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Experimental and Numerical Investigations of Plasma Ignition Characteristics in Gas Turbine Combustors

Shizheng Liu, Ningbo Zhao *, Jianguo Zhang, Jialong Yang *, Zhiming Li and Hongtao Zheng

College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China; liushizheng1990@163.com (S.L.); 18646297262@163.com (J.Z.); lizhimingheu@126.com (Z.L.); zhenghongtao9000@163.com (H.Z.)

* Correspondence: zhaoningbo314@126.com or zhaoningbo314@hrbeu.edu.cn (N.Z.); yangjialongheu@126.com (J.Y.); Tel.: +86-0451-8251-9647 (N.Z.)

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Abstract: Reliable ignition is critical for improving the operating performance of modern combustor and gas turbines. As an alternative to the traditional spark discharge ignition, plasma assisted ignition has attracted more interest and been shown to be more effective in increasing ignition probability, accelerating kernel growth, and decreasing ignition delay time. In this paper, the operating characteristic of a typical self-designed plasma ignition system is investigated. Based on the optical experiment, the plasma jet flow feature during discharge is analyzed. Then, a detailed numerical study is carried out to investigate the effects of different plasma parameters on ignition enhancement of a one can-annular combustor used in gas turbines. The results show that plasma indeed has a good ability to expand the ignition limit and decrease the minimum ignition energy. For the studied plasma ignitor, the initial discharge kernel is not a sphere but a jet flow cone with a length of about 30 mm. Besides, the numerical comparisons indicate that the additions of plasma active species and the increases of initial energy, plasma jet flow length and discharge frequency can benefit the acceleration of kernel growth and flame propagation via thermal, kinetic and transport pathways. The present study may provide a suitable understanding of plasma assisted ignition in gas turbines and a meaningful reference to develop high performance ignition systems.

Keywords: plasma; ignition; gas turbine; combustor

1. Introduction

Ignition reliability is a key index in designing combustors because it directly affects the operation performance of gas turbines and their based power plant. In recent years, driven by the need for energy conservation and emissions reduction, many lean combustion concepts including twin annular premixing swirler (TAPS) [1], lean direct injection (LDI) [2], lean premixed prevaporized (LPP) [3], trapped vortex combustion (TVC) [4], flameless combustion (FC) [5,6], and pressure gain combustion (PGC) [7] were developed and attracted considerable attention. However, due to the fact that lean mixtures have slow flame speeds and a highly unstable flame, reliable ignition becomes one of the biggest challenges in the practice of lean combustion-based gas turbines. Besides, if affected by wet air or carbon deposition, the combustor of gas turbines is usually inevitably confronted with performance degradations of fuel spray nozzles and air swirlers, which can decrease ignition probability [8]. Therefore, developing an effective technology to achieve the reliable and robust ignition of gas turbines under various extreme operation conditions is urgently needed.

Initial kernel formation with energy deposition, early kernel growth to generate flame, flame stabilization and propagation to the whole reaction zone are the typical phases of ignition in gas turbine combustors [9,10]. In order to achieve ignition enhancement, there are three types of pathways [11–15]:

thermal, kinetic and transport. Thermal enhancement is increasing the reactant temperature to accelerate the chemical reaction rate according to temperature-sensitive Arrhenius dependence. Kinetic enhancement is realized by decreasing activation energies with the addition of many active key species and radicals, which can effectively accelerate, bypass or modify the slow initiation reaction pathways. Transport enhancement is accomplished by increasing the early kernel size (greater than the so-called critical flame initiation radius) and motion with multi-channels/points or jet flow.

Plasma, considered as a distinct "fourth state of matter", provides an unprecedented opportunity for ignition control and enhancement owing to its unique capabilities in fast thermal heating via electron collision [16], producing active species (such as O, H, OH, O_3, HO_2, and NO) [17,18], reforming fuel from large molecules to small ones [19] and increasing kernel size and reactant mixing via ionic wind [20]. Over the past few decades, a large number of experimental [21–28] and numerical [29–36] investigations have been carried out to study the performance and mechanism of various plasma assisted ignition systems. Mariani et al. [37] measured the ignition performance of radio frequency sustained plasma in engines and observed that plasma had a great ability to remarkably decrease ignition temperature and extend lean limit. Wang et al. [38], Hwang et al. [39], Wolk et al. [40], Michael et al. [41], Ikeda et al. [42] and Le et al. [43] respectively experimentally investigated the ignition characteristics of microwave plasma under various operating conditions. Their results consistently showed that compared to traditional spark thermal ignition, microwave assisted plasma ignition not only significantly extended the lean limit (about 20%), but also greatly improved flame stability due to the large kernel volume and the high amount of active species. Meanwhile, they also indicated that the ignition ability of plasma was heavily dependent on the discharge type, ignitor structure and operating parameters. Sun et al. [44,45] measured the effects of nanosecond pulsed plasma on ignition and extinction of CH_4–O_2–He diffusion flames and demonstrated that the non-equilibrium plasma generated by nanosecond pulsed discharge could make the conventional S-curve with separated ignition and extinction limits degenerate to the stretched S-curve without ignition or extinction limit, which thereby enhanced ignition. Besides, other studies [46–48] revealed that owing to non-equilibrium plasma, nanosecond pulsed discharge promoted the transition from the early ignition kernel to a self-propagating flame, and the increase of pulse frequency could effectively accelerate the growth of the kernel and reduce ignition delay time and minimum ignition energy. Using the well-defined counter-flow combustion system, Ombrello et al. [49] experimentally and numerically studied the kinetic ignition enhancement of CH_4–air and H_2–air diffusion flames by non-equilibrium magnetic gliding arc plasma. It was found that plasma discharge of air leaded to significant kinetic ignition enhancement, illustrated by large decreases in ignition temperature for a broad range of strain rates. They also stated that a combination of thermal/equilibrium plasma and non-thermal/non-equilibrium plasma might be a better choice for ignition enhancement. More research investigations into plasma assisted ignition can be found in the papers by Ju and Sun [50,51] and Starikovskiy and Aleksandrov [52].

Up until now, although significant progress has been made in the validation of plasma assisted ignition, the detailed enhancement mechanisms are still not clear because of the complex multi-scale physical and chemical interactions between plasma and flame. Besides, for the present experimental investigations, most of them are performed using simple lab burners, such as constant volume combustion chambers, counter-flow systems, flow tunnels, and swirled flow reactors, etc., but limited to one focus on the gas turbine combustor under the actual operating conditions. Moreover, in terms of numerical simulation, the plasma ignition kernel is usually replaced by a spherical heat source and ignores the effects of jet flow and active species, which further restrict the understanding of the plasma ignition mechanism and the design of advanced plasma ignition systems in practice. So, it is very necessary to do more investigations on plasma assisted ignition.

In this study, an unpublished self-designed plasma ignition system which has been successfully used in a gas turbine is presented. Firstly, the discharge and jet flow characteristics of the plasma ignitor in air are optically measured to obtain the actual shape of the initial kernel. Then, taking one can-annular combustor of a gas turbine as a sample and based on the above experimental results,

the ignition process is numerically analyzed. Finally, the effects of several key factors including the initial energy, concentration of active species generated by plasma, plasma jet flow length and discharge frequency on combustor ignition performance are discussed in detail.

2. Experiment Setup and Numerical Strategy

2.1. Experiment Setup

Figure 1 presents the test rig to measure the plasma jet flow characteristic during discharge in air. The basic experiment setup mainly consists of a plasma ignition system, a visualization measurement system, and a data acquisition and control system. As shown in Figure 1, the plasma ignition system is composed of the plasma ignitor, high voltage power source and cable. Once the high voltage pulse energy is delivered to the ignitor, a strong electric field between the anode and cathode will be established. When the electric field strength exceeds the breakdown threshold of air or a combustible mixture, discharge channels and the initial kernel are established. In order to obtain a large ignition kernel, several holes in the cathode wall and a unique structure for the anode are designed. More detailed information on the plasma ignition system can be found in [53]. Besides, the images of plasma jet flow during the discharge process are recorded by a high-speed camera (Phantom V7.3) with over 190×10^3 fps in the standard mode. The data acquisition and control system is used to trigger the high voltage power source and camera, record the discharge images, and change the discharge pulse parameters including voltage, frequency, and width.

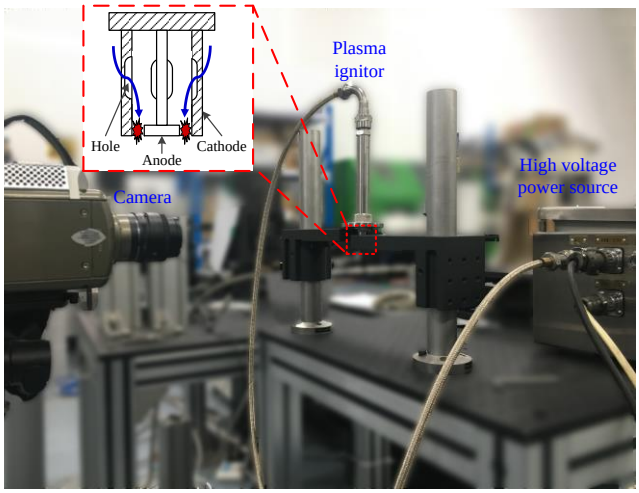

Figure 1. Schematic of the plasma ignition experiment setup.

2.2. Numerical Strategy

In the present study, a typical can-annular combustor (as shown in Figure 2) designed for gas turbines is used to numerically analyze the effects of plasma parameters on the ignition process. The length and outer diameter of the combustor are 760 mm and 1255 mm, respectively. There are 10 primary holes with a diameter of 14 mm, five dilution holes with a diameter of 13 mm (up) and 16 mm (down), and 10 rows cooling holes with diameter of 1–1.5 mm.

Comprehensively considering the basic ignition characteristics and the simulation ability of the computer, a simple physical model shown in Figure 3a is selected as the computational domain. All of its geometric parameters are consistent with the corresponding ones in Figure 2. Figure 3b presents the location of the plasma ignitor. The structured grids are generated by ANSYS ICEM to discretize the computational domain, and the grid densities near the ignition zone are sufficiently high. After the grid convergence and mesh independence validations, the final total grid number used in this numerical study is 360,000.

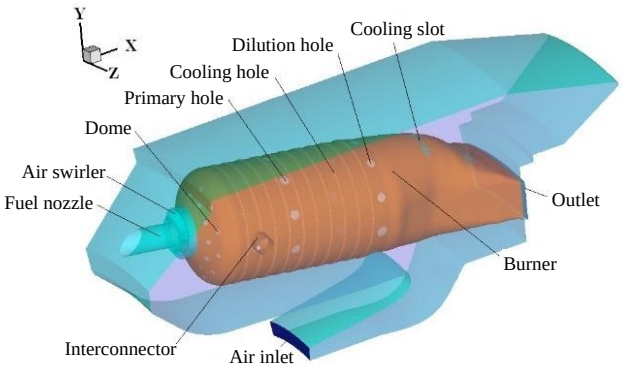

Figure 2. Can-annular combustor of a gas turbine.

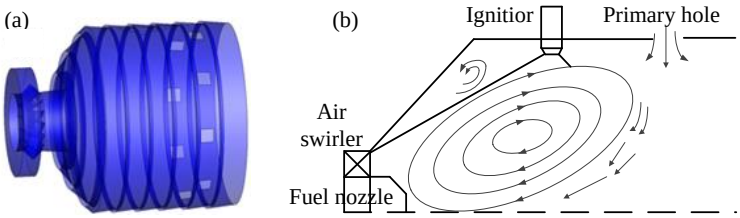

Figure 3. (**a**) Three-dimensional (3-D) computational domain and (**b**) 2-D profile.

Based on our previous numerical comparison and analysis [54], the ideal gas assumption and pressure-based Navier–Stokes solver are employed to solve the equations. The viscosity of the reactant mixture is considered, and the realizable k-ε turbulence model is selected. Gravity, buoyancy, thermophoretic force, and radiation heat transfer are ignored. The eddy dissipation concept (EDC) combustion model and cone spray model are employed. The numerical time step is 0.1 ms. The reaction rate constant is calculated using the Arrhenius formula. Due the reasonable computational cost and to discuss the effects of several plasma active key species on ignition enhancement, a reduced detail chemical mechanism for air–$C_{12}H_{23}$ (12 species and 10 steps [55]) including the intermediate species of O, OH, and CO, is used.

During numerical simulation, mass flow inlet boundaries are used for the inlet of air (0.19875 kg/s) and $C_{12}H_{23}$ (0.00600 kg/s) which are the actual values of one operating condition of a gas turbine. The temperature and pressure of air are 366 K and 0.218 MPa, respectively. The outlet selects the pressure outlet boundary. The ignition process simulation is realized by user defined function (UDF).

Figure 4 shows the numerical temperature fields of a can-annular combustor in Li [54] and the above simple model. The comparison shows that there is little difference between them. This means that it is feasible to numerically study the ignition process of a gas turbine combustor using the presented simple computational domain and numerical approach.

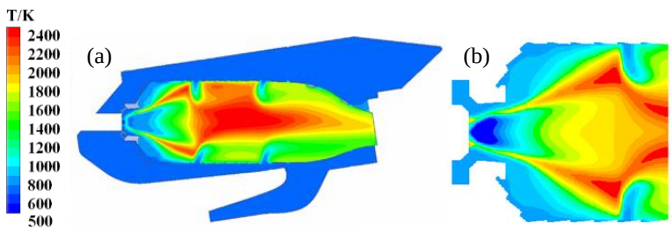

Figure 4. Numerical results of (**a**) Li [54] and (**b**) the present study.

3. Results Analysis and Discussion

3.1. Plasma Jet Flow Characteristics During Discharge

As mentioned above, the initial kernel size is an important factor affecting the ignition process and directly dependent on the geometric and discharge characteristic of the plasma ignitor. To better capture the jet flow information of plasma, the frequency and width of the discharge pulses are properly increased in the present test. Based on the experiment setup shown in Figure 1, Figure 5 images one discharge process of the self-designed plasma ignition system. As shown in Figure 5, a small initial discharge kernel is generated at time of 0.4 ms with the trigger of a high voltage pulse. Then, due to the design of the holes in cathode wall and the unique structure of the anode, the generated plasma or the heated air expand quickly, which is the so-seen jet flow. After 2.4 ms, the jet flow size begins to decrease gradually due to the interruption of the discharge.

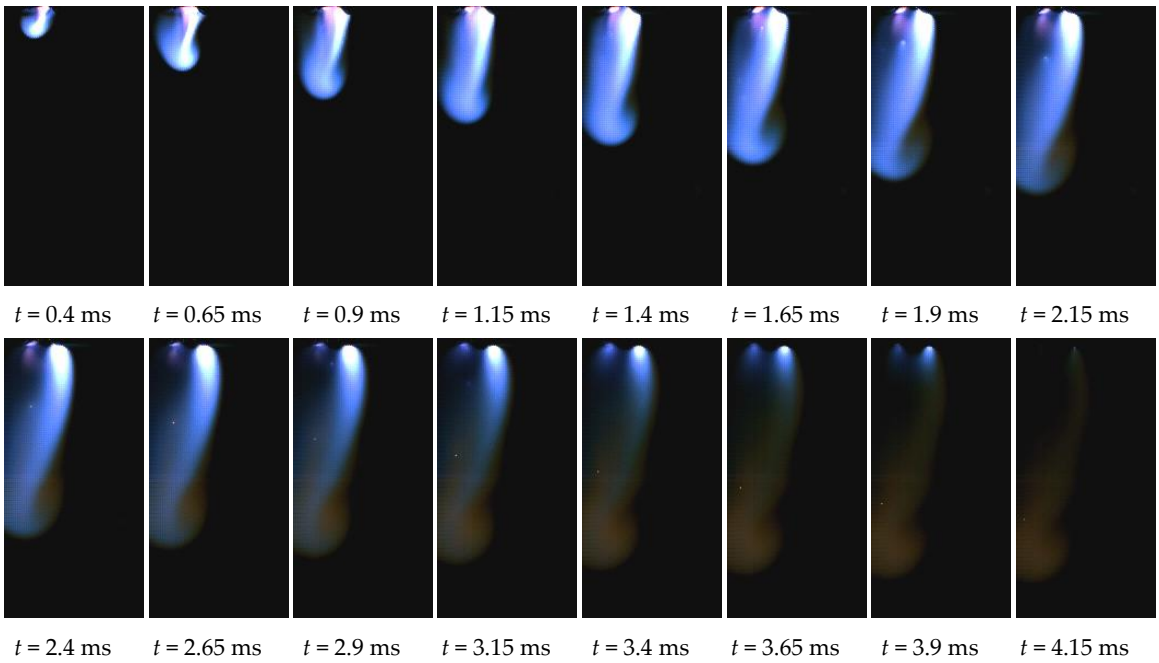

Figure 5. Plasma jet flow sequence during discharge.

Besides, a careful inspection of Figure 5 reveals that for the designed plasma ignition system, the discharge kernel is cylindrical or cone-shaped which is significantly different from the normal sphere obtained by most conventional spark or high-energy ignition systems. In addition, according to the further quantitative analysis (as shown in Figure 6), it is found that the maximum jet flow size has a length of 30 mm and a diameter of 10 mm. The kernel filled by active species and high temperatures (which is the highlighted area in Figure 6) has a length of 10 mm and a diameter of 6 mm, which is larger than those of many other spark or plasma assisted ignition systems [56,57]. This may mean that the present plasma ignition system has great potential to enhance the ignition performance of combustors and to improve the operational ability of engines.

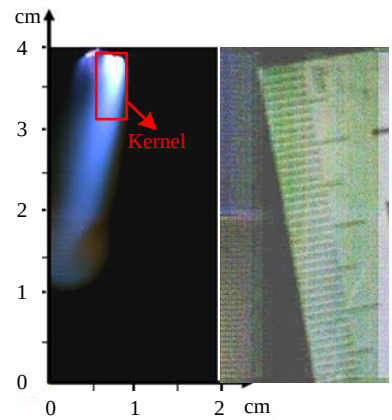

Figure 6. Plasma jet flow size at t = 2.4 ms.

3.2. Ignition Process Analysis in Gas Turbine Combustors

Considering the above plasma jet flow characteristic, Figures 7 and 8 respectively present the profile and cross section (X = 130 mm) numerical temperature field evolution of a successful ignition process of a can-annular combustor. Before ignition, the temperature of air is so low that the evaporation rate of the fuel droplet is very slow. Once a discharge kernel is generated, the produced high temperature can accelerate the evaporation of the droplet [10,14,16,58]. When the discharge heat energy is high enough to trigger the chemical activity of the reactant, a local ignition kernel is formed. Subsequently, owing to the comprehensive effects of plasma discharge in flow jet and active species (mainly including O, OH and CO, etc.), the initial ignition kernel gradually grows and develops into a flame, as shown at t = 6 ms. Then, the local flame rapidly propagates to the surrounding combustible reactant in the secondary backflow zone. The temperature field at the time of 50 ms shows that the tangential flame spread area is affected by the strong shear stress of the swirled air, and is now obviously larger than the axial one. Later, with the propagation of the flame to the primary hole, the flame propagation speed in the tangential direction will be slower than that in the axial direction. This is because for the present combustor geometry and boundary conditions, the axial velocity of the flow field is high, as shown in Figure 9. Besides, careful observation of Figures 7 and 8 reveals that up to a time of 150 ms, the flame still mainly propagates in the secondary backflow zone and has not yet been into the main backflow zone which has high turbulent kinetic energy and can easily cause the flame to extinguish. On this basis, at a time of 260 ms, most of the reactants in the secondary backflow zone are ignited, and due to the strong jet flow of air from the primary hole, the flame is rapidly transported to the main backflow zone. After that, driven by the main backflow field, the flame gradually propagates towards the inlet and then ignites the whole combustor head and forms the stable self-sustaining flame.

According to the above analysis, it can be concluded that both ignition parameters and flow field distribution are important factors that affect ignition performance of a combustor. In order to realize a successful ignition of a gas turbine under the actual operating condition, there are two necessary constraints. Firstly, high temperature, large volume and massive active species for the initial ignition process are needed to enhance the evaporation of the fuel droplet, the acceleration of the chemical reaction, and the stable growth of flame kernel. Secondly, the heat generated by the formed local flame must be higher than the cold flow, which ensures the stable propagation of the flame in the secondary and main backflow zones. Otherwise, the generated ignition kernel or flame cannot be effectively propagated and will be extinguished.

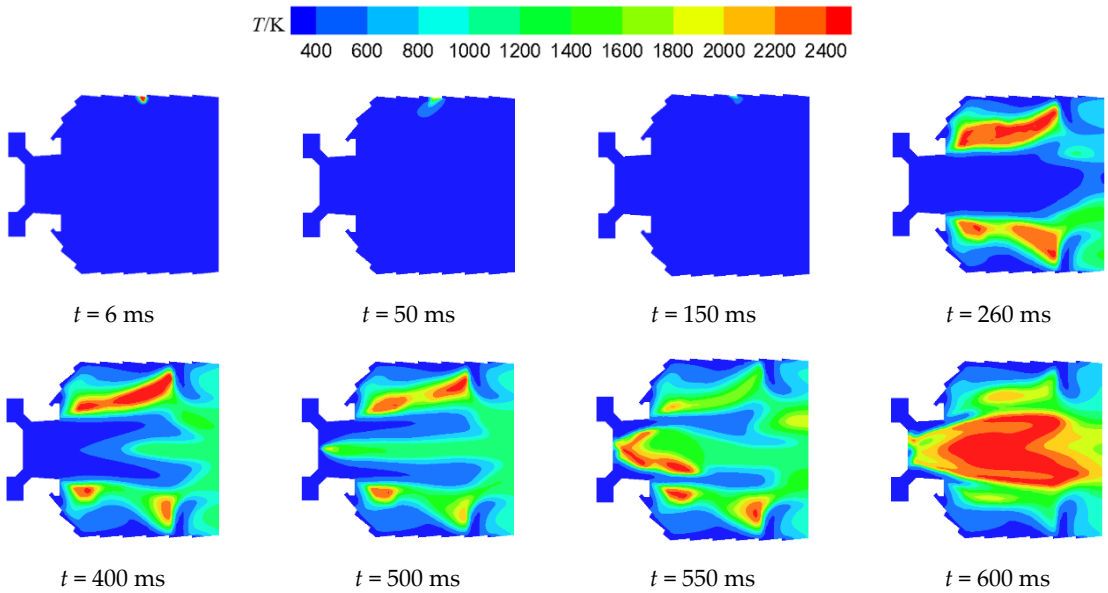

Figure 7. Numerical temperature field of combustor profile.

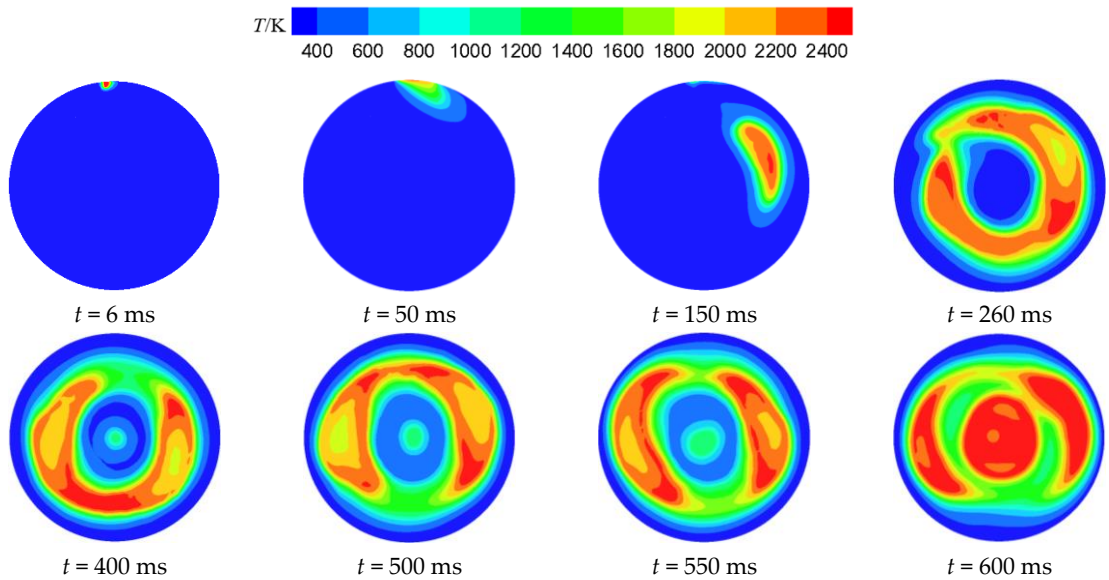

Figure 8. Numerical temperature field of combustor cross section (X = 130 mm).

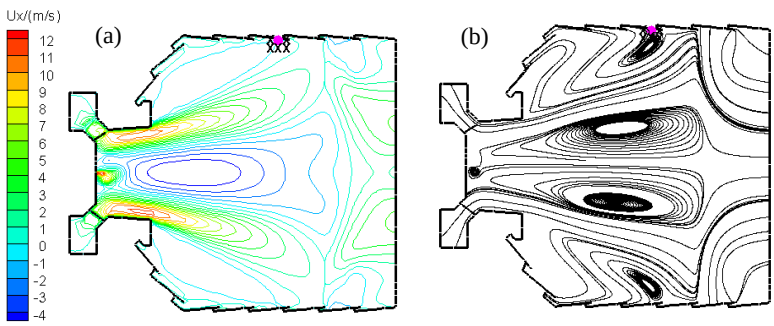

Figure 9. (**a**) Axial velocity and (**b**) streamline distribution.

3.3. Effects of Different Factors on Plasma Ignition Performance

Thermal, kinetic and transport are three well-known mechanisms for plasma ignition enhancement. In order to better understand the plasma assisted ignition process in an actual gas turbine combustor, this section will discuss the effects of the above three mechanisms by changing the initial energy, active species concentration, jet flow length and discharge frequency.

- *Energy and Active Species*

The generation, evolution and disappearance of active species during plasma discharge result from the multiscale interactions between electrons, positive and negative ions, and radicals. Such complex physical and chemical processes usually imply that the type of active species are directly dependent on the plasma discharge behavior and reactant properties. To the best of our knowledge, it is still very difficult to accurately numerically simulate the detailed characteristics of plasma active species and their effects on ignition or combustion using the commercial software ANSYS FLUENT. In order to overcome this problem, the effects of plasma active species on the air–$C_{12}H_{23}$ based ignition process is realized by simply varying the concentrations of the O atom, OH radical and CO [59,60].

Table 1 lists the detailed parameters of one-time ignition for numerical comparisons. From Table 1, it is clearly seen that under the present operating conditions, both increasing ignition energy and increasing active species can enhance the ignition performance. In the absence of plasma, the energy to ignite the combustor is not less than 400 W. However, when the active species are added, the corresponding energy can be decreased to 300 W. Besides, the comparisons of Cases A–E show that the addition of plasma active species improves the combustor ignition ability. One of the main reasons behind this is that the excited O, OH and CO will significantly contribute to the induction of the chain reaction and the enhancement of chain propagation with fuel molecules, which effectively shorten the ignition delay time. This is commonly regarded as the kinetic mechanism of plasma.

Table 1. The detailed ignition parameters and results.

Cases	Initial Kernel Radius (mm)	Initial Jet Flow Length (mm)	Ignition Energy (W)	Active Species	Results
A				0	failure
B				1% (O+OH+CO)	failure
C			300	2% O + 1% (OH+CO)	successful
D	4	12		3% O + 1.5%(OH+CO)	successful
E				4% O + 2%(OH+CO)	successful
F			400	0	failure
G			500	0	successful

Further, the results shown in Figure 10 indicate that at lower concentrations of active species, plasma can reduce the time needed for successful ignition (it is the difference between the initial time and the time when temperature is up to 660 K and chemical reaction rate is up to 2.0 kmol/m^3 s). For example, the time in Case C is about 276 ms, but the time in Case D is only 215.5 ms, which means that there was a decrease of 28%. However, in the case of strong plasma (i.e., Cases D and E), active species have little effect on ignition behavior. Compared to OH and CO, O plays a more positive role in ignition enhancement. The above results indicate that the generation and control of plasma active species is the key factor to realize the compact design and performance optimization of plasma ignition systems.

In order to further evaluate the enhancement performance of plasma ignition, Figure 11 compares the maximum excess air coefficient which can reflect the lean ignition limit under different inlet air temperatures. The greater the maximum excess air coefficient, the more lean the reactant. As pictured in Figure 11, due to the effects of active species, the lean ignition limit of the combustor can be extended. The enhancement is about 3% when the inlet air temperature varies from 280 K to 400 K. Meanwhile, the results show that with the increase of inlet air temperature, the ignition performance is also enhanced. This is because increasing air temperature is beneficial to the evaporation of fuel droplets, the mixing and transportation of the reactant, and the induction of the chemical reaction.

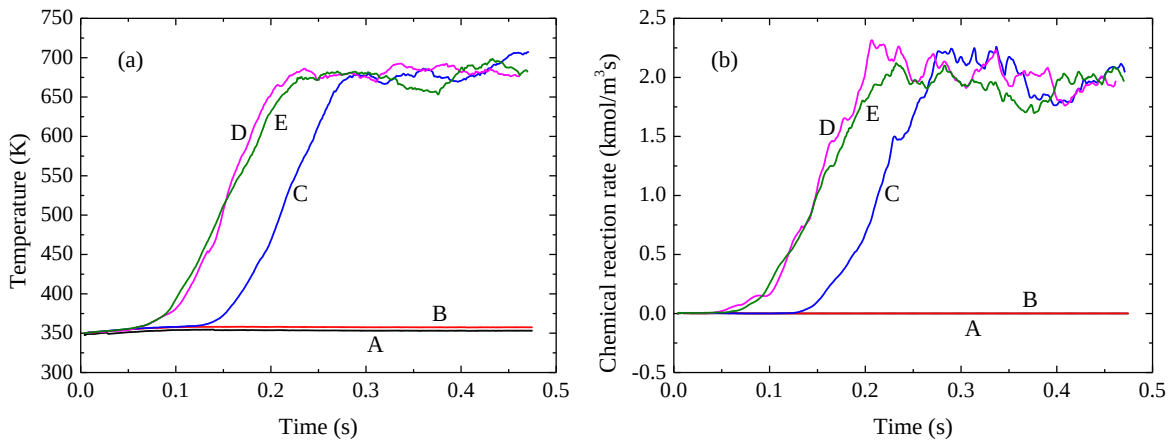

Figure 10. The changing of the combustor (**a**) average temperature and (**b**) chemical reaction rate with time in Cases A–E.

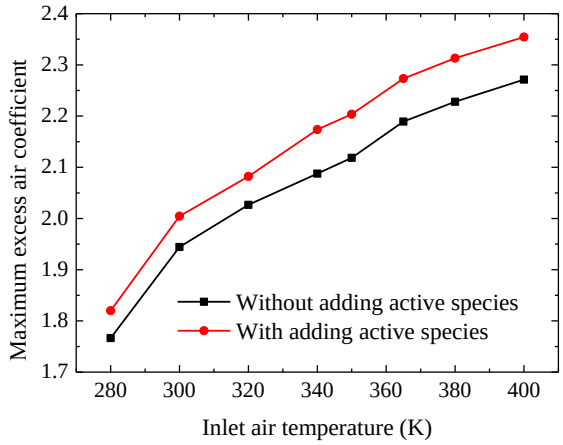

Figure 11. Effects of plasma active species on lean ignition limit.

- *Jet Flow Length of Plasma*

In practice, besides the geometry of the ignitor, the complex electromagnetic coupling phenomena can accelerate the movement of electrically charged particles, which then improve the jet flow of plasma. Motivated by this reason, this section will discuss the effects of plasma jet flow length (changing from 4 mm to 20 mm) on the ignition process of a combustor. All other parameters are consistent with those in Case C.

Table 2 gives the ignition results under different jet flow lengths. The results show that when the length is larger than 8 mm, the combustor can be ignited successfully. This effectively verifies the concept of critical flame initiation radius discussed by Chen et al. [61], Kim et al. [62], Kelley et al. [63] and Lin et al. [64]. However, in Case H, the jet flow length is so small that the high temperature and large number of active species are only gathered near the combustor wall and cannot be effectively transported into the secondary backflow zone (as shown in Figure 12a), which leads to the generated local flame kernel being very unstable. Besides, the fuel field distribution shown in Figure 12b reveals that due to the effect of velocity profile, the mass fraction of the fuel near the combustor wall is less than 0.045. Such a lean mixture will furtherly decrease the ignition ability of a combustor.

Table 2. Combustor ignition ability under different plasma jet flow lengths.

Cases	Initial Jet Flow Length (mm)	Results
H	4	failure
I	8	successful
J	12	successful
K	16	successful
L	20	successful

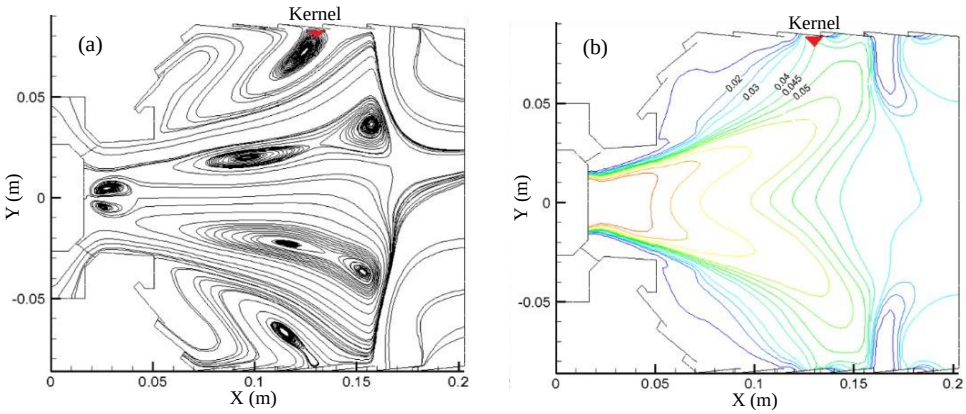

Figure 12. (**a**) Streamlines and (**b**) fuel mass fraction distributions.

On this basis, Figure 13 compares the time varying average temperature and chemical reaction rate of the combustor with different plasma jet flow lengths. The results show that with the increase of jet flow length, although the combustor can be ignited successfully, the time for successful ignition will be increased firstly and then decreased. For Cases I–L, the corresponding times for successful ignition are 211 ms, 276 ms, 251 ms and 202 ms, respectively. This is because although increasing jet flow length increases the kernel volume, the energy density is decreased as the initial ignition energy is consistent. Lower energy densities cause flame instability. So, the time for successful ignition will decrease when the jet flow length is slightly larger than the critical value (about 12 mm in this study). Then, with the further increase of jet flow length, a larger backflow zone center area and larger high mass fraction fuel area can be covered by the local flame kernel. When the positive effects exceed the adverse ones, the time for successful ignition will be shortened.

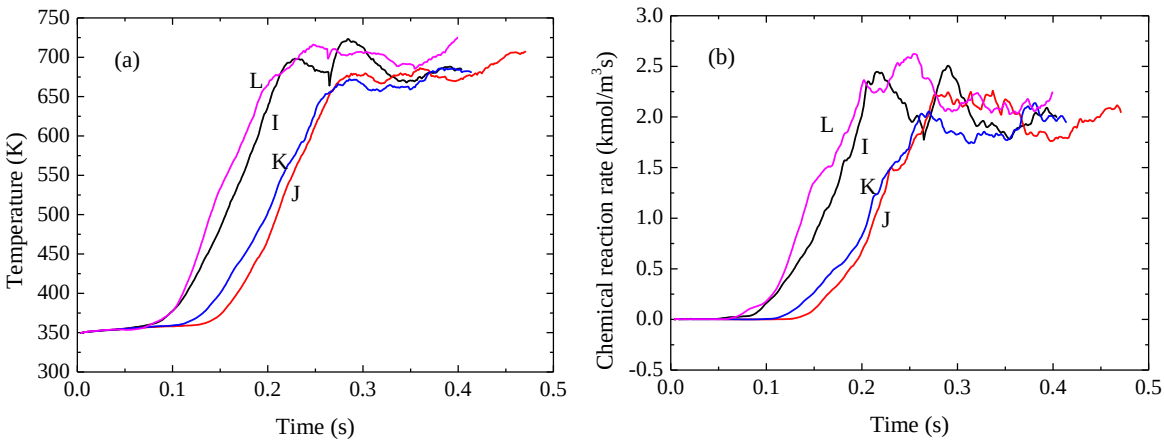

Figure 13. The changes of a combustor (**a**) average temperature and (**b**) chemical reaction rate with time in Case I–L.

From the above analysis, it can be concluded that plasma jet flow length is indeed an important factor affecting the ignition performance of a combustor. Meanwhile, both the flow and fuel fields should be considered comprehensively during the actual design of plasma ignition systems and combustors. When the ignition energy is more concentrated in the center of the backflow zone and is closer to the appropriate equivalent ratios, the ignition performance of the combustor is better.

- *Discharge Frequency*

Many available experimental investigations emphasized that at a constant discharge energy, increasing the pulse number would benefit the plasma properties and extend the lean ignition limit. In this section, the discharge frequency is varied from 19.2 Hz to 31.3 Hz, and all other parameters are consistent with those in Case B.

Table 3 lists the ignition results under different discharge frequencies. From Table 3, it is observed that the increase in discharge frequency can indeed enhance the ignition ability of a combustor. Combined with the numerical temperature fields shown in Figures 14 and 15, we found that multi-time discharge is helpful to improve the generation and propagation of the flame kernel. One of the main reasons for this is that increasing the discharge frequency can effectively enhance the transport of active species and heat to the surrounding mixture. Moreover, the results shown in Figures 14 and 15 also indicate that compared to Case N, Case O has a shorter time for successful ignition.

Table 3. Combustor ignition ability under different discharge frequencies.

Cases	Discharge Frequency (Hz)	Results
M	19.2	failure
N	23.8	successful
O	31.3	successful

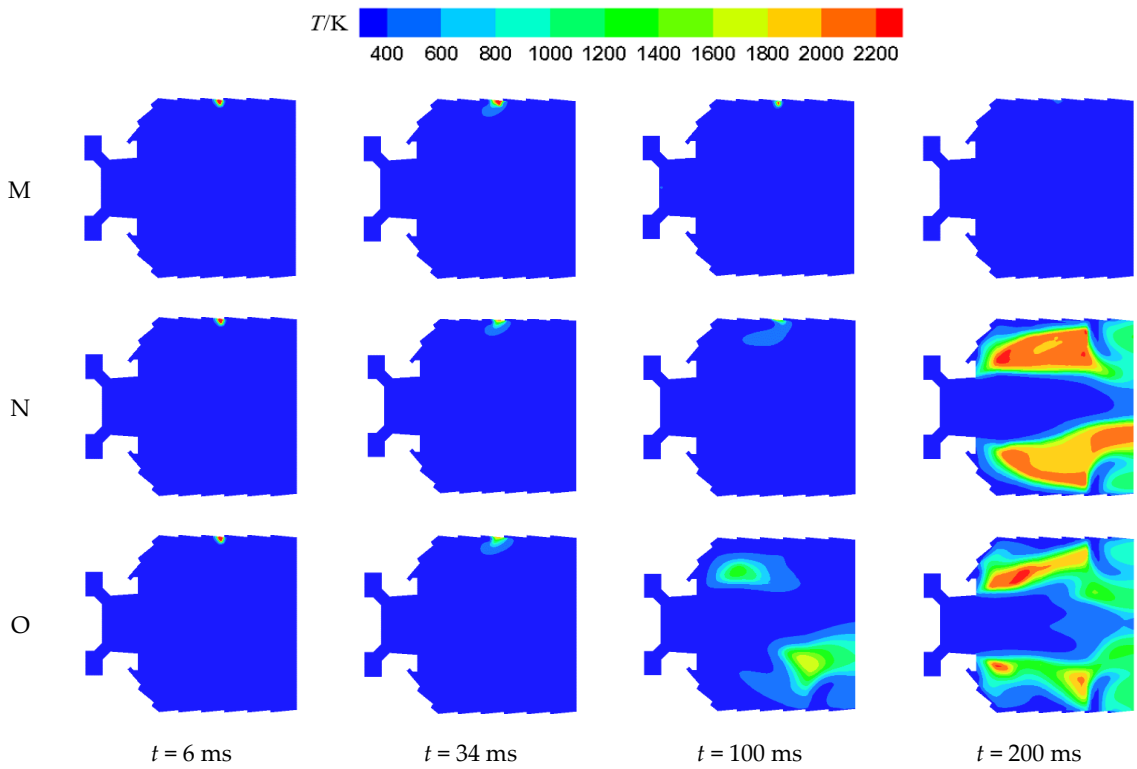

Figure 14. Numerical temperature field of combustor profile in Cases M–O.

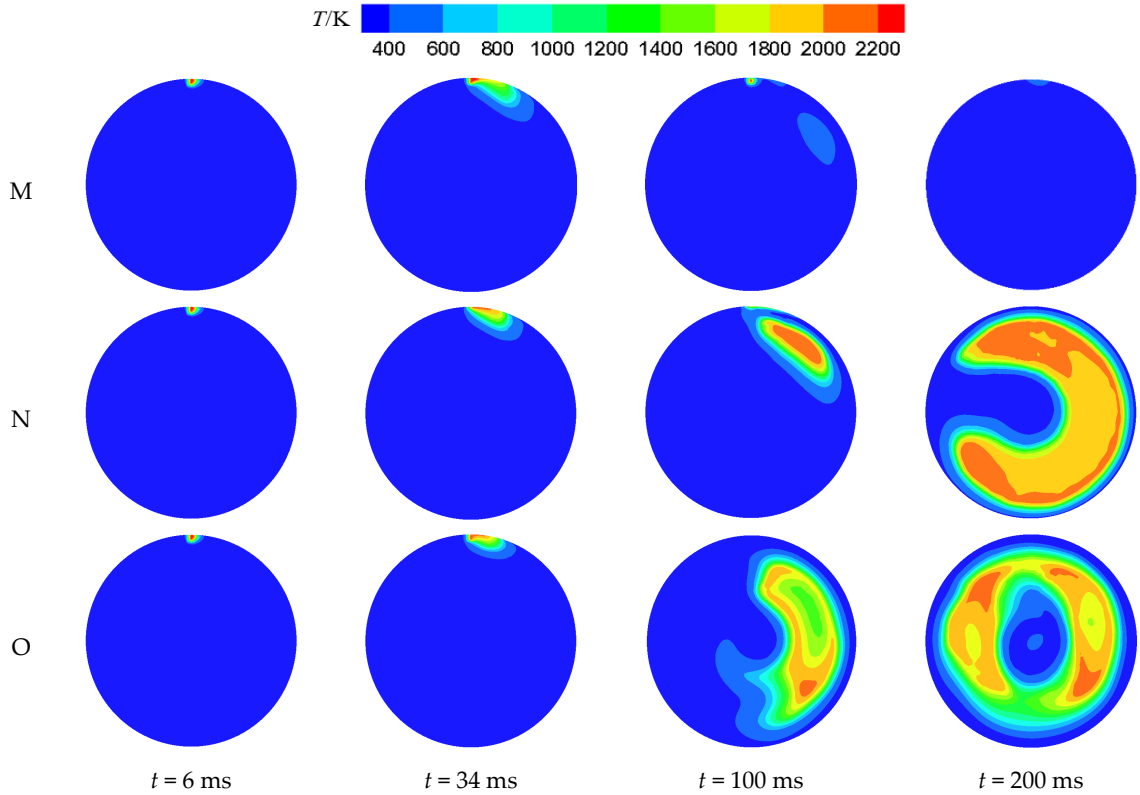

Figure 15. Numerical temperature field of combustor cross section (X = 130 mm) in Cases M–O.

To analyze the failure mechanism of Case M, Figure 16 illustrates the time varying average temperature and chemical reaction rate of the combustor. The results show that although every discharge can increase the chemical reaction rate, the formed local flame kernel is so small that it extinguishes quickly before triggering next discharge. Since the ignition energy is difficult to accumulate, the formed flame is usually very unstable and cannot self-sustain its propagation in the combustor. On the other hand, in order to realize the ignition enhancement via control discharge frequency, the time interval between two discharges should be shorter than the burnout time of the previous discharge, especial for the early phase of ignition.

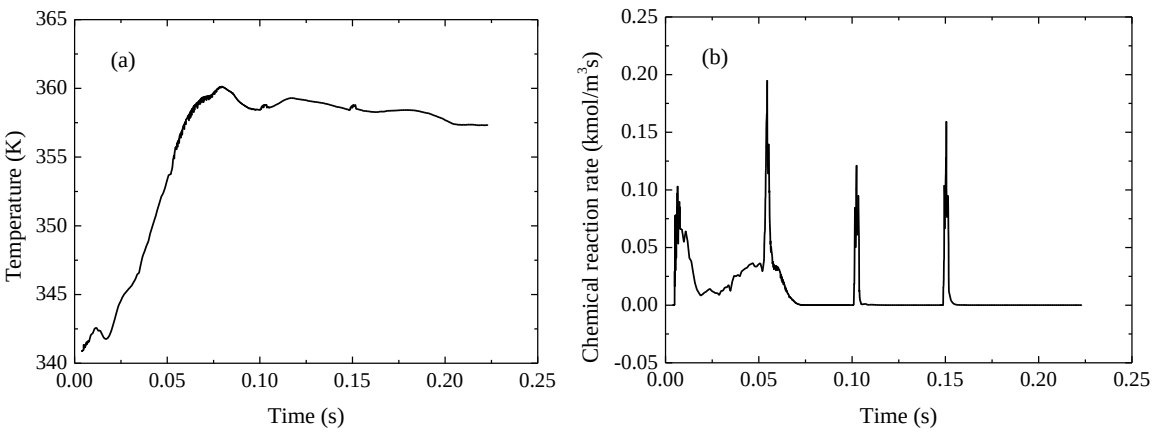

Figure 16. The changes of combustor (**a**) average temperature and (**b**) chemical reaction rate with time in Case M.

Overall, the ignition of combustor is a very complex transit chemical reaction process and its performance can be significantly affected by ignition parameters, inlet conditions and flow field

distribution, etc. Therefore, in practice, the optimizing of various factors is very important to improve the ignition ability of gas turbine combustors.

4. Conclusions

The effects of plasma on the ignition process is investigated for the combustor of gas turbines. Taking one self-designed plasma ignition system as an example, high speed imaging is utilized to capture the jet flow development of plasma. On this basis, the plasma assisted ignition phase and the performance of the combustor are numerically analyzed at different ranges of initial energy, active species concentration, jet flow length and discharge frequency. The major findings of this study are summarized as follows:

(1) In contrast with the conventional spark ignitor, the present measured ignitor possesses the obvious plasma jet flow feature during discharge. Based on the effective design geometry, the jet flow length can be larger than 30 mm.
(2) The actual ignition process of a gas turbine combustor is related to the ignition parameters, backflow zone and fuel distributions. Therefore, realizing the complex optimization of different factors is the key to improve combustor ignition ability.
(3) The application of plasma can significantly enhance the ignition performance, not only for time for successful ignition but also for lean ignition limit. Besides, initial energy, active species concentration, jet flow length and discharge frequency are very critical factors affecting the ignition process. With the increase of the above four parameters, the ignition ability can be enhanced to different degrees.
(4) Although the effects of plasma on ignition is analyzed, the detailed physical and chemical process of plasma generation and evolution are not considered in this study due to limitations in the numerical approach and software. This means that many enhancement mechanisms of plasma assisted ignition cannot be clearly understood. Therefore, it is very necessary to develop an effective tool to improve the numerical precision of plasma assisted ignition.

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