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Cavity ignition and flameholding of ethylene–air and hydrogen–air flows by a repetitively pulsed nanosecond discharge

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ABSTRACT

Repetitive nanosecond pulse plasma assisted ignition and flameholding of premixed and non-premixed ethylene–air and hydrogen–air flows are studied in a cavity flow at a pressure of 0.2 atm and flow velocities of up to 100 m/s. Ignition occurs via formation of multiple filaments in the fuel–air plasma, although air plasma remains diffuse until the fuel is added. After ignition occurs in the cavity, with ignition delay time of a few milliseconds, the plasma becomes diffuse and the flame couples out to the main flow. The use of a short cavity (length-to-depth ratio $L/D = 1$) results in repetitive ignition and flame blow-off, caused by slow mixing between the main flow and the cavity. Increasing the length-to-depth ratio to $L/D = 3$, as well as choking inlet air and fuel flows resulted in stable flameholding and nearly complete combustion in both premixed and non-premixed ethylene–air and hydrogen–air flows at $u = 35$–100 m/s. Air plasma temperature before fuel is added ranges from 70 °C to 200 °C. When the nanosecond pulse discharge is operated in repetitive burst mode, continuous ethylene–air flame is maintained only at a high duty cycle, which increases with the flow velocity. In hydrogen–air, the flame remains stable after the plasma is turned off. Nanosecond pulse discharge ignition of ethylene–air is compared with ignition by DC arc discharge of approximately the same power. DC arc discharge results in sporadic ignition and flame blow-off, much lower burned fuel fraction, and significantly lower flow velocity at which ignition can be achieved. Kinetic modeling is used to identify the reduced mechanism of plasma chemical oxidation and ignition of hydrogen, and to demonstrate the mechanism of energy release low-temperature reactions of radicals generated in the plasma (primarily O and H atoms).

1. Introduction

Over the last decade, plasma assisted combustion has become a rapidly developing research field [1]. The main motivation for recent work in this area is development of efficient plasma ignition, flameholding, and relight systems, which could operate in a wide range of fuel–air ratios, flow velocities, temperatures, and pressures. Nonequilibrium plasmas generated by high peak voltage, repetitively pulsed, nanosecond pulse duration discharges appear especially promising for these applications since they operate at high values of the reduced electric field, $E/N \sim 100$ Td (1 Td = 10^{-17} V cm^2). At these conditions, a significant fraction of the input discharge power is spent on electronic excitation of molecules and molecular dissociation by electron impact. Recent plasma assisted combustion experiments using nanosecond pulse discharges include ignition and flameholding in room-temperature quiescent and flowing air–fuel mixtures [2–7], ignition delay time reduction in quiescent shock-preheated mixtures [8,9], flame stabilization [10–14], as well as metastable and radical species generation [15,16] and CARS thermometry [17,18].

The main objective of the present work is to extend the use of these discharges to ignition and flameholding of low-temperature air–fuel flows at high flow velocities. Recent work at Stanford University [19,20] demonstrated ignition of hydrogen and flame stabilization in supersonic cross flows ($M = 2.3$–2.6) using repetitively pulsed nanosecond discharge, both in the cavity geometry [19] and in a flat plate geometry [20]. These measurements have been conducted at high static temperatures ($T = 1300$–1500 K), significantly above hydrogen auto-ignition temperature. At these conditions, the use of the discharge significantly reduces ignition delay time, to ~80 μs [19]. However, our previous work [7,18] showed that ignition delay time in room temperature ethylene–air and hydrogen–air flows excited by a repetitive nanosecond pulse discharge at $P = 40$–60 torr, $u \sim 1$ m/s, and $\nu = 25$–50 kHz in a plane-to-plane geometry is much longer, 5–25 ms. Ignition delay time measured in quiescent propane–air mixtures, initially at room temperature, excited by a repetitive nanosecond pulse plasma at $P = 0.35$–2.0 atm and $\nu = 30$ kHz in a point-to-plane geometry is also quite long, 7–15 ms [3]. This suggests that nanosecond pulse

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plasma ignition of low-temperature, high-speed flows in a wide range of pressures would require the use of a cavity to increase flow residence time in the plasma. Feasibility of this approach using high-temperature plasmas has been shown using high-power (1–10 kW) DC arc discharges to ignite hydrogen and ethylene injected into a cavity of a $M = 2$ air flow channel [21]. The objectives of the present paper is to demonstrate ignition and flameholding of premixed and non-premixed ethylene–air and hydrogen–air flows using a low-temperature, repetitively pulsed nanosecond discharge sustained in a cavity; to determine the range of plasma and flow parameters at which ignition can be achieved; and to identify the reduced kinetic mechanism of low-temperature plasma assisted ignition of hydrogen.

2. Experimental setup

The schematic of the plasma ignition/cavity flow test section used in the present experiments shown in Fig. 1. The rectangular cross section (5 cm × 1 cm) flow channel is made of aluminum and has a cavity machined in the bottom wall of the channel. In the present work, two different cavity geometries have been used, a "short" rectangular cavity ($L = 1.8$ cm long, $D = 1.8$ cm deep, $L/D = 1$), and a "long" cavity ($L = 5.7$ cm, $D = 1.8$ cm, $L/D = 3$, with a 60° exit ramp on the downstream side), both shown in Fig. 1. While the short cavity has a less pronounced effect on the flow in the main channel, it also reduces the rate of mixing between the main fuel–air flow and the flow of combustion products in the cavity. In both cases, a 3.2 mm diameter cylindrical high voltage brass electrode is located 9 mm from the upstream wall of the cavity, perpendicular to the flow direction, as shown in Fig. 1. The electrode is placed inside a 6.4 mm outside diameter alumina ceramic tube, with the gap between the electrode and the tube filled with a silicon rubber adhesive. The walls of the main flow channel are covered by 0.65 mm thick alumina ceramic plates, and the cavity walls are covered by 1.6 mm thick macor ceramic plates. Both sets of plates are attached to the walls using a silicon rubber adhesive. This is done to preclude secondary electron emission from exposed grounded metal surfaces and the resultant arc filament ("hot spot") formation in the discharge. The main objectives of the present design are (i) to generate volume-filling plasma in the cavity and (ii) to increase flow residence time in a recirculation flow region in the cavity, thereby producing ignition and flameholding at high flow velocities.

The high-voltage electrode is connected to a Chemical Physics Technologies high-voltage pulsed power supply producing 25–30 kV peak voltage pulses with individual pulse duration of approximately 15 ns FWHM, coupled pulse energy of ~2 mJ/pulse [5], maximum pulse repetition rate of 50 kHz, also used in our previous work [5,6,15–18]. The present experiments have been conducted at the pulse repetition rate of $\nu = 40$ kHz.

The test section is connected to 1 in. diameter, 6 ft long main air/fuel delivery line 21 cm upstream of the cavity. In the present experiments, the main line delivers either a premixed air–fuel flow or air flow (for non-premixed flow/fuel injection ignition experiments). Both air and fuel are supplied from high-pressure cylinders. During premixed operation, air and fuel flow rates are measured using sonic chokes placed in their respective delivery lines, before mixing in the main line. A honeycomb 1.2 cm long is placed 1.5 cm downstream of the test section inlet to improve flow uniformity in the main flow channel (see Fig. 1). The test section inlet flow can also be choked by placing a sonic choke plate at the delivery line exit (see Fig. 1). The total flow rate is up to 12 g/s, which maintains flow velocity in the test section of up to 110 m/s at the test section static pressure of 150 torr. For non-premixed operation, transverse jets of fuel are injected into the air flow through a choked injector, using 3 injection ports 1 mm in diameter each, 16 cm upstream of the cavity (see Fig. 1). The injection flow rate is measured by Omega FMA-A2322 (75 SLM) or Omega FMA-A1844 (500 SLM) mass flow controllers. During non-premixed flow experiments, the injection jet momentum ratio was quite high, $J = 35–115$ in ethylene–air ($u_{\text{air}} = 35–100$ m/s) and $J = 50–340$ in hydrogen–air ($u_{\text{air}} = 20–90$ m/s). Also, the distance from the injection ports to the cavity exceeds the diameter of the injection ports by more than two orders of magnitude. For these reasons, the flow arriving at the cavity may be considered partially premixed. Time-resolved test section static pressure is monitored by a high accuracy Omega PX811-005GAV pressure transducer. Downstream the test section is connected to a 1 cm × 5 cm cross section, 32 cm long extension channel leading to a 6-in. diameter vacuum pipe. The flow in the vacuum pipe is diluted with atmospheric air through a vent valve to prevent further

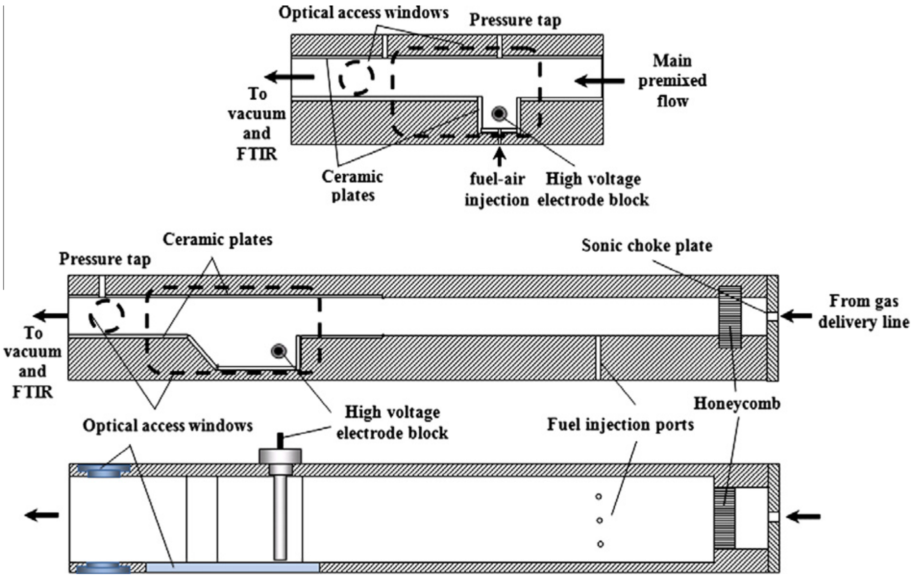

Fig. 1. Schematic of plasma assisted combustion test section, with two cavity geometries used. Top, short cavity ($L/D = 1$); middle, long cavity ($L/D = 3$), front view; bottom, long cavity ($L/D = 3$), top view.