Flame Stability in Inverse Coaxial Injector Using Repetitive Nanosecond Pulsed Plasma

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Recently, methane has been investigated as a feasible fuel for propulsion systems. The higher boiling point and higher density of methane, compared with hydrogen, makes its storage tank lighter, cheaper, and smaller to launch. Methane is abundant in the outer solar system and can be harvested on Mars, Titan, Jupiter, and many other planets and therefore, it can be used in reusable rocket engines. However, there are still some technological challenges in the methane engines development path. For example, ignition reliability and flame stability are of great importance. These challenges can be addressed by integrating low-temperature plasma (LTP) through repetitive nanosecond pulsed (RNP) discharge to the injector design. This research focuses on air/CH4 jet flames in a single-element coaxial shear injector coupled with RNP plasma discharge to study the influence of LTP on ignition characteristics and flame stability using advanced diagnostic techniques. The experiments have been performed for different fuel composition, jet velocities, discharge voltages, and frequencies at atmospheric conditions. The transient flame behavior including flame oscillation is studied using direct photography by CMOS high-speed camera. The effect of plasma discharge location on flame stability is also investigated. To demonstrate the effectiveness of RNP discharge on liftoff and blowout/blowoff velocities, the jet velocity at the critical conditions is measured and the enhancements of flame stability are then evaluated. The collected experimental data have shown that the RNP discharge can significantly extend the stability by reducing the liftoff height and increasing the velocity of blowout/blowoff phenomena. [DOI: 10.1115/1.4046227]

Keywords: *low-temperature plasma, repetitive nanosecond pulsed discharge, methane, jet flame, flame stability, fuel combustion*

1 Introduction

There has been recently a growing interest in the use of methane as a strong candidate for both interplanetary and descent/ascent propulsion solutions. The development of methane propulsion system technology became a priority for NASA over the last decade. This is due to some beneficial characteristics of methane compared with other fuels in this application. For example, for the same amount of fuel, it needs a smaller and cheaper tank compared with hydrogen, because it is more dense and boils at higher temperature [1–3]. Compared with refined kerosene, methane has a higher specific impact, higher regenerative cooling capability, and lower coking property [4,5]. Moreover, methane exists in the outer solar system and can be extracted from many solar system objects to be used in reusable rocket engines [6]. On the other hand, it comes with some technical challenges which make the methane engines development more complex. Among those challenges, ignition reliability and flame stability [7,8] are of great importance particularly due to methane longer ignition delay, higher ignition energy requirement, and lower diffusive characteristics as compared with hydrogen. The ignition should occur uniformly and simultaneously with exact timing to avoid detonation and conflagration pressure waves. In addition, at the high-speed flow and high-power conditions, the combustion instability will result in a flame blow-out. To take advantage of methane [9,10] in the next generation propulsion devices, an external low-power stabilization and enhancement system is required.

One method that has been shown effective to improve the stability of the combustion system is adding an electric field [11]. Ju et al. [12] presented major enhancement pathways of plasma-assisted combustion and a significant kinetic effect on ignition and flame stabilization, particularly at low temperatures. Starikovskii [13] investigated the importance of plasma to the burner. The flammability limit of the propane-air mixture could be reduced to $\varphi = 0.55$ using a pulsed nanosecond barrier discharge. This value in the absence of discharge is $\varphi = 1.1$. Meanwhile, Min Lee et al. [14] measured the decreases of liftoff height, implying that flame stabilization can be enhanced with negligible power consumption by the open circuit. Pham et al. [15] claimed the plasma energy deposited in one pulse is less than 1% of the power of the flame. Won et al. [16,17] focused on the relationship between propagation speeds and electric field intensity. In the research of Vincent-Randonnier et al. [18], the detachment height of a lifted diffusion flame of methane is lowered when a dielectric barrier discharge is activated. Kim et al. [19,20] discussed the effect of plasma in different voltage regimes and frequency regimes. The variation of blowoff velocity with alternating current (AC) frequency showed a non-monotonic behavior in that the velocity decreased and then increased, exhibiting minimum blowoff velocity near 6–8 Hz. Celano et al. [21] presented detailed temperature distribution and derived heat flux data sets using large-eddy simulation. De Giorgi et al. [22] applied plasma actuation to enhance flame stability under two different conditions: central fuel jet and central oxidizer jet. Plasma actuation effects become evident when voltage and/or frequencies reached values of, respectively, 20 kV and 1750 Hz. Morovatiyan et al. [23] investigated how the electrode characteristics affect the discharge properties. The soot formation characteristics were investigated under the effects of temperature, fuel structure, and fuel concentration, underlining that central oxidizer jet had lower soot loading. Other researches [24,25] confirmed that plasma actuation

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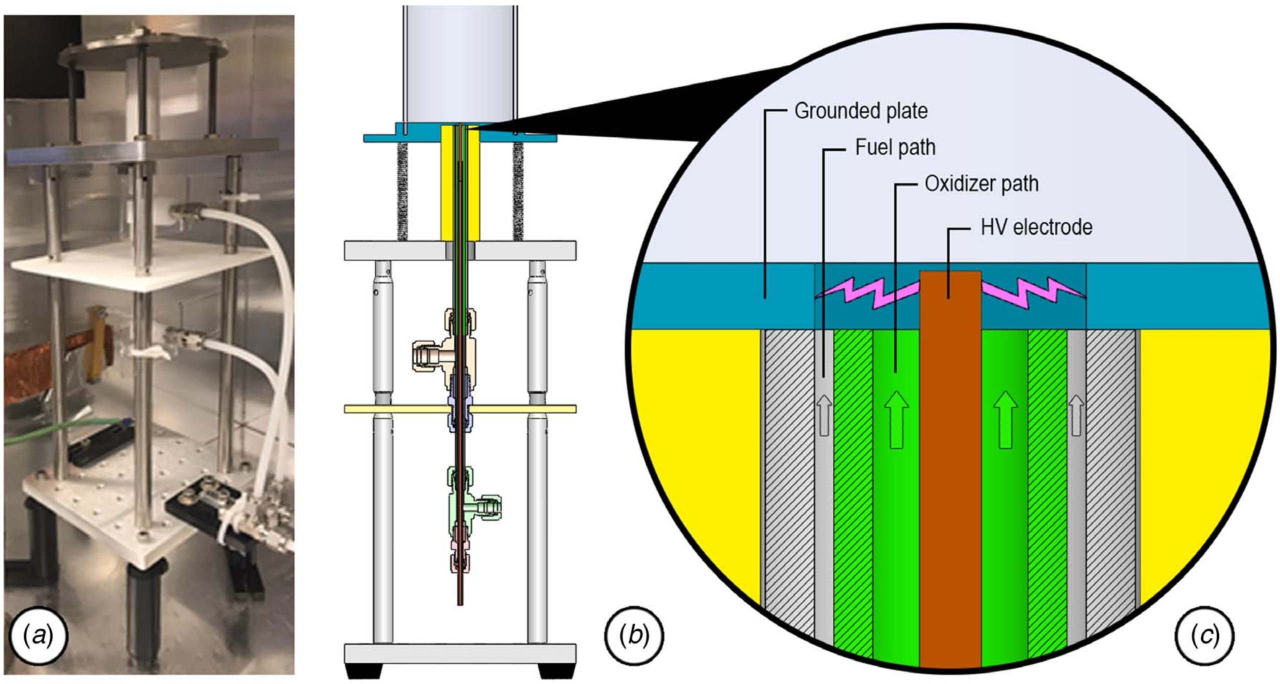

Fig. 1 (*a*) Real picture and (*b*) cross section of the plasma-assisted burner with (c) illustration on nozzle and discharge spot

had an evident increase in the lean blowout limits under different fuel/air ratios and electric fields. Plasma also enhanced the emission intensities of crucial radicals in combustion. Results [26] showed the rise of the OH* intensity by increasing the airflow rate in the inner tube.

Plasma is divided into two main categories: (1) thermal (high-temperature) plasma [27–29] and (2) non-thermal (low-temperature) plasma. In the present work, low-temperature plasma (LTP) through repetitive nanosecond pulsed (RNP) discharge, for the first time, is integrated with a single-element coaxial inverse injector of an air-methane diffusion jet flame to stabilize the flame, enhance the ignition, and extend the blowout limit. The low-temperature plasma has emerged as a new promising technology to stabilize the flames [30–32], to control the ignition [33–36], to reduce the emissions [37–39], and to increase the efficiency while not increasing the complexity of combustion devices [40,41], particularly at extreme conditions [42–46]. Tests are conducted with varying methane and air flow rates under different plasma frequency conditions to see how the lean blowout limits and lift-off height change.

2 Experimental Setup

The experimental setup consists of three main parts: the plasma-assisted burner, nanosecond pulse generator, and Faraday cage. The plasma-assisted burner is a single-element coaxial shear inverse injector which enables us to impose high-voltage low-temperature nanosecond plasma on the fuel and oxidizer jets. The injector geometry was designed and built based on the methane-powered additive-manufactured thruster that has been developed at Marshall Space Flight Center [47]. Figure 1(*a*) shows a real picture of the plasma-assisted burner. For further illustration, Fig. 1(*b*) defines the different parts of the plasma-assisted burner in a cross-sectional view. The discharge and fuel-oxidizer nozzle areas are also presented in more details in Fig. 1(*c*). The burner structure includes stainless steel stands, bases, bolts, and a grounded plate to ensure rigidity of the system. Moreover, a polytetrafluoroethylene (PTFE) plate holds the burner core. A ceramic stand has been used to make sure that the grounded plate stands firm and concentric to the core.

The tungsten high-voltage (HV) electrode has been located in the center of the burner and surrounded by the fuel and oxidizer glass tubes. The inlet and connection fittings are all made of PTFE. The implication of PTFE parts guarantees the insulation of the HV core from the surrounding metal parts and the discharge at the top. The nanosecond plasma generator system is responsible for delivering high-voltage (up to 20 kV) high-frequency (0.5–10 kHz) pulses of nanosecond width (≈10 ns). Power supply, pulse generator, and trigger device are the main three components of HV nanosecond pulse generator. The SSPG-20X-HP1 pulse generator (Fig. 2) from the Transient plasma system is the nanosecond pulse generator powered by Ametek XG600-2.8 power supply device (0–600 V and 0–2.8 A direct current (DC) output). In addition, an Agilent MSO-X2024A oscilloscope was used as the triggering device to provide the transistor–transistor logic (TTL) signal in the desired range of frequency (0.1–5 kHz).

Fig. 2 SSPG-20x nanosecond pulse generator and XG600 dc power supply

The high-voltage high-frequency discharges generate a huge amount of electromagnetic interferences (EMI) which may disturb the electronic devices in the surrounding environment. In some cases, it may even damage some sensitive devices. This is especially an important issue considering the measuring devices in the lab. To minimize the amount of EMI exposed to the lab, a Faraday cage has been designed and built. The cage is shown in Fig. 3. Moreover, it was designed in a way that can provide reliable grounding and HV connectivity for the burner. Using a copper sheet, the lower stainless-steel plate has been connected to the Faraday cage as well as to the grounding of the pulse generator. This will provide a unified grounding for the whole system and prevent a ground loop. Three windows have been cut through the sidewalls to make photographing and optical diagnosis possible. Another exhaust hole has been made on the top wall right above the flame. Two ventilation fans have been placed on two corners to avoid system overheating.

The fuel and oxidizer flow measurements have been done via FMA-A2100 Mass-flow Meters from Omega. These flowmeters can measure the flows up to 70 standard liters per minute (SLM) with an accuracy of $\pm 1\%$. In addition, the flame shape has been recorded by means of two cameras in different plasma and flow conditions. A high-speed mono-color complementary metal–oxide–semiconductor (CMOS) camera, Phantom V611 [48], has been utilized to deliver suitable photos for image processing and geometrical data extraction. A second color CMOS was used to take color photos from the flame.

3 Results and Discussion

Using the supply system and flowmeters, different conditions of flow regimes and combustible mixture compositions have been prepared and tested. Some combinations of discharge voltages and frequencies were selected to provide information about the effects of plasma streamers on flame stability. The main point of interest in this research is determining the effects of nanosecond plasma on diffusion jet flame in an inverse coflow burner. The data are presented in three parts. First, the feasibility of RNP discharge on enhancing and initiating the ignition process is shown. Second, the effects of nanosecond plasma discharge on flame stability and liftoff height are investigated. Finally, it is discussed how discharge extends the flammability limit.

3.1 Laminar Flame Enhancement. To investigate the effects of RNP on flame structure, a rich laminar flame is considered. The

Table 1 Flow conditions for air and methane in the inverse diffusion burner as in Fig. 4

	Flowrate (SLM)	Mass flowrate (g/s)	Flow velocity (m/s)	Reynolds (–)
CH_4	6.0	0.07	9.79	1543
Air	7.0	0.14	11.03	1464

flow conditions are illustrated in Table 1. The ignition can be initiated with RNP discharge even without an external ignition source. This means that RNP discharge not only can improve the flame stability but also can eliminate the need for an external ignition source for non-autoignited jet flames at which the temperature is lower than the autoignition temperatures. In addition, the RNP discharge changes the flame structure and flame becomes shorter and wider which are the specifications of premixed jet flames as shown in Fig. 4 (dashed line shows the location of the burner top). The intermediate radicals generated during the discharge have higher diffusivity which leads to lowering the molecular diffusion time and consequently enhancing the mixing process through the RNP discharge. In addition, the flame becomes more turbulent and stable.

3.2 Liftoff Height Reduction. Figure 5 shows the effect of applying plasma in different discharge frequencies from 0 to 5 kHz by steps of 1 kHz. The methane-air flow conditions in Fig. 5 are introduced in Table 2 at which the air flow is laminar and the methane flow has gone fully turbulent. The flow conditions have been selected in a way that the flame in the no-plasma case would be lifted off. As shown in Fig. 5, RNP discharge will reduce the liftoff height linearly by plasma frequency which is equivalent to enhancing flame stability. The flame becomes fully attached at a frequency of 4 kHz and increasing the frequency beyond this point does not have an effect on liftoff height but can still improve the stabilization through mixing enhancement (dashed line shows the location of burner top).

Liftoff height is a representation of either ignition delay time [49,50] of the fuel in diffusion flames that the surrounding air is hot enough to cause autoignition. In other words, the flow moves along the flow direction for a time equal to ignition delay time [51], so higher the ignition delay time longer the liftoff height [52]. On the other hand, when the temperature of the flow is low, the laminar burning speed [53–55], can be used to describe the liftoff height. In high velocities where the flow speeds are higher than the

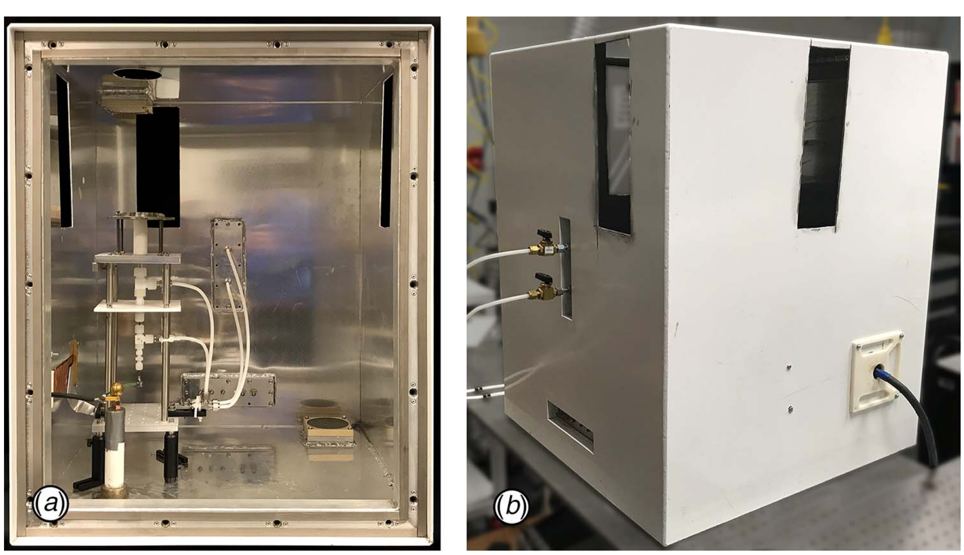

Fig. 3 Faraday cage (*a*) front-view with the lid opened and (*b*) side-view with the lid closed

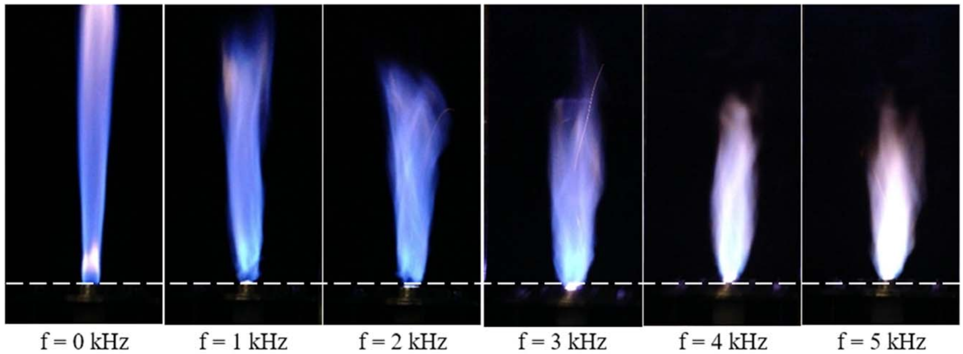

Fig. 4 Effect of RNP discharge on ignition enhancement (dashed line shows the location of the burner tip)

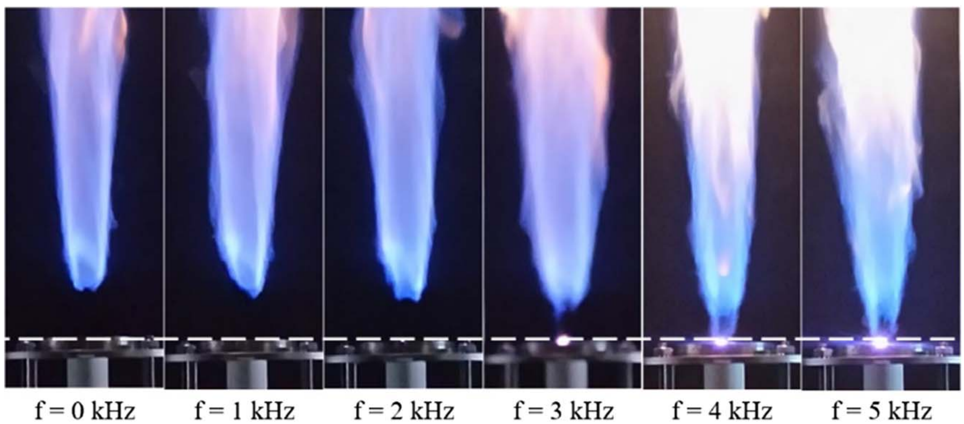

Fig. 5 Effect of RNP discharge frequency on flame stability at different discharge frequencies

Table 2 Flow conditions for air and methane in the inverse diffusion burner as in Fig. 5

	Flowrate (SLM)	Mass flowrate (g/s)	Flow velocity (m/s)	Reynolds (–)
CH_4	20	0.220	32.65	5143
Air	10	0.201	15.75	2091

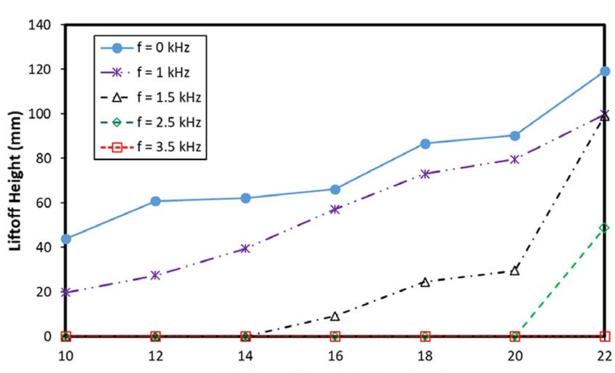

Fig. 6 Effect of fuel flowrate and discharge frequency on liftoff height for air flowrate of 10 SLM

flame speed, the flow pushes the flame back to a point where both speeds are equal.

Figure 6 shows the effect of RNP discharge frequency on the behavior of the flame at different methane flowrates. In this figure, the air flowrate was kept constant at 10 SLM. As shown, the employment of plasma has two main effects on the flame. First, it delays the flame liftoff, so the flame is attached at much higher fuel flowrates. Second, the liftoff height is reduced as the frequency increases from 0 to 3.5 where the flame is attached.

3.3 Flammability Region Extension. The plasma utilization in the burner is expected to expand the flammability region. An experiment has been designed to investigate this phenomenon. In this experiment, the CH_4 flow is fixed. Then, the air flow increases to the point that the flame blowout. The same set of experiments was conducted with plasma discharge at different frequencies. The resulted extinction points are previewed in Fig. 7 as the global equivalence ratio versus air jet velocity. It shows that RNP plasma is extending the lean-flammability limit and results in lower global equivalence ratios.

4 Conclusion

Methane jet propulsion has been an important part of combustion investigation in recent years, but it comes with some limitations. In this research, nanosecond plasma discharges have been investigated as a tool to solve some of the practical limitations. An innovative experiment setup, in conjunction with a nanosecond plasma generator, was introduced to apply high-frequency nanosecond plasma to fuel/oxidizer flow and visualize the outcomes. The effects were discussed regarding the flame structure and initiation, liftoff height, and flammability region. It was shown that repetitive nanosecond plasma was capable of starting the combustion and enhance the flame structure. They can also reduce the liftoff height and make the combustion more stable. It was also observed that as a result of adding nanosecond plasma to the combustion, flames can

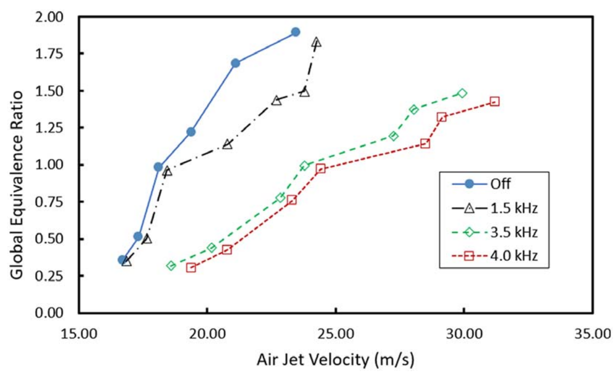

Fig. 7 Flame extinction conditions in different flow condition by increasing air flowrate at different plasma frequencies

occur in a wider area regarding the global equivalence ratio. An important point of interest in the RNP application is the low energy deposition at the burner outlet compared with the combustion heat release. As a comparison, although the heat released by the lowest methane flowrate is in the order of 3.5 kW, the deposited energy by RNP at 5 kHz, i.e., the highest deposited power, is in the range of 13 W.

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