On the low-temperature plasma discharge in methane/air diffusion flames

Saeid Zare, Hao Wei Lo, Shrabanti Roy, Omid Askari

Mechanical Engineering Department, Mississippi State University, Starkville, MS, 39762, USA

Abstract

Interest in methane has grown recently because of its encouraging characteristics. However, methane comes with serious concerns regarding stability and flammability limitations. Some methods have been proposed to improve the ignition characteristics of methane in diffusion flame burners such as electrical fields, dielectric barrier discharge, and low-temperature plasma. In this study, an innovative single-element coaxial shear injector coupled with a high-voltage nanosecond pulse generator has been used to study the effects of low-temperature plasma (LTP) discharge on methane/air inverse diffusion flame at different plasma and flow conditions. The stability analysis focuses on the detachment conditions of the flame and how RNP discharge can delay this phenomenon, explaining the presence of an optimal operating point with the least applied energy. Comparing the lean blow-off limits for the cases with and without plasma discharge, it is shown that low-temperature plasma discharge enhances the flammability of the diffusion flame. The effect of LTP discharge on laminar flames is also discussed using chemiluminescence photography. It shows that the shape of the diffusion flame becomes more similar to premixed flame with more air entrainment and stability. Resultantly, it is shown that RNP discharge can improve the flame stability and ignition characteristics.

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1. Introduction

Recently, there has been a growing interest in the utilization of methane [1] as a strong source of energy for both interplanetary and descent/ascent propulsion solutions. It has also shown some promising characteristics in comparison with other fuels used for this application. For instance, it is denser than hydrogen and has a higher boiling point, so the storage tank would be cheaper and lighter. Moreover, methane is harvestable on many objects, e.g. Mars and Titan, in the solar system [2,3]. In this case, you don’t need to carry fuel for the return trip. As a result, aerospace agencies and corporations like NASA and SpaceX have prioritized the development of methane propulsion system technology [4–6] in reusable rocket engines. Raptor engines are an example of these methane-fueled systems.

Moreover, fossil fuels have been of great concern due to their important shortcomings and search for alternatives is a hot topic in the literature [7,8]. Methane is also an important part of natural gas which as the alternative energy sources is facing a growing interest and market due to presenting various advantages in comparison with traditional fossil fuels like coal and petroleum [9–13]. Because of its low carbon to hydrogen ratio, methane produces lower levels of pollutants. Furthermore, leaner combustion of methane leads to reduced emissions, such as NOx, and higher thermal efficiency. However, the low heating value of the methane should be mentioned as a shortcoming of this fuel [14], as well as its low ignitability and relatively low flame speed. These shortcomings lead to the combustion instability issues [15] which should be addressed in the advanced combustion systems.

Flames used in combustion systems are divided into two main categories of premixed and non-premixed (diffusion) flames. Premixed flames are the main choice for the commercial applications (reciprocating engines and various types of burners) because of their fast combustion characteristics with less soot formation [16], however, they have an inherent risk of flashbacks [17]. Premixed flames also have some important drawbacks of low flame temperature, narrow flammability limits, easy blow-off, and low stability [18,19]. As a result, in many practical applications, diffusion-flame-based systems are of great interest because they can be controlled easily, are more stable, and safer. They also have a larger...
flammmability range. Some applications of non-premixed flames are rocket combustors, furnace heating, turbine engines, pilot flames, and even chemical synthesis [18,20–23]. For example, in plans for Mars2020 mission, NASA has performed preliminary tests on 3-D printed, methane-powered thruster which is made by a series of diffusion injectors as shown in Fig. 1 [24].

Depending on the arrangement of the fuel and oxidizer outlets in the combustor, diffusion flames are categorized into two groups of normal diffusion flame (NDF) and inverse diffusion flame (IDF). While the NDF burners have a central fuel jet surrounded by annular airflow, the IDF can be recognized in a coaxial burner by a central high-speed air jet and a low-speed annular fuel jet [21,25]. NDFs are known for relatively higher rates of soot formation.

In contrast, it was shown that the significant difference in momentum between the air and fuel jets in IDF configuration causes better entrainment of fuel flow and improves mixing in the IDF configuration [23]. Subsequently, the soot formation is reduced in IDF as shown in some investigations [21,26–28]. Moreover, it was shown methane/oxygen IDF leads to enhanced radiation heat flux compared to an NDF burner with the same condition [23].

In spite of the stability and flammability improvements in IDF burners, there are still some challenges in using low carbon fuels like methane. Ignition reliability and flame stability are of great importance particularly due to longer ignition delay, higher ignition energy requirement and lower diffusive characteristics. Therefore, to take advantage of methane in the next generation propulsion devices, an external low-power stabilization, and enhancement system is required.

Flame stability is dependent on various parameters such as geometry, flow conditions, and fuel composition. Stability enhancement through these parameters is very challenging and sometimes leads to a major and expensive design change. However, generating a region of charged/excited species and active radicals sometimes leads to a major and expensive design change. However, enhancement through these parameters is very challenging and

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Flame stability is dependent on various parameters such as geometry, flow conditions, and fuel composition. Stability enhancement through these parameters is very challenging and sometimes leads to a major and expensive design change. However, generating a region of charged/excited species and active radicals (by electron impact excitation and dissociation reactions) [29] right upstream of the lifted flame can significantly promote the stability of flames even under high strain rate (e.g., turbulence) and/or near-lean-flammability-limit conditions. This can be done using different techniques like applying an electrical field, dielectric barrier discharge (DBD), or low-temperature plasma.

Electrical discharges in different forms have been suggested to improve flame characteristics through kinetic enhancement [30]. Some of these studies will be discussed to highlight the contribution and achievements of these prior studies. Min Lee et al. [31] performed a series of experiments on non-premixed propane jet flames assisted by AC electrical field, including measuring the liftoff height, reattachment velocity, and propagation characteristics. The flame became more stable through increasing discharge voltage and AC frequency. They also modeled the correlation of liftoff velocity with given voltage and frequency, it is easy to estimate the point where flame detaches from the exit tube. Won et al. [32,33] continued the experiments with the same device setup, showing that the propagation speeds of tribrachial flames in both AC and DC electric fields were correlated nearly linearly with the electric field intensity. Kim et al. [34,35] focused on the detailed effect of DC and AC power supply on different voltage and frequency regimes. In the low-frequency regime (<60 Hz), the blow-off velocity was lower than the baseline condition and had a linear dependence on AC voltage. A transition regime with a frequency between 40 and 50 Hz was identified, where the minimum electric field enhanced flame stabilization.

Investigating the advantages of DBD, Vincent-Randonnier et al. [36] conducted a series of tests using dielectric barrier discharges, also called as silent discharges. When a DBD was activated at the exit of the tube, the detachment height of a lifted diffusion flame reduced drastically. This process consumed an outstandingly small electrical power, which was less than 1 Watt. De Giorgi et al. [23,37] investigated the effects of sinusoidal dielectric barrier discharge (DBD) on an inverse diffusive methane/air flame at under different flame and plasma actuation conditions. They found that the plasma flame enhancement is significantly influenced by the plasma discharge, which is due to the enhanced mixing and chemical reactions.

In addition, with the aim to produce stable flames, there has been a growing interest in repetitive nanosecond pulsed (RNP) plasma as a low-temperature plasma (LTP). LTP is a class of plasma for which the temperature of the electrons is greater than the gas temperature. These electrons generate combinations of excited species, radicals, and ions by dissociation, excitation, and ionization of the gas molecule. Both consequences of nanosecond spark discharges, the thermal and chemical effects, are presumed to enact effectively in plasma assisted combustion applications [38]. In jet flames, as the fuel (oxidizer) stream passes through the region affected by RNP discharges, the electron number density and concentration of charged/excited species and active radicals are significantly increased. The high reaction rate of electron impact excitation and dissociation reactions (picosecond to nanosecond scales) significantly accelerate the fuel pyrolysis and oxidation and reduce the autoignition delay times by orders of magnitude. These species tend to react at a much lower temperature through the kinetic enhancement pathways [39] which only require small energy input and generate multiple ultra-fast, reliable, repeatable, and co-existing autoignition sources which in turn enhance the flame stability [40]. This technology is receiving considerable attention due to its low-power consumption and uniform discharge distribution while not significantly increasing the complexity of combustion devices [41,42]. The LTP has emerged as a new promising technology to stabilize the flames [43–45], accelerate the ignition [46–48], reduce the emissions [49–51] and increase efficiency drastically [52–54], particularly at extreme and near-lean-flammability-limit conditions [55–59]. In RNP plasma the power consumption required for the electric field is relatively small to the power of the flame [60]. Therefore, it is an efficient and realistic method to generate a stable flame.

Starikovski et al. [61] investigated the principal role of processes with the formation of excited molecules that supports the development of the chain oxidation. They showed that applying a non-equilibrium discharge leads to the electronic excitation of the gas components, the production of active particles (in particular, atomic oxygen), and the acceleration of the processes governing the combustion rate and the flame propagation velocity. Nagaraja et al. [62] demonstrated how the radical evolved inside McKenna burner at different time spot. The simulation results showed a significant

![Fig. 1. Methane-powered thruster: Injector (left) and chamber (right) [24].](image-url)
increase in O, H, and OH density due to nanosecond plasma discharges. Pilla et al. [63] applied the nanosecond repetitively pulsed plasma on turbulent premixed flame and found an advantage on extending the stability of the flame at lower equivalence ratios. High concentration of active radicals recorded by spectrometer, are used to explain the improved characteristics. Pham et al. [60] showed that the of the lean extinction limit can be reduced about 10–15%, by applying RNP discharges and using small amount of energy. It was also shown in previous studies [74] that RNP discharges can be used effectively as a source of ignition.

General studies in literature show the benefits of LTP techniques such as repetitive nanosecond pulsed discharge on flames. However, further studies are required to cover the special application. Coaxial inverse jet flame, is one of these applications which lack enough data in the literature. In this work, low-temperature plasma in the form of repetitive nanosecond pulsed (RNP) discharges was employed on a single-element inverse coaxial diffusion flame burner to improve the ignition and flame characteristics. The single-element burner is designed and built in a way that its geometry is similar to one of the single injectors used in the NASA 3D printed rocket engine shown in Fig. 1. This will help to fundamentally study the effect of RNP discharge by isolating the complicated aerodynamic effect imposed by other injectors. The RNP discharges in this setup are applied directly to both air and fuel flows at the nozzle location, due to the special geometry. A technique that is found rarely in the literature. The main objective of this work is to study the influence of RNP discharge on stability mechanism, e.g., lift-off, blow-out, lean blow-off, re-attachment, and re-detachment, as well as ignition characteristics of diffusion air-methane flame. This paper is structured as below. In section 2, the experimental setup consisting the intuitive burner, high-voltage pulse generation system, and supporting accessories used in the tests are illustrated. In section 3 of the paper, the changes in the characteristics of the inverse diffusion flame with respect to stability and shape are discussed. Discharge power measurements are also provided to show the efficiency of RNP discharge employment and find optimal conditions.

2. Experimental setup

The experimental setup involved in this experiment consists of three main parts: The plasma-assisted burner, the nanosecond pulse generator, and the Faraday cage. A schematic illustration of the experimental system and the components involved are shown in Fig. 2.

The plasma-assisted burner is a single-element inverse diffusion flame injector designed to apply the RNP plasma on the fuel and oxidizer jets [74]. Based on the desirable conditions of the test, it is capable of producing sheet plasma discharge, volume plasma discharge and dielectric barrier discharge (DBD). In this paper, only the sheet plasma discharge at the exit of the injector is studied. The other types will be discussed in future works. The injector geometry was designed and built based on an individual injector of the methane-powered additive-manufactured thruster that has been developed at Marshall Space Flight Center as shown in Fig. 1 [24]. Fig. 3 presents a cross-section view of the plasma-assisted burner. The structure of the burner includes stainless steel bases, stands, bolts, and grounded plate to provide rigidity of the system as well as the non-conductive Polytetrafluoroethylene (PTFE) plate which holds the burner core. A ceramic stand is used to keep the grounded plate stands firm and concentric to the core fuel/air lines. The high voltage (HV) electrode, made of tungsten, has been placed at the center of the burner core and surrounded by the oxidizer and fuel glass tubes. For more details, a magnified version of the nozzle area and the discharge location are also given in Fig. 4. The lengths of the tubes are selected to provide fully developed flows at the nozzle. The connections and tube fittings are all PTFE-made for full-electric isolation of the HV electrode from the grounded plates and stands. Two 3D-printed metal spacers are used to ensure that the tubes and the electrode are concentric despite the length of them. The result is a uniform distribution of the plasma discharges between the electrode and grounded plate over the nozzle outlet area, as shown in Fig. 5. The 10-inch-length quartz glass is placed on top of the burner to isolate the jets and avoid air-entrainment from the surrounding air into the methane jet.

The plasma generator system delivers high-voltage (peak voltages of up to 30 kV) and high-frequency (up to 10 kHz) nanosecond pulses with a duration of 10–15 ns at FWHM.\(^1\) Power supply, pulse generator, and trigger device are the main three components of the high-voltage nanosecond pulse generator. The SSPG-20X—HP1 nanosecond pulse generator from Transient Plasma System (TPS) is powered by Ametek XG600—2.8 power supply device (0–600 V and 0–2.8 A DC output). During the tests, it was found that the peak voltage of the discharge pulse is linearly related to the input DC voltage provided by power supply by a ratio of about 93.1:1; so hereafter we use only the peak voltage in our discussion for consistency. In addition, an Agilent MSO-X2024A oscilloscope was

\(^1\) Full width at half maximum.
used as the triggering device to provide the 5 V TTL signal in the desired range of frequency (0.1–10 kHz). The same oscilloscope is used to record the power measurement data (voltage and current). The power measurement is done by coupling a modified NorthStar high-voltage probe (PVM-2) and a fast-rise current monitor (Pearson 6595) with total uncertainties of 6% and 1%, respectively. Fig. 6 shows the voltage, current, and discharge power versus time for a single pulse. The discharge power is defined and calculated by multiplying the voltage and current as

\[ P(t) = V(t) \times I(t) \]  

(1)

The electromagnetic interferences (EMI) generated by the high-voltage discharges may result in a significant disturbance in measurement systems involved in the experiment, especially the flowmeters or may even damage the high-precision systems in the lab. To protect the systems from high amounts of EMI in high frequencies a Faraday isolation cage was designed and built as shown in Fig. 7 along with plasma-assisted burner. The cage is also
responsible for providing a reliable single-point grounding for the burner, HV pulse generator, and probes. This will ensure preventing a possible ground loop. Proper windows for the exhaust and visual access are placed in the cage.

The flows are measured using FMA-A2100 \( \Omega \) mass-flow meters which can measure flows up to 70 standard liters per minute with an uncertainty of \( \pm 1\% \). Moreover, depending on the discharge frequency a random uncertainty of 0.1–0.3 SLM is observed due to EMI fluctuation. In addition to mass flow measurements, the flame shape has been recorded using two cameras in different flow and plasma conditions. A 315 nm bandpass filter was used on the high-speed mono-color CMOS camera, Phantom V611, and an Invisible Vision intensifier (UVi 1850 series) to record \( \text{OH}^* \) chemiluminescence data for geometrical data extraction. Another color CMOS camera was also used to provide color photos from the phenomenon. The uncertainty corresponding to the measurements is calculated by standard uncertainty analysis method [64] and reported in the figures as error bars. For each case, three tests have been performed over a period of time at the same conditions to insure the repeatability of the experiments and confidence of greater than 95%.

3. Results and discussion

The results are discussed in two main parts. In section 3.2, the power is measured for several cases to show the efficiency of the nanosecond discharge application in a methane flame burner. Then in sections 0 to 3.4, the effects of RNP discharge on the shape and stability of the inverse diffusion flame will be discussed. The seven flow and plasma conditions that were used in our experiments are presented in Table 1. These flow conditions are selected to cover the effects of RNP discharges on the attached, lifted and blown-out turbulent flames, as well as the laminar flames. Moreover, the range of voltage/frequency applied on the system includes both the mild and heavy plasma intensity regions in which the plasma effects are obvious. The parameter \( Z \) in the table is the mixture fraction, an extremely useful variable for diffusion flames defined as the ratio of the fuel mass flow rate to the overall mass flow rate [65].

\[
Z = \frac{m_f}{m_f + m_{air}}
\]  

In the following sections, the advantages of RNP discharges are demonstrated. It is worth mentioning that in the following tests where plasma discharge is employed, it acts as the source of ignition initiation. In other words, an external ignition source such as spark igniter [66,67] is no longer required.

3.1. Lift-off height reduction and reattachment

At high jet velocity flames, non-premixed jet flames have shown a tendency to lift off from the nozzle position of the burner [68]. If the jet velocity increases, the lifted height will increase. When this height exceeds a certain critical point the flame will be blown out [69]. Therefore, the lifted flame is known as an unstable state of the flame and engine designers should try to avoid this phenomenon in the diffusion flame burners. To investigate the effects of RNP discharge on the flame lift-off behavior, two different tests are executed. It is noticed that by applying RNP discharges with a certain frequency and voltage, the lifted flame can be attached to the nozzle position. This frequency is called the attachment frequency, \( f_{att} \). Fig. 8 shows the attachment frequency at different peak voltages for two jet flame conditions of the Cases 1 and 2. These two cases are selected because they both have the same mixture fraction and the flames are lifted. To find the attachment points, the
flame is lit up with the associated jet flow rates then it is subjected to the RNP discharge starting from 100 Hz. As frequency increases, at a specific frequency, the flame is attached to the burner base and will stay attached if the frequency is increased beyond that point. By decreasing the frequency, it will be noticed that the flame will stay attached up to a frequency lower than \( f_{att} \), which is called redetachment frequency, \( f_{rdt} \). In all cases that are tested, the \( f_{att} \) is higher than \( f_{rdt} \). This gap is suggested to be due to hysteresis effects.

Using these frequencies, we can divide different voltage and frequency condition into three regions of attached flame below the red line, lifted flame over the black line, and hysteresis effects in between.

**Fig. 8** also shows that the higher the peak voltage of the pulse the lower the frequency required for the attachment of the flame. If the peak voltage is increased from some point, this correlation will not rule but we will see some fluctuations or increase in \( f_{att} \) and \( f_{rdt} \). This point is associated with the instabilities in plasma discharge, i.e. for voltages higher than this point, the RNP discharges are not evenly distributed over the outlet region. This critical voltage depends on the plasma actuator and flow conditions, for example, Case 1 is between 20.7 and 21.6 SLM but for Case 2 between 19.7 and 20.7 SLM. This phenomenon will be discussed with more details in future works.

**Fig. 9** shows the lift-off height of turbulent flames as the outcome of the second series of tests done to investigate the RNP discharge on lifted flames. In these tests, the airflow rate is set to be constant at 4.3 SLM. The flame is ignited with low methane flow rate where it is attached. Then the methane flow rate is increased.

As the fuel flow rises, the flame will be lifted, the lift-off height will increase, and finally, it will be blown out. The procedure is repeated with different RNP discharge frequencies for a pulse with a peak voltage of 17.8 kV. The solid arrows show the point that the flame is lifted, and dashed ones are associated with the moment that the flame is blown out. The lift-off height measurements are done using the high-speed CMOS photos that are taken from the flame. Therefore, the flame fluctuations and the image resolution are the two sources of error in measurement. For Case 3, the uncertainty

<table>
<thead>
<tr>
<th>Case</th>
<th>Gas</th>
<th>Flow rate (SLM)</th>
<th>Flow velocity (m/s)</th>
<th>Z</th>
<th>Peak Voltage (kV)</th>
<th>Discharge frequency (kHz)</th>
<th>Related figures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>CH(_4)</td>
<td>14.0</td>
<td>22.9</td>
<td>0.72</td>
<td>12–28</td>
<td>0.0–8.0</td>
<td>Fig. 8</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>3.0</td>
<td>4.7</td>
<td></td>
<td></td>
<td></td>
<td>Fig. 8</td>
</tr>
<tr>
<td>Case2</td>
<td>CH(_4)</td>
<td>20.0</td>
<td>32.7</td>
<td>0.72</td>
<td>12–28</td>
<td>0.0–9.0</td>
<td>Fig. 8</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>4.3</td>
<td>6.8</td>
<td></td>
<td></td>
<td></td>
<td>Fig. 11</td>
</tr>
<tr>
<td>Case3</td>
<td>CH(_4)</td>
<td>2.0–32.0</td>
<td>3.3–52.2</td>
<td>0.20–0.80</td>
<td>17.8</td>
<td>0.0–4.0</td>
<td>Fig. 9</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>4.3</td>
<td>6.8</td>
<td></td>
<td></td>
<td></td>
<td>Fig. 10</td>
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<td>Case4</td>
<td>CH(_4)</td>
<td>2.0</td>
<td>3.3</td>
<td>0.22–0.03</td>
<td>17.8</td>
<td>0.0–5.0</td>
<td>Fig. 12</td>
</tr>
<tr>
<td></td>
<td>Air</td>
<td>4.0–35.0</td>
<td>6.3–55.1</td>
<td>0.35–0.06</td>
<td>17.8</td>
<td>0.0–5.0</td>
<td>Fig. 12</td>
</tr>
<tr>
<td>Case5</td>
<td>CH(_4)</td>
<td>4.0</td>
<td>6.5</td>
<td>0.12</td>
<td>17.8</td>
<td>0.0–7.0</td>
<td>Fig. 13</td>
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<tr>
<td></td>
<td>Air</td>
<td>8.0</td>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
<td>Fig. 13</td>
</tr>
<tr>
<td>Case6</td>
<td>CH(_4)</td>
<td>0.4</td>
<td>6.5</td>
<td>0.24</td>
<td>17.8</td>
<td>0.0–7.0</td>
<td>Fig. 15</td>
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<tr>
<td></td>
<td>Air</td>
<td>8.0</td>
<td>12.6</td>
<td></td>
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<td>Fig. 15</td>
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<tr>
<td>Case7</td>
<td>CH(_4)</td>
<td>4.0</td>
<td>6.5</td>
<td>0.24</td>
<td>17.8</td>
<td>0.0–7.0</td>
<td>Fig. 15</td>
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<td></td>
<td>Air</td>
<td>8.0</td>
<td>12.6</td>
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<td>Fig. 15</td>
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* Standard liters per minute.
caused by the fluctuation is about ±5 mm and the one caused by image resolution is negligible (about 0.1 mm).

As presented, the fuel flow rate at which the flame detaches from the burner is delayed by applying the higher frequencies of the RNP discharge up to 3 kHz. Higher frequencies don't show any specific advantages. On the other hand, the blow-out flow rate is higher when no RNP is applied. This may be due to the disturbances caused by plasma discharge, but since the burners are designed to work in the attached region of the flame conditions, the RNP employment seems to come with considerable advantageous. Fig. 10 shows the evolution of the flame in tests in Fig. 9 for the cases where plasma is off or applied with the frequency of 0 and 3 kHz.

3.2. Power measurement

According to Fig. 8 of section 0, as the discharge voltage increases the frequency to produce an attached flame decreases to a minimum until the plasma discharge becomes unstable. This voltage with a minimum value of frequency varies for different air/methane jet-flow rates and may be considered as an optimal condition for RNP discharge. On the other hand, Fig. 11 shows the overall discharge power of repetitive nanosecond discharge for case 2 with respect to the peak voltage. The frequency of the points in Fig. 11 is the same as the attachment frequencies in Fig. 8(a). The overall discharge power seems to be a more promising parameter to determine the optimal operating condition and is calculated by multiplying the discharge energy of a single pulse (in mJ) and the frequency of the repetitive discharges (in kHz). The discharge energy of a single pulse is calculated as

\[ DE = \int V(t)I(t)dt \]  

(3)

As demonstrated in Fig. 11, there is an optimal operating point with the lowest overall discharge power. Comparing to Fig. 8 the minimum happens at a lower peak voltage (~17 kV). The reason for this difference can be found in the definition of overall power. In Fig. 8, the attachment frequency is decreasing as the voltage is increasing causing the discharge energy of a single pulse increase.

One of the concerns that have been raised, regarding the use of an external source to improve the characteristics of the flame, is the power consumption compared to energy released by the combustion. To address this concern, we can compare the power measured in Fig. 11 with the heat of combustion at 20 SLM. Considering a heat release of 50.1 kJ per gram of methane and 20 SLM being equal to 0.22 g/s of methane, the rate of heat release for Case 2 (Table 1) will be about 11 kW. In comparison, the maximum overall RNP discharge power in Fig. 11 is 12 W which is about 0.1% of the heat generated by the burner. This means that using the RNP discharge to advance diffusion flame characteristics is beneficial.

3.3. Lean flammability limit

As noted in the introduction, limited flammability is one of the problems associated with methane burners. To investigate the
The effects of repetitive nanosecond plasma discharge on non-premixed methane/air are investigated using an innovative inverse diffusion flame burner. This burner is designed and manufactured to apply the discharges at the burner nozzle and work as a single element nozzle of a multi-element methane burner. Imaging is done using both a CMOS RGB camera system and an OH* chemiluminescence imaging setup.

The results are discussed both on the high-speed turbulent lifted flames and laminar attached flames. The applied plasma, which has a discharge power less than 0.1% of the flame heat release, not only could initiate the combustion but also improved the stability of the IDF significantly. Firstly, on lifted flames, a delay in detachment is observed when applying RNP discharges which means that the flame remains attached even in higher flow rates (about 100% higher). Secondly, it is shown in figures that a lifted flame can be attached if nanosecond discharges are applied with sufficient frequency and voltage. Based on these tests, the plasma hysteresis and
instability effect on the attachment of the flame is demonstrated. An optimal working point is found at which the energy is minimum. Finally, the dimensions (width and height) of low-speed laminar flames are measured under different frequencies of RNP applied. As the frequency increases the flame gets shorter but wider. This behavior may imply more cohesion in the flame and thus more stability.

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