism and collected the electron collision cross-sectional data. Step 2: initial code setting and boundary conditions on ZDPlasKin for plasma reaction simulation in terms of temperature, pressure, electrical feeding, and initial mixture composition in companies with the preparation of plasma chemistry file (detailed reaction mechanism) and compiling the cross-section data file. Step 3: simulations of plasma discharge on ZDPlasKin performed to estimate the species as a function of time. Step 4: the results obtained from ZDPlasKin incorporated in CHEMKIN to examine the pulsation effects of plasma discharge on ignition timings at low temperature conditions.

Figure 3. Detailed numerical procedure.

The deposition of high energy electrons in the combustible mixture showed a significant influence on the combustion performance during electron impact reactions which results in decomposition of the fuel mixture. In the plasma kinetic model, when electrons reacted with the methane–air mixture,

it produced different excitation states and reactions. The reaction mechanism consists of dissociation, ionization, recombination, charged transfer reactions, relaxation reactions, three-body recombination reactions, electronically and vibrational excitation states of species, concluded from the previous studies where available. The detailed plasma kinetic reaction mechanism involves 161 species and 1382 reactions involving electron impact and gas-phase reactions. It contained 3 reactants, 5 elements, 80 radicals, 35 charged species, and 38 excited species. It was developed by expanding the mechanism of N_2 - O_2 [35,36] with the reactions of the CH_4 - H_2 - O_2 mixture [37] and the mixture of CH_4 - H_2 - N_2 from [38]. However, for plasma analysis, it is important to define the reaction rates coefficient of electron impacted reactions. Rate coefficient depends on the induced electron energy and collision cross-sectional data of electron impacted plasma reactions obtained from the LXCat database [39].

4. Results and Discussions

4.1. Experimental Results

4.1.1. Electrical Characterization

Table 2 highlighted the peak voltage, repetition rates, and the electrical power data such as the single pulse electrical power and the mean electrical power delivered to the fluidic flow for the different test cases reported in Table 1.

Table 2. Electrical data for the different test cases.

Test Case No.	Voltage Peak (V)	Repetition Rate, F (Hz)	Pulse Electrical Power (W)	Mean Electrical Power (W)	Uncertainty Pulse Electrical Power (W)
1.	16,796	755.29	660.8	1.2	70
2.	14,600	202.18	766.2	0.4	80
3.	15,600	245.03	864.3	0.5	90
4.	14,800	627.74	790.9	1.2	80
5.	15,500	710.22	861.3	1.5	90
6.	16,600	257.66	1029.3	0.6	100
7.	189.98	1059.1	6.2	0.01	0.5

Figure 4 shows typical experimental current and voltage temporal signals for test Case 1; from the acquired current and voltage time series, the power characteristics were calculated and are shown in Table 3, then the voltage signal was used for the estimation of the reduced electric field E_N , knowing the distance between needle and disk. It is a highly variable signal because of the nano pulsed repetitively discharge. The temporal behavior of E_N is shown in Figure 5, underlining the several E_N peaks. From this temporal signal, the integral mean of E_N in the pulse duration time up to 10^{-6} s was then calculated. Therefore, the E_N value for the single pulse was about 200 Td for Case 1. In our previous study, we found that the ignition has been significantly improved at 200 Td [40]. Similar results were also observed by [41] at the same E_N value. Therefore, test Case 1 was better investigated for further analysis.

Figure 4. Electrical characterization, $I(t)$ and $V(t)$ acquired temporal signals for the test Case 1.

Table 3. Production of neutral radicals and power consumption during air and methane/air plasma actuation.

Case No.	O	O3	H	OH	CH	CH3	Power (W)
Methane/air	8.69×10^{-4}	7.92×10^{-5}	4.42×10^{-2}	1.3105×10^{-2}	3.39×10^{-4}	3.084×10^{-2}	10.23
Air	3.02×10^{-3}	1.09×10^{-2}	----	----	----	----	8.006

Figure 5. Experimental E_N (Td) for the test Case 1.

4.1.2. Flow Visualization and Proper Orthogonal Decomposition (POD)

Smoke flow visualization was performed by using a high-speed CCD camera MEMRE-CAM GX-3 equipped with a Nikkor 60 mm f/2.8d A/F objective and an interference filter ($\lambda = 532$ nm). The images were taken at 50 Hz for 1 s of acquisition time. The resolution was 288×384 . Incense smoke (particle average diameter of 0.3 microns) has been used for filling the test chamber. A Laser 532 nm 300 mW mod. MGL-III-532 was used to illuminate the visualization plane.

Flow visualization was also used to make a quantitative estimation of the induced velocity field and the calculation of the various flow parameters was performed by PIV lab which is a MATLAB based program, for the analysis of the induced flow field, a region of interest (ROI) of $100 \text{ mm} \times 100 \text{ mm}$. The acquired images were cropped to analyze only the region of interest; then, to improve the contrast between the object and the background, the Contrast Limited Adaptive Histogram Equalization (CLAHE) method was used, enabled with 20 pixels window size [42]. As per the PIV algorithm, the FFT-based cross-correlation method was applied [43]. The interrogation window size was set to 64×64 pixels in the first pass and then was reduced to 32×32 pixels in the second pass and 24×24 in the third passage, with a 50% overlapping for each pass and adaptive interrogation window. Non-overlapping image sequencing (1–2, 3–4 . . .) was chosen for each run of image processing. Finally, improperly matched vectors were removed and vectors having a signal-to-noise ratio (SNR, ratio of the highest peak to the second highest peak in each individual correlation map) over 3 were analyzed. The time-averaged flow field was based on an ensemble size of 100 images.

Figure 6 showed the instantaneous smoke flow visualizations and the time-average flow streamline in the proximity of the electrodes for the identification of vortical flow pattern generated in quiescent atmospheric air using a disk and needle type actuator powered by a nanosecond repetitively pulsed discharges generator. It was observed that the vortices were generated at the corners of a closed rectangular box that could be used to highlight the recirculation of flow in the burner applications, and this aerodynamic effect could be essential to control the combustion characteristics. The contours of the instantaneous and time-average velocity magnitude are presented in Figure 7. The induced majority induced flow was on the right and covered about the 5 cm height region. The maximum velocity time-average magnitude is approximately 0.012 m/s and the maximum instantaneous magnitude velocity is in the order of 0.065 m/s.

Figure 7. Contour of flow produced by disk-needle plasma actuator: (a) Time-averaged velocity magnitude; (b) Instantaneous velocity. (Axes dimensions in mm).

However, for a better understanding of flow structures, it was challenged to extract the coherent flow motions from a random signal. Proper orthogonal decomposition (POD) analysis is the most powerful and established technique in the field of fluid dynamics to obtain the most relevant and protuberant spatial flow structures. That could help to control the flow dynamics. Before the analysis of POD based structures, it is mandatory to examine the criteria of the broadness of modes which has captured almost all the relative energy.

Therefore, Figure 8 is showing the individual relative energy contributions of the first 10 eigenmodes. It has been perceived that relative energy is generally consumed and distributed by the first three modes. Though, the contribution of Mode 1 guided high; it captured approximately 80% of the total energy, with POD modes above number 3 having very little impact. Therefore, only the first three modes were essential for the analysis of flow vortexes and structures. The first three eigenmodes which showed the flow field and vortexes in two-dimensional space for test Case 1 are shown in Figure 9. It has been noticed that Mode 1 is not symmetric with Mode 2 and Mode 3; this is because Mode 1 contained around 80% of total energy, so the main dominant structure could be as in Mode 1. However, Mode 2 and Mode 3 have somehow resembled each other because they acquired almost the same energy distribution. The first mode showed the dominant and actual structure produced by the swirling of flow around the walls of a closed box. This flow structure could contribute to improving the mixing performance of flow and combustion enhancement.

Figure 8. Relative energy of first 10 POD modes of test Case 1.

Figure 9. First three POD modes.

4.2. ZDPlaskin Results

In order to predict the effect of the plasma needle-ring actuator on the flame ignition, numerical simulations have been performed using a hybrid approach, coupling ZDPlasKin code and Chemkin code and the experimental data of [44] regarding the nanosecond repetitively pulsed discharges in air, and methane/air mixture were used to validate the kinetic modeling of the plasma discharge. ZDPlasKin was used to validate the kinetic mechanism by following experimental parameters. Single pulse discharge of 20 ns with peak tuned at E_N of 289 Td, the initial pressure of 8000 Pa and temperature of 300 K and equivalence ratio of 1, and pure air ($O_2 + 3.76 N_2$) were used. It was found that the plasma kinetic model permitted a good fitting with experimental study of the decay process of the O atom in mole fraction for both air and methane/air mixture at similar equivalence ratios as presented in Figure 10. Furthermore, it was also analyzed that in the methane/air mixture, the decay rate of the O atom was relatively high in comparison with the case of pure air; because, due to methane dissociation, H atoms and CH_3 radicals were produced and reacted with O atoms, which leads to the reduction of O atoms in the methane/air mixture.

Numerical analysis of plasma kinetics of air and methane/air mixture were performed, considering E_N equal to 200 Td, the repetition frequency of 10,000 Hz, ambient pressure equal to 1 atm, and temperature set at 300 K. $CH_4/O_2/N_2$ were used as initial reactants. ZDPlasKin was integrated with the Boltzmann equation solver (BOLSIG+) in order to predict the time dependent evolution of species.

Figure 10. Validation: Time evolution of predicted vs. experimental data [44] of O atoms decay process with air and methane/air at 300 K and 8000 Pa.

Figure 11 shows the comparative analysis of energy deposition and electrical power for plasma discharges in air and methane/air mixture. Energy and power utilized for methane/air actuation is higher than the pure air actuation. It could be due to the excitation and ionization of methane that required more energy deposition and power.

Figure 11. Energy deposition (mJ/cm^3) and electrical power (W) of air and methane/air plasma actuation.

Figure 12 shows the comparison of the temporal evolution of O atoms and ozone, produced in the presence of air and methane/air plasma actuation. The mole fractions of O atoms and ozone were higher in the air than in the methane/air plasma discharges. The reason behind the lower production of O atoms in methane/air mixture is due to the consumption of O atoms produced during plasma discharge in reactions with other intermediate species and free radicals resulting from the decomposition of CH_4 , such as OH. The peak of ozone was close to 10^{-2} for air and 10^{-5} for methane/air. However, in the case of O atoms, the concentration peak was close to 10^{-3} for air and 10^{-5} for methane/air. Besides this, O atoms are produced in the very short time interval of 10^{-7} to 10^{-6} because the electronic excitation states of O atoms were very reactive, when they reacted with oxygen molecules such as $\text{O}(1\text{S}) + \text{O}_2 \rightarrow \text{O} + \text{O} + \text{O}$ and $\text{O}(1\text{S}) + \text{O}_2(\text{A}1) \rightarrow \text{O} + \text{O} + \text{O}$. In contrast, the concentration of ozone was gradually increased with the time interval and the peak was observed around 10^{-1} ; this is because ozone reactions are too slow in comparison with other reactions (time scale of about 10^{-1} s) such as $\text{O} + \text{O}_2 + \text{O}_2 \rightarrow \text{O}_3 + \text{O}_2$.

Figure 12. Temporal evolution of O atoms and O₃ in air and methane/air at 10,000 Hz and $E_N = 200$ Td.

In contrast with plasma discharges in air, in the case of methane/air, other important radicals were produced that could enhance the combustion process. Figure 13 shows the temporal evolution of H, CH₃, CH, and OH radicals. It was noticed that the concentration of H species is the highest among all and lies nearly 10^{-1} . The concentration peak of CH₃ and OH was almost the same; however, OH species were suddenly reduced because it was unstable and very reactive to form other radicals. CH concentration was between 10^{-4} to 10^{-3} .

Figure 13. Temporal evolution of H, CH, CH₃ and OH in methane/air at 10,000 Hz and $E_N = 200$ Td.

4.3. CHEMKIN Results: Effects of Pulses Number on Flame Ignition Characteristics

The ignition delay timings are predicted by means of time required for achieving the flame temperature, which could be enough for the combustion process. Successful ignition was only achieved when the temperature reached the threshold value of chain branching of methane. Plasma discharges give energy directly to the free electrons in the plasma. Later, electron energy was converted into bond energy of neutral radicals. Finally, during the ignition, the bond energy of intermediates was transformed into internal energy, which could endorse the combustion augmentation. Furthermore, plasma has a significant impact on the fluid dynamics, such as induced flow velocity, which created the recirculation zone near the corners of the combustor, which improved the mixing performance of the mixture, ultimately resulting in the reduction of ignition delay timings.

The effects of the number of pulses on the ignition delay timings were numerically investigated at $E_N = 200$ Td, in accordance with the value experimentally estimated by the electrical characterization in Section 4.1.1; in the previous section, it was concluded that

by using nanosecond repetitively pulsed discharges, a fast heating process was present, resulting in the rise of the temperature of the mixture, and the estimated results obtained from the ZDPlasKin in the form of fuel and air decomposition and rise in the temperature of the mixture, reported in Table 3, were introduced into the CHEMKIN to characterize the flame ignition process.

The chemical kinetic reaction model was comprised of gas-phase and combustion reactions from the GRI-Mech v3.08 mechanism. The ozone reaction list reported in [45] was also added to the combustion kinetics scheme to consider the production and decomposition reactions of ozone, oxidation of ozone, HO_2 formation, ozone reactions of NO, CH_3 , N, and H_2O , and methane–ozone reactions. In addition, the neutral radicals and ozone produced from the plasma discharge of air and methane/air mixture were considered, because it was also noticed that ozone was increased in both air and methane/air plasma actuation. The closed homogenous batch reactor (CHBR) solver was selected to predict the effects of air and methane/air plasma actuation on ignition enhancement by comparing with the clean baseline case without plasma actuation at different low inlet temperature and pressure keeping 1 atm. Two major control factors were set to monitor the ignition process, such as the temperature inflection point and the maximum production of OH particles. The ignition delay timings were computed by using these two kinds of techniques; for each condition, comparisons were performed between the clean case (without plasma) with two plasma assisted ignitions, one with plasma actuation in the mixture of methane/air and the other acting only in the air.

Figure 14 highlights the ignition delay timings for air plasma actuation and methane/air plasma actuation with a single pulse discharge at an inlet temperature of 1400 K. This temperature value was chosen because it was the minimum value to have ignition in the case without plasma actuation (clean case). It has been observed that during the pulse discharge, the temperature gradually increased for both types of actuations. The horizontal red and blue line corresponded to the end of the plasma discharge. The rise in temperature in the case of methane/air activation (1815 K) is higher than the air activation (1675 K) as shown by the vertical red and blue lines. The ignition timings significantly reduced nearly up to (10^{-5} s) as compared with clean case (10^{-3} s). Furthermore, the peak temperature of air activation (2718 K) and methane/air activation (2754 K) was also increased in comparison with the clean case (2677 K), but the difference was slightly low between the two actuated cases.

Figure 14. Ignition timings analysis by comparing the clean case without plasma (black), and plasma actuation in air (blue) and in methane/air (red) after a single pulse discharge at $T_i = 1400$ K, $E_N = 200$ Td, and stoichiometric conditions.

In contrast to the case with $T_i = 1400$ K, the comparison of ignition timings at inlet temperature $T_i = 700$ K shows a significant improvement when plasma is used for the

activation of methane/air mixture as compared with air, as shown in Figure 15. Ignition timings were 0.01 s for methane/air while in the case of air, ignition was achieved at 0.018 s. Besides this, in the methane/air case, 12 pulses were required to achieve successful ignition; however, in air, 19 pulses were needed to ignite.

Figure 15. Ignition timings analysis by comparing plasma actuation in air (blue) and in methane/air (red) at fixed low inlet temperature 700 K, fixed $E_N = 200$ Td, fixed frequency 10,000 Hz, and stoichiometric conditions.

A parametric study was performed to compute the effects of different pulses numbers on the ignition enhancement at different values of the inlet temperature. Figure 16 showed that at a low inlet temperature, such as at 700 K, the plasma actuation in the air required 19 pulses to achieve flame ignition. However, during the methane/air plasma actuation, the ignition has been reached after the 12th pulse discharge; below this number, just a rise in temperature of the combustible mixture was observed due to plasma discharge. The total energy consumed for the plasma activation of the methane/air mixture and air were 5.04 J and 6.27, respectively. It means that ignition is even possible at inlet temperatures lower than 700 K, but it consumed more energy because it required several pulses. Moreover, it was also concluded that ignition delay timings and pulses numbers are heavily reduced in methane/air activations as compared to air activations. Meanwhile, as the inlet temperature is increased, the number of pulses, as well as the ignition timings, were also reduced. Therefore, at 1000 K, ignition occurred after the first pulse in both types of plasma activations.

Figure 16. Comparative analysis of ignition timings of plasma actuation in air (blue) and in methane/air (red) by varying pulses number at different parametric temperature, fixed $E_N = 200$ Td, fixed frequency = 10,000 Hz, and stoichiometric conditions.

Figure 17 shows the peak temperature values of the mixture after a certain amount of pulses at different inlet reactant temperatures. It was found that one pulse is sufficient

to activate combustion only if the inlet temperature is 1000 K or higher. At this condition, the peak flame temperature in the presence of methane/air plasma actuation (2500 K) was higher than the air activation (2170 K); while at lower inlet temperatures (700, 800, and 900 K), only a small rise in the mixture temperature was observed and there was no flame after the first pulse in both air and methane/air.

Figure 17. Comparative analysis of peak temperature achieved during the ignition process by varying pulses number at different parametric temperatures, fixed $E_N = 200$ Td, fixed frequency = 10,000 Hz, and stoichiometric conditions: (a) methane/air plasma activation (solid lines), (b) air plasma activation (dashed line).

At the inlet temperature of 700 K, a single pulse took the mixture to 1000 K; at 800 K, the pulse took it to 1050 K. At 900 K, the pulse increased the temperature to 1200 K; while at 1000 K, ignition occurred and the resultant mixture temperature was 2600 K. Furthermore, at 700 K, the combustion occurred after 12 and 19 continuous successful pulses for methane/air and air, respectively, leading to the peak flame temperature at almost around 2500 K; at an inlet temperature of 800 K, the combustion was achieved after the 2nd and 3rd continuous pulses for plasma discharges in methane/air and air, respectively.

Figure 18 shows the maximum molar fraction of OH achieved during the combustion by varying pulses numbers at low inlet temperature. It was observed that after the 1st pulse, maximum OH concentrations is only possible when the inlet temperature is 1000 K; while for a lower inlet temperature (700, 800, and 900 K), there is a slight rise in temperature during the 1st pulse in both air and methane/air. Finally, when the inlet temperature was 700 K, the maximum molar fractions of OH were observed after the 12th and 19th successful pulses for methane/air and air, respectively. The trend of OH concentrations also endorsed the behavior of ignition timings and peak flame temperature with the number of pulses.

Figure 19 showed the maximum mole fraction of O atoms after a certain number of pulses at different inlet temperatures. The maximum mole fractions of O atoms were observed after the 1st pulse, only when the inlet temperature was 1000 K or higher for both air and methane/air plasma actuation. It endorsed the same trend of peak flame temperature and OH concentrations, as shown above in Figures 17 and 18. When the inlet temperature was reduced, the number of pulses required to achieve the maximum O atoms increased. For example, when the inlet temperature was 700 K, a peak concentration of O atoms was observed after the 12th and 19th successful pulses for methane/air and air, respectively, to activate the combustion.

Figure 20 shows the value of the total pulse energy consumed to achieve successful ignition for both methane/air and air actuation at different inlet temperatures. It has been observed that when the inlet temperature was 1000 K, almost the same pulse energy was used for flame ignition in both methane/air and air actuation configurations. However, at low inlet temperature (700 K, 800 K and, 900 K), air plasma actuation required more

energy consumption than the methane/air plasma actuation, which was due to the more pulses required for the ignition. Air plasma actuation leads to fewer excited species and combustion radicals than methane/air actuation; furthermore, it requires more pulses to reach the same OH^* concentration values, as shown in Figure 18. As the inlet temperature reduced, the total pulse energy consumption was increased. At 700 K, the total pulse energy required for ignition of methane/air and air was 5.04 J/cm^3 and 6.27 J/cm^3 , respectively.

Figure 18. Maximum molar fraction of OH achieved during the combustion by varying pulses number at different parametric temperature, fixed $E_N = 200 \text{ Td}$, fixed frequency = 10,000 Hz, and stoichiometric conditions: (a) methane/air plasma activation (solid lines), (b) air plasma activation (dashed lines).

Figure 19. Maximum molar fraction of O atoms achieved during the combustion by varying pulses number at different parametric temperatures, fixed $E_N = 200 \text{ Td}$, fixed frequency = 10,000 Hz, and stoichiometric conditions: (a) methane/air plasma activation (solid lines), (b) air plasma activation (dashed lines).

Figure 20. Total pulse energy used to achieve successful ignition for methane/air and air actuation at low inlet temperatures, considering fixed $E_N = 200 \text{ Td}$, fixed frequency = 10,000 Hz, and stoichiometric conditions.

5. Conclusions

This study investigated the experimental and numerical characterization of flow dynamics and combustion characteristics in a rectangular burner. Plasma has a significant impact on the fluid dynamics, such as increased induced flow velocity, which created the recirculation zone near the corners of the combustor which improved the mixing performance of the mixture, and ultimately resulted in the reduction of ignition delay timings. It has been observed that energy and power utilized for methane/air actuation are higher than the pure air actuation. This could be due to the excitation and ionization of methane that required more energy deposition and power. The mole fraction of O atoms and ozone was higher in the air than the methane/air actuation. However, O atoms were produced in a very short time interval of 10^{-7} to 10^{-6} ; on the contrary, the concentration of ozone was gradually increased with the time interval, and the peak was observed around 10^{-1} . Methane/air plasma actuation also produced the other important radicals that played a key role to enhance the combustion process. It was noticed that the concentration of H species is the highest among all radicals and lies at nearly 10^{-1} . The concentration peak of CH_3 and OH was almost the same, 10^{-2} . Finally, the comparative behavior of ignition characteristics considering low inlet temperature values by subjecting different numbers of pulses was analyzed for both air and methane/air plasma actuation. Ignition timings were significantly reduced up to 0.01 s for methane/air, while in the case of air, ignition was achieved at 0.018 s. Besides this, in the methane/air case, 12 continuous pulses were required to achieve successful ignition; however, in air, 19 continuous pulses were needed to ignite. This means that ignition is even possible at low inlet temperature, but it requires excessive energy in the form of total pulse energy. However, as the inlet temperature is increased, the number of pulses required for ignition is decreased, and not only the number of pulses but ignition timings are also reduced.

Furthermore, at 700 K, the total pulse energy required for ignition of methane/air and air was 5.04 J/cm^3 and 6.27 J/cm^3 , respectively. Therefore, it was possible to reach flame ignition at inlet temperature lower than the minimum required temperature in the absence of plasma actuation, which means ignition was even possible in cold flow conditions, which could be important to address the re-ignition problems of aeroengines at high altitudes.

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