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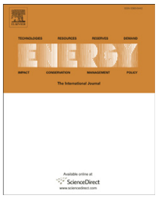

Improvement of lean flame stability of inverse methane/air diffusion flame by using coaxial dielectric plasma discharge actuators

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ABSTRACT

Low environmental impact is a main issue in the design of novel combustion systems, as aircraft engines. In this context, the present work investigates the possibility to increase the combustion efficiency of a lean flame through the use of sinusoidally driven dielectric barrier discharge (DBD) plasma actuator. The effect of the plasma discharge on a lean non premixed methane/air flame in a Bunsen-type burner has been studied for two different configurations: the normal diffusive flame (NDF) and the inverse diffusive flame (IDF). The flame behavior was investigated by chemiluminescence imaging through an intensified CCD camera. Optical filters were installed in front of the camera, aiming to selectively record signal from the chemiluminescent species OH^*, CH^*, or CO_2^*. This allowed evaluating the changes occurring in presence of plasma actuation in term of flame emissions. It was shown that the plasma effects are significantly influenced by the burner and DBD configuration. A plasma power of approximately 25 W permitted to increase the air mass flow rate at which lean blowout appears; it rose up to 30% for low methane flow rate and up to 10% at high fuel flow rate.

1. Introduction

Diffusion-flame-based combustion systems are of great interest in power plants and aeronautical jet engines, due to their better stability under wide ranges of operating conditions and safety with respect to premixed-flame-based combustion [1–3]. Premixed or partially premixed flames can easily blow off in absence of external stabilization facilities [4], hence pilot flames are frequently used to stabilize a turbulent premixed/partially premixed flame jet. In contrast, a normal diffusive flame (NDF) that can be established in a coaxial burner with a central fuel jet and an annular oxidizer jet has a small tendency to blow off, even if it presents low heat release rate and high soot emission, and might present incomplete combustion [5,6].

The inverse diffusion flame (IDF), a special kind of non premixed flame, is observed to produce less soot than the normal diffusion flame. Hence there has been a growing interest in the inverse non premixed coflow flames [7].

The turbulent inverse jet flames are used in various fields as rocket engines and staged combustion systems. The injection of central oxidizer with annular hydrogen or methane jet in rocket engine combustors helps in minimizing the oxidation of combustor walls [8–12].

The flame structure of inverse diffusion flame is different from the premixed flame and the normal coaxial jet flame. Previous works [13] investigated the effect of air–fuel velocity ratio on the characteristics of IDF. It was shown that the high momentum between the central air jet and fuel jet ensured better entrainment of fuel flow momentum along with the ambient air and it enhanced mixing in the IDF configuration, in comparison with normal diffusion flame. Furthermore, methane–oxygen IDF leads to enhanced radiation heat flux with respect to NDF given by central fuel and annular oxygen jets [14].

However inverse CH_4/air coflow flames present reduced stability limits with respect to normal non premixed CH_4/air coflow flames [7,15].

Recently investigations have been performed regarding the flame stabilization by the use of non-thermal plasma (NTPs)

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electrical discharges, sometimes called non-equilibrium or 'cold' plasmas.

Non-thermal plasmas present high energy efficiency, due to low ionization/excitation energy with respect to the total energy consumption, and small temperature rise. Characteristic electron temperatures in these discharges are of few electron volts, which permit to dissociate the fuel and to produce free radicals [16,17].

Several studies focused on the application of high voltage (HV) pulses to improve the ignition of fuel/air mixtures [18,19], to increase flame propagation [20], to enhance flame stabilization [21–23], and to extend flammability limits [24].

In Refs. [25] and [26] it was shown that nanosecond HV pulses might reduce the ignition delay time. However, few works were focused on the application of the plasma discharges for the flame stabilization [25] and [26]. A plasma actuator is substantially a device able to change locally the chemical and fluid dynamic state using the action of an applied electric field [27].

In Ref. [28] Nanosecond Repetitively Pulsed (NRP) discharges produced by electrical pulses of about 10 kV during 10 ns at a frequency of 30 kHz were applied to stabilize a lean premixed methane/air flame at atmospheric pressure. The plasma created in the recirculation zone improved the flame stabilization and reduced the lean extinction limit by about 10–15% with respect of the baseline case with plasma off, with an electrical power consumption less than 1% of the power of the flame.

In Ref. [29] a repetitive discharge at 9 kHz and with voltage pulse duration of about 100 μs was used to extend the flammability limit of a lean premixed propane/air mixture at atmospheric pressure.

A promising non thermal plasma source is the DBD. Non-equilibrium DBD plasmas can be produced between two electrodes on the dielectric surface when an alternating current (AC) HV passes through them [27,30,31].

The DBD, also called silent discharge, can be simply operated and it has relatively low cost in producing non-equilibrium plasma, high discharge stability and simple operability of equipment.

Repetitive pulsed plasmas have been applied to stabilize normal methane jet flames [32] and propane jet flames [33]. In Ref. [33] it was shown that the liftoff height of propane and air-diluted propane jet flames is reduced by more than 50% in the presence of a DBD.

Previous studies investigated the plasma actuation mostly in premixed burners or normal coaxial burner with central fuel jet even if in several fields inverse configurations with central oxidizer and annular fuel jet are of great attention.

Even if there is a need for stabilizing the methane flame in conditions near the blowout due to the varied applications of this configuration ranging from rocket combustor to gas burners [34], there is a lack in the literature regarding the stability of inverse methane diffusion flames by DBD plasma devices.

Hence in the present work the flame behavior and the blowout limits of lean methane inverse diffusive flames were experimentally investigated in presence of a DBD. A sinusoidal pulsed plasma produced by electric pulses with electrical dissipated power up to 33 W has been used to stabilize and improve the combustion efficiency of bunsen-type normal and inverse diffusive flames. Different operating parameters have been considered, in terms of: air and methane flow rates, voltage amplitude of the sinusoidal signal applied to the plasma actuator and its geometrical configuration.

Flame imaging was done by using an intensified CCD camera, equipped with various optical filters to selectively record signal from the chemiluminescent species OH*, CH*, or CO_2*. This allowed evaluating the changes occurring in presence of plasma actuation in terms of flame emissions.

2. Experimental set-up and methodologies

2.1. Experimental apparatus

The experimental set-up consists of: (1) a coaxial burner equipped with the plasma actuator and associated gas feeders (air and methane); (2) an HV generator and (3) a measurement system, involving: a personal computer (PC), a compact Charge-Coupled Device (CCD) camera, an intensified CCD camera, a HV probe, a current probe and an oscilloscope.

2.2. Burner configurations and gas supply system

The gas feeder is composed by air and methane tanks, connected to the burner through pressure regulators and flow controllers. The flow rates of air and methane are controlled by two flow meters: the SFAB-50U-HQ12-2SV-M12 of Festo® for the air, with a measurement accuracy of ±3% of measured value, and the EW-32907-57 of ColeParmer® for the methane, with a measurement accuracy of ±0.8% of reading.

The burner is composed of an internal stainless steel tube (external diameter 8 mm and internal diameter 7 mm) and by a coaxial quartz tube (10 mm of internal diameter, 1 mm of thickness). The mixing region, which is the zone between the top ends of the two coaxial tubes, is 60 mm long. It is the zone in which the reactants mix themselves and its dimension influences the mixture formation and the zone where the flame clings to.

Two different fueling configurations have been used: in the first one the fuel flows in the outer coaxial quartz tube and air in the inner tube, this leads to the plasma activation of methane (herein referred as "IDF configuration"). The second configuration has an inner fuel jet surrounded by an outer air jet (herein referred as "NDF configuration"). The gases are ignited at the end of the quartz tube.

The positioning of the powered electrode with respect to the superior edge of the steel tube influences the plasma action. The standoff distance, s, which is the distance between the plasma region and the mixing region, was set alternatively to 0 and to 6 mm. In the first case ($s = 0$) the influence of the plasma actuation affects the fuel-air mixing, in the second case ($s = 6$ mm), the distance is sufficient to ensure that only fuel was activated, without significant effects on the mixture.

2.3. DBD reactor and electrical system

The non-thermal plasma generation system involved a DBD reactor and a power supply. The steel tube was connected to the ground (herein referred as "grounded electrode"). A copper tube (80 mm long, thickness 0.6 mm), placed on the outer surface of the quartz tube was instead connected to the HV (herein referred as "HV electrode").

The HV generator was the PVM500 Plasma Resonant and Dielectric Barrier Corona Driver, commercialized by Information Unlimited® [35]. A sinusoidal waveform actuation signal with different voltage amplitudes and a frequency of 20 kHz was applied to the copper tube.

A high voltage probe (*Tektronix P6015A*), a current probe (*Bergoz Current Transformer CT-D1.0-B*) and an oscilloscope (*Tektronix TDS2024C*) were used to retrieve the voltage-current characteristic curves as a function of time t and the electrical power dissipation $\overline{P}_{el}$.

The HV probe was located on the HV connector side and the current probe on the ground side. The HV and current probes were connected to the oscilloscope, and the measured signals (applied voltage and current flowing in the discharge, respectively) were