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Ignition and flameholding in a supersonic combustor by an electrical discharge combined with a fuel injector

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ABSTRACT

The paper presents the results of an experimental study of supersonic combustor operation enhanced by an electrical discharge. A novel scheme of plasma assisted ignition and flameholding is demonstrated, which combines a wall fuel injector and a high-voltage electric discharge into a single module. The experimental combustor with the cross section of 72 mm (width) × 60 mm (height) and length of 600 mm operates at a Mach number of $M = 2$, initial stagnation temperature of airflow of $T_0 = 290–300$ K, and stagnation pressure of $P_0 = 1.3–2.0$ Bar. The combustor is equipped with four plasma ignition modules, flush-mounted side-by-side on the plane wall of the combustion chamber. The combustion tests were performed using ethylene injection with a total mass flow rate of $G_{C2H4} < 10$ g/s and discharge power in the range of $W_{pl} = 3–24$ kW. The scope of the experiments includes characterization of the discharge interacting with the main flow and fuel injection jet, parametric study of ignition and flame front dynamics, and comparison of the present scheme to previously tested configuration. The present approach demonstrates a significant advantage in terms of flameholding limits. An operation mode with strong combustion oscillations was observed at high fuel injection flow rates. Methods of flame front stabilization based on plasma application are discussed. The technique studied in the present work has significant potential for high-speed combustion applications, including cold start/restart of scramjet engines and support of transition regime in dual-mode and off-design operation.

1. Introduction

Compared to a basic scramjet design, operation of scramjet combustors using plasma assisted ignition and flameholding offers considerably more flexibility over the choice of its geometry, due to replacing mechanical flameholders with a highly effective electrically driven apparatus. Over the years, many studies have been conducted to develop an alternative plasma-based ignition system that could consistently and reliably ignite non-stoichiometric mixtures over a wide range of pressures and temperatures [1–3]. Plasma technologies, such as plasma torches, plasma rails, and others, rely on high energy density electrical discharges to produce ionization and initiate combustion due to thermal/chemical activation of fuel or fuel/air mixtures [3,4]. A number of experimental studies have been performed at conditions typical for scramjet operation [5–9]. In most of these experiments, a modification of supersonic duct geometry was used, such as a backward facing wall step or a contoured cavity, and plasma was employed as an igniter of a combustible mixture in a low-speed flow region. At the same time, some of previous experiments using an alternative configuration, where an electric discharge was sustained over a plane wall [10,11], demonstrated feasibility of plasma application as an effective igniter and flameholder in a supersonic combustor, without relying on mechanical obstacles for flameholding.

Another aspect of the problem is the effect of highly non-equilibrium chemical kinetics, which may help reducing the plasma power needed for reliable ignition by enhancing specific chemical reactions pathways. Significant progress in this field has been made over the last 15 years [3,4,12–15]. Dramatic reduction of ignition time has been demonstrated, up to several orders of magnitude at premixed conditions, over a range of stagnation temperatures specifically important for scramjet technology, $T_0 = 500–900$ K. In spite of these promising results, this approach appears to be rather impractical for high-speed flow engines with direct fuel injection. In most cases, the main limiting factor is rather slow fuel–air mixing, resulting in strong gradients of fuel/oxidizer ratio across the combustion chamber. The most challenging issue in this case is to determine the most effective location of the electric

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discharge plasma, which is typically non-uniform, in a shear layer between the fuel injection jet and the main airflow.

In this work, a novel pattern of plasma-fuel interaction is studied experimentally. In the present method, an electric discharge is located partially inside the fuel injection orifice, chemically preprocessing (i.e. partially reforming) the fuel prior to injection and accelerating mixing by introducing strong thermal inhomogeneity into the flowfield. This approach employs the following three critically important physical effects: (1) fast ionization wave propagating predominantly along solid surfaces (such as walls of delivery lines) and gas flows [16,17]; (2) penetration of discharge current into the main airflow, following a fuel injection jet [18]; and (3) discharge localization within the shear/mixing layer between two components of the mixture [19]. The first effect causes near-surface ionization wave propagation along gas delivery lines during high-voltage breakdown, over long distances, resulting in significant reduction of breakdown voltage over long gaps between the electrodes. After breakdown, the electric current follows the injection jet flow, due to convective transport of the plasma and lower density in the jet. Finally, the axial part of the plasma filament is localized inside the fuel–air mixing layer.

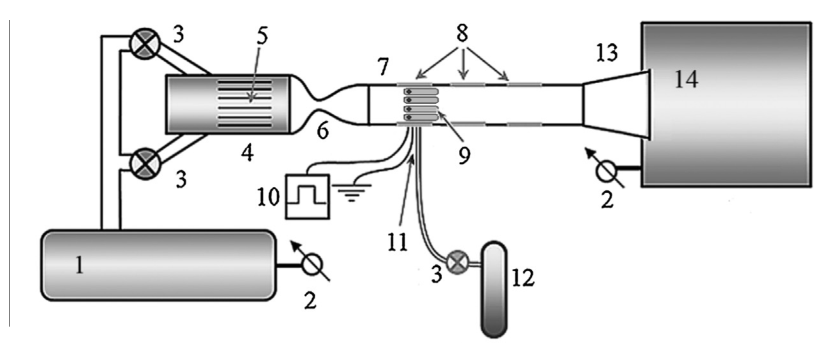
The present paper is focused on an experimental study of hydrocarbon fuel ignition and flameholding in a novel configuration of the plasma/injection module. The experimental data obtained using the new plasma-injection module (PIM) are compared to previously tested schemes, where the plasma is generated in airflow in front of the fuel injection port [10,11]. This type of PIM has a significant potential for mixing enhancement and flameholding in supersonic combustors.

2. Experimental apparatus

The experiments were performed in a supersonic blow-down wind tunnel PWT-50H [10,11], the schematic of which is shown in Fig. 1a. In the present configuration, the test section operates as a supersonic combustor, with the PIM for ethylene ignition and flameholding flush-mounted on a plane wall, as shown in Fig. 1b. The combustor cross section is $Y \times Z = 72$ mm (width) $\times$ 60 mm (height), with the length of $X = 600$ mm. It is furnished with three pairs of circular high-quality quartz windows, providing ample optical access. To avoid thermal chocking during fuel ignition, the test section has a 10° expansion angle downstream of the PIMs on the opposite (bottom) wall, to the cross section of $Y \times Z = 72$ mm (width) $\times$ 72 mm (height). The experimental conditions are as follows: initial Mach number $M = 2$; static pressure $P_{st} = 160–250$ Torr; air mass flow rate $G_{air} = 0.6–0.9$ kg/s; ethylene mass flow rate $G_{C2H4} = 1–8$ g/s; duration of steady-state aerodynamic operation ~0.5 s.

The test section of PWT-50H high-speed combustion facility is equipped by 3 pairs of 100 mm diameters windows placed in the side walls of the duct for optical access. The first pair of windows is located near the upstream side of the combustor and provides optical access to the area where PIM modules are installed. The second pair of windows is placed downstream, with a 65 mm gap between the two pairs of windows. The third pair of windows is typically used for Tunable Diode Laser Absorption Spectroscopy (TDLAS) measurements, as has been done in our previous work [20]. Instrumentation includes the pressure measuring system, the schlieren system, UV/visible optical emission spectrometer, current and voltage sensors, TDLAS apparatus for water vapor concentration measurements, 5-component exhaust flow chemical analyzer, high-speed cameras, and operation sensors.

The schematic of a single PIM module is shown in Fig. 2(a). The high-voltage electrode (anode) is integrated into the fuel injector. For this, a metal tube is inserted into a ceramic injection orifice. The distance between the end of the tube and the duct wall surface, Z1 ⩽ 10 mm, is sufficiently long to ensure significant impact of the discharge on the fuel flow prior to its injection into the main airflow. The fuel is injected into the main flow through circular orifices $d = 4$ mm in diameter. In the present experiments, four PIMs are inserted into the top wall of the test section, arranged side-by-side spanwise, as shown in Fig. 2(b). The fuel mass flow rate is evenly distributed between the injection orifices using the fuel



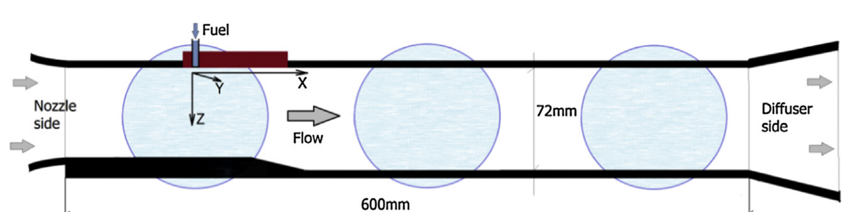


Fig. 1. Schematic of experimental facility PWT-50H. (a) General layout: 1 – high pressure tank; 2 – operation gauges; 3 – solenoid valves; 4 – plenum section; 5 – honeycomb; 6 – nozzle; 7 – test section; 8 – optical access windows; 9 – plasma-injector modules; 10 – high-voltage power supply; 11 – fuel ports/discharge connectors; 12 – fuel tank; 13 – diffuser; 14 – low-pressure tank. (b) Test section wall profile: optical windows are indicated by circles, location of plasma injection modules (PIM) is shown by a rectangle in the top wall of the test section.