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Multi-channel nanosecond discharge plasma ignition of premixed propane/air under normal and sub-atmospheric pressures

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ABSTRACT

Relight of jet engines at high altitude is very difficult due to the relatively low pressure and temperature of inlet air. Currently, advanced ignition technology for high-altitude relight in jet engines is urgently needed. Successful ignition is achieved only when the ignition kernel can propagate outwardly beyond the so-called critical flame initiation radius. At high altitude with low pressure, the critical flame initiation radius becomes large and it cannot be easily reached by the ignition kernel. Therefore, in order to achieve successful ignition at low pressure conditions, large ignition kernel should be generated. In this study, plasma assisted ignition using multi-channel nanosecond discharge (MND) is proposed to induce a large ignition kernel and to achieve successful ignition at low pressures. Ignition experiments for propane/air mixtures at different equivalence ratios ($\Phi = 0.8\sim1.6$) and under normal and sub-atmospheric pressures ($P = 0.3\sim1.0$ bar) were conducted in a constant volume combustion chamber. The performance of three ignition methods, spark discharge, single-channel nanosecond discharge (SND) and MND, were assessed; and the advantages of MND for ignition at sub-atmospheric pressures were demonstrated. The ignition kernel development, ignition probability, minimum ignition energy, and flame development for these three ignition methods (spark, SND and MND) were measured and compared. It was found that compared to spark and SND, MND can generate a much larger ignition kernel with stronger flame wrinkling and has much higher ignition probability, especially at low pressures. Therefore, MND has the advantage in achieving successful ignition at low pressure. Besides, it was shown that though the ignition kernel evolution and ignition probability strongly depend on ignition methods, the subsequent flame propagation is not greatly affected by ignition and there is little change in the flame rise time for different ignition methods.

1. Introduction

Reliable high-altitude relight is crucial for safety and performance of jet engines [1,2]. At high altitude, the pressure and temperature of inlet air to the combustor are relatively low, which results in slow fuel vaporization and chemical reaction [2,3]. Consequently, high-altitude relight become extremely difficult, especially at altitude above 10 km [2,4–7]. Currently, advanced ignition technology for high-altitude relight in jet engines is urgently needed [8,9].

To achieve successful ignition, the amount of energy deposited into the combustible mixture should to be larger than the minimum ignition energy (MIE) [10], otherwise, the resulting ignition kernel eventually decays and it cannot reach the so-called critical flame initiation radius [11–13]. The critical flame initiation radius depends on the Lewis number of the deficient reactant and is proportional to the flame thickness [13]. At higher altitude with lower pressure, the flame thickness becomes larger and so does the critical flame initiation radius. In order to achieve successful ignition, large ignition kernel should be generated at low pressure conditions.

Non-equilibrium plasma is a promising technology for ignition and combustion control [14]. Among different plasma technologies, the nanosecond discharge plasma has recently received great attention and it has been shown to greatly enhance ignition and combustion [14–17]. For examples, Xu et al. [18,19] investigated the development of the ignition kernel induced by nanosecond discharge in lean propane/air mixture. They found that nanosecond discharge with higher frequency or larger number of pulses can effectively reduce the MIE. Sun et al. [20,21] demonstrated that

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the nanosecond discharge can make the classical S-curve with separated ignition and extinction limits degenerate to the stretched S-curve without ignition or extinction limit. Starikovskiy et al. [22,23] used nanosecond discharge to control ignition in a rapid compression machine and achieved two-order of magnitude reduction in ignition delay. Lefkowitz et al. [24] examined the effects of nanosecond discharge on ignition using both flame-development visualization and pulsed detonation engine testing platforms. They found that at higher pulse-repetition frequencies (>10 kHz), multiple pulses promote the transition from a ignition kernel to a self-propagating flame and thereby enhance ignition. Besides, though it is not considered in the present study, microwave was also demonstrated to be able to enhance the ignition (e.g., [25–28]). Other examples can be found in the recent review paper by Ju and Sun [14].

However, previous studies mainly focused on single-channel nanosecond discharge (SND) and volumetric nanosecond discharge. Although SND is useful for ignition and combustion enhancement, it is not effective to increase the ignition kernel size at low pressure. The multi-electrode geometries for ignition were investigated in previous studies. Schenk et al. [29] used the multiple tips to distribute the corona directly in a larger ignition volume and thus have better ignition performance. Yu et al [30] used multi-coil power supply to generate distributed spark discharge, which produces faster early flame kernel growth than that of a single high energy spark. Briggs et al. [31] compared several ignition methods including multi-electrode ignition, which shows that a large effective flame kernel and/or a long kernel lifetime is very important for ignition at lean condition.

For nanosecond discharge plasma ignition, the transient nanosecond plasma [32,33] and the nanosecond surface dielectric barrier discharge plasma [34–36] can generate several random discharge channels, which is very useful for ignition. Comparison of transient nanosecond plasma ignition with spark ignition was done, and the effect of electrode geometry (needle to needle, needle to semicircle and rod to ring) on transient plasma induced ignition performance was studied [32,33]. Several fuel-air mixtures ignition using nanosecond surface dielectric barrier discharge plasma was investigated [34–36]. Ignition delay times, energies deposited in the gaseous mixtures and other parameters were analyzed. Three regimes of multi-point ignition were observed: ignition with a few kernels, quasi-uniform ignition along the edge of high voltage electrodes and ignition along the plasma channels.

In this study, a novel method of multi-channel nanosecond discharge (MND) is introduced to increase the ignition kernel size and to achieve successful ignition at low pressure. To the authors' knowledge, MND has not been used for ignition in previous studies. The objectives of this study are to assess the performance of three ignition methods, spark, SND and MND, and to demonstrate the advantages of MND for ignition at sub-atmospheric pressures. Ignition experiments of premixed propane/air mixture at different equivalence ratios and pressures were conducted in a constant volume combustion chamber. The ignition kernel development, ignition probability, minimum ignition energy, and flame development for different ignition methods were measured and compared.

2. Experimental methods

The experimental setup is shown schematically in Fig. 1. Ignition experiments were conducted in a closed cylindrical combustion chamber whose inner diameter is 5 cm and length is 6 cm. The combustion chamber is made of stainless steel. A pair of quartz windows is mounted at the ends of the cylindrical combustion chamber to allow optical access. Propane/air mixture at specified equivalence ratio was first prepared in a premixing chamber and then filled into the combustion chamber. A broad range of the equivalence ratio, $\Phi = 0.8{-}1.6$, was considered. In all experiments, the initial temperature was fixed to be 300 K. Different initial pressures in the range of 0.3–1.0 bar were considered. A 20-kHz pressure transducer (Jcsensor CYG-1102) was used to record the pressure evolution inside the combustion chamber.

As indicated by in Fig. 2(a), a replaceable electrode and its base are placed in the middle of the cylindrical combustion chamber. The electrode holder is made of a nylon insulating material and it separates the electrode from the metal combustion chamber. Figure 2(b) and (c) show two types of electrode assembly which were used to investigate the performance of different ignition methods. The electrode assembly in Fig. 2(b) is referred to as the single-channel nanosecond discharge (SND), which adopts the single channel discharge actuator. For SND, nanosecond discharge is generated between two electrodes with a gap distance of 1 mm. The multi-channel nanosecond discharge (MND) shown in Fig. 2(c) adopts multiple channel discharge actuator. For MND, all the electrodes are on the same vertical plane and the gap distance is 4 mm. Reliable multi-channel nanosecond discharge was obtained through circuit optimization.

Two types of power supply were used respectively for the nanosecond discharge and spark discharge. The nanosecond discharge generator is a FID Technology FPG 20-20NK with input impedance in the range of 200–500 Ω. The discharge frequency is in the range of 0–20 kHz, and its voltage can be varied continuously from 0 to 20 kV. For spark discharge, the electrode assembly is the same as that of SND shown in Fig. 2(b). In order to make SND and MND comparable, the same voltage output control of FID power supply is adopted. The comparison between the SND and MND is done with the same position of voltage regulation knob. The electrical circuit for spark discharge is shown in Fig. 3. It consists of a DC power supply, a resistor, a capacitor and a trigger module. The output voltage range of the DC power supply is 0–10 kV. The capacitor is 10 nF and the resistor is 167 MΩ.

To quantify the ignition energy, the voltage and current signals were measured by a 75-MHz high-voltage probe (Tektronix P6015A) and a 120-MHz current probe (Pearson 6600), respectively. A 1-GHz oscilloscope (Tektronix DPO4014) was used to record these two signals. The ignition kernel propagation was imaged by high-speed schlieren photography. A high-speed CCD camera operated at the frame rate of 40,000 fps and exposure time of 15 µs was used to record these images.

3. Results and discussion

3.1. Comparison between spark and nanosecond discharge in air

Figure 4 shows the voltage and current profiles during a spark discharge in air. It is well known that the spark discharge process consists of three stages: the breakdown stage, the arc stage and the glow stage [37]. During the breakdown stage, the voltage is shown to be around 4.7 kV. A narrow plasma channel appears and the gap impedance decreases rapidly. Consequently, the current increases rapidly and it goes through the channel with little energy loss. During the arc stage, the plasma channel expands rapidly and transforms into a current channel. As shown in Fig. 4, the current reaches the peak value of 318 A at the time around $t = 0.145$ µs, which is followed by oscillating attenuation. The mixture around the plasma channel reaches very high temperature and thereby an ignition kernel is generated. During the glow stage, most of the discharge energy is released though the current and voltage both decrease. The energy loss at the glow stage is much larger than that at the arc stage, which leads to low energy availability for ignition. The total energy of the spark discharge shown in Fig. 4 is 61.6 mJ.