

Jet Flame Ignition in a Supersonic Crossflow Using a Pulsed Nonequilibrium Plasma Discharge

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Abstract—A short-pulse repetitive discharge is used to ignite hydrogen jet flames in supersonic crossflows. Nonequilibrium plasma is produced by repetitive pulses of 7-kV peak voltage, 20-ns pulsewidth, and 50-kHz repetition rate. Sonic or subsonic hydrogen jets are injected into a pure-oxygen supersonic free-stream flow of Mach numbers $M = 1.7$ – 2.3 . The fuel injection nozzles and electrodes are mounted flush with the surface of a flat plate that is oriented to be parallel to the flow to minimize stagnation pressure losses associated with generated shock waves. A configuration combining an upstream subsonic oblique jet and a downstream sonic transverse jet serves to provide an adequate flow condition for jet flame ignition. The flow pattern and shock waves induced by the dual hydrogen jets are characterized by Schlieren imaging. Planar-laser-induced fluorescence and emission spectroscopy are employed for imaging the distribution of OH radicals. The OH fluorescence image of the region in the vicinity of the discharge confirms jet flame ignition by the plasma.

Index Terms—Plasma-assisted diffusion flame, pulsed plasma, supersonic flame ignition.

I. INTRODUCTION

THE PROBLEM of igniting and sustaining combustion in high-speed gas flows continues to be a critical issue in the aerospace industry. The recent advent of supersonic/hypersonic aircraft has prompted the demand for stable combustion in high-speed flows to achieve reliable thrust over the broad range of flight conditions. Supersonic combustion is essential for air-breathing scramjet engines designed for hypersonic aircraft. The scramjet engine has drawn particular attention, as it is a reusable and highly cost-effective engine possibly enabling flight into low Earth orbit. The scramjet engine is used when the aircraft reaches approximately Mach 3 flight. The supersonic incoming ambient airflow passes through the combustor, mixes and burns with fuel, and expands through the aft end of the engine to produce thrust. While bluff bodies providing recirculation regions are often implemented as flame holders in subsonic flows such as in the afterburner of a turbojet engine,

a greater challenge is faced in the ignition and sustenance of combustion in supersonic flows because the use of such bluff bodies leads to significant stagnation pressure losses that limit engine thrust and could induce engine unstart. New methods are therefore sought out for igniting and sustaining ignition in supersonic flows.

Previously explored methods for igniting and sustaining combustion in supersonic gas flows include the use of geometric surface alterations and plasma discharges [1]–[9]. Geometric surface alterations such as cavities [1]–[3], ramp injectors [4], [5], wall steps, and angled combustor walls [6] generate recirculation regions for fuel and oxidizer to mix and reside long enough to be ignited and burned. In addition to promoting mixing, these geometric surface alterations also reduce the local flow speed and elevate the local static temperature and pressure. However, these methods of enhancing combustion share an important limitation—the introduction of undesirable shock waves due to flow disturbances. The generated shock waves are a primary source of stagnation pressure loss. Plasma discharges have been used to facilitate combustion in supersonic flows [6]–[9]. It is well known that plasma discharges can be effective and energy-efficient flame ignition sources, as they can produce reactive radicals that enhance combustion reactions [10]–[17]. However, most of the plasma-assisted methods applied to the ignition of diffusion flames in supersonic flows have been used in conjunction with geometric alterations. For example, in recent studies, an arc jet was injected into the downstream region of fuel injection ramp [6], and a quasi-direct-current (dc) discharge plasma was generated within a surface cavity [7]. Microwave plasma discharges were used in the absence of cavities or ramps to ignite supersonic premixed combustible gases [8]. We are not aware of any technique that has yet achieved successful ignition of diffusion flames at relatively high Mach number without geometric variances to the flow surface.

In this paper, a jet diffusion flame in a supersonic crossflow is ignited using an ultrashort repetitively pulsed plasma discharge (USRD). The discharge electrodes are embedded to be flush with the surface of a flat plate with a sharp leading edge that is oriented parallel to the flow. As described in detail in the following, a combination of an upstream oblique (subsonic) jet and a transverse (sonic) jet is used to provide flow conditions for flame ignition. The USRD produces nonequilibrium plasma by applying very short (nanosecond-regime) high-voltage (many-kilovolt range) pulses to generate relatively high reduced electric fields. A high repetition rate (10–100 kHz) is needed to maintain the local plasma density, i.e., to overcome plasma recombination between pulses [10]. In our previous study of

Manuscript received March 31, 2008; revised June 20, 2008. Current version published December 12, 2008. This work was sponsored by the AFOSR/MURI Program—Experimental/Computational Studies of Combined-Cycle Propulsion: Physics and Transient Phenomena in Inlets and Scramjet Combustors, with Julian Tishkoff as the Technical Monitor.

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Digital Object Identifier 10.1109/TPS.2008.2005986



Fig. 1. Sketch of the expansion tube.

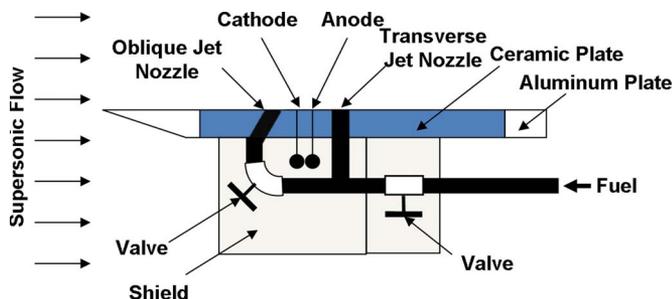


Fig. 2. Schematic of the jet in crossflow model.

diffusion flame combustion in subsonic crossflows [11], [12], we found that the effectiveness of the USRD in aiding combustion is strongly dependent on discharge placement. The discharge should be placed in regions of the flow field where adequate fuel and oxidizer mixing has taken place, while other factors, such as the local flow strain rate, must also be taken into consideration. These prior studies [12] prompted the use of a subsonic oblique jet nozzle placed upstream of the USRD to generate the necessary local mixture fraction adjacent to the discharge region. The fuel injection flow rate of this (secondary) upstream subsonic jet is adjusted and optimized for the ignition of the primary transverse fuel jet, located just downstream of the USRD. In addition to providing the majority of the fuel for combustion, the main sonic jet also provides a recirculation region for the upstream subsonic jet flame. The complex but important interactions provided by the combination of these two jets, augmented by the nonequilibrium discharge, result in a piloted flame without the use of reentrant cavities or ramps.

II. EXPERIMENTAL SETUP

The experimental setup consists of the following four components: 1) an expansion tube for generating the supersonic flow; 2) a pulsed-plasma generation system; 3) optical diagnostics; and 4) a flow model introduced into the supersonic stream that has the embedded electrodes and jet nozzles. A sketch of the expansion tube facility is shown in Fig. 1, and a schematic of the flow model highlighting specific features is provided in Fig. 2.

The expansion tube facility developed at Stanford University is used to generate high-enthalpy supersonic flows spanning a range of hypersonic flight conditions [18], [19]. A brief review of its operation is provided here, and a detailed description is available in [18]. The expansion tube is a tube of 6-in inner diameter that is connected to a dump tank. A test section, optically accessible for diagnostics, is located between the expansion tube and the dump tank. The tube consists of three parts (the driver, driven, and expansion sections) separated by two breakable diaphragms. Prior to operation, the driven section is filled with the desired test gas, i.e., the gas that will flow across the model in the test section during the run time. The

driver and expansion sections are filled with high- and low-pressure helium, respectively. When the primary diaphragm separating the driver and driven sections ruptures, a shock wave propagates through the driven section, elevating the temperature and pressure of the test gas. The elevated pressure in the driven section subsequently ruptures the second diaphragm, releasing the test gas to undergo an unsteady expansion and flow through the lower pressure test section which houses the test model (see in the following). The facility is designed to reproduce generic scramjet-engine inlet flow conditions with flight conditions as high as $M = 9$.

The voltage pulses generating the USRD are produced by a pulse generator (FID Technology Model F1112) triggered by a delay generator (SRS 535). Two supplemental dc power supplies provide the primary power consumed by the discharge and secondary power of the pulse generator's cooling system, respectively. Approximately 40 W of power is supplied to the pulse generator by the primary dc power supply. We estimate from voltage and current traces that approximately one-fourth of this power (10 W) is coupled into the discharge. The pulse generator produces a 7-kV peak voltage pulse with a pulsewidth of approximately 20 ns and a pulse repetition rate of 50 kHz ($\sim 2 \times 10^{-4}$ J/pulse). Output of the pulse generator is directly connected to electrodes embedded in the test model, as described in the following. A single discharge pulse produces current peaks in excess of 15 A. Approximately 50 pulses are generated during the typical test duration of 1 ms provided by the expansion tube.

OH planar-laser-induced fluorescence (PLIF), OH emission spectroscopy, and Schlieren imaging are used to visualize the OH radical distribution and to investigate the formation of compressible flow features. The characterization of OH emission and ground-state distribution provides an indicator of combustion and, more specifically, the location of the flame region. A Nd:YAG laser (Spectra Physics) that pumps dye laser (Lumonics HD-500) generating 3-mJ per pulse at 283 nm with a 10-Hz repetition rate is used to excite the A-X(1,0) Q1(7) line of the OH molecule. The laser beam is transformed into a thin sheet by a set of cylindrical concave/spherical convex lenses. The spectrally filtered laser-induced fluorescence (from 305 to 325 nm) is captured by an intensified camera (Andor iStar ICCD) at right angles to the plane of the laser sheet. Spontaneous OH emission is also captured by the camera (in the absence of the laser) along the same direction but with a narrow-band (10-nm-wide) filter centered at 313 nm. The limiting resolution of these images is approximately 80 μm , determined by the camera array of 512×512 pixels imaged onto a 40×40 -mm region of the flow. The images depict noncalibrated OH excited-state and ground-state concentration fields, which serve to only provide a qualitative depiction of the flame structure. Schlieren imaging is carried out with an ultrafast framing camera (Imacon 486 intensified CCD camera) and a pulsed xenon flash lamp (Hamamatsu Model E6611). The camera can record eight frames at maximum frame rate of 100 MHz. Schlieren imaging enables the visualization of flow features that lead to sudden changes in the refractive index, such as compressible shear layers and shock waves. Schlieren imaging is also used to determine the sonic jet momentum by

characterizing the position of the sonic jet's Mach disk formed by its injection into a static ambient gas.

Fig. 2 shows the details of the design of the test model which houses the fuel jet nozzles and discharge electrodes. The jet in crossflow model consists of the following three parts—an aluminum plate, a ceramic subplate, and the nozzle and electrode assemblies. The aluminum plate that is 10 cm wide, 16.5 cm long, and 2 cm thick, which is intended to represent one wall of a supersonic combustor, has a sharp leading edge (22° angle) and a rectangular cavity to accommodate the ceramic subplate. The ceramic plate (2×6.3 cm) is used to electrically insulate the aluminum plate from the high electrode voltages. Four drilled holes in the ceramic plate (which is oriented to be parallel to the flow direction) serve to provide access to two nozzles (2-mm inner diameter) and two electrodes (0.8-mm-diameter tungsten rods). The nozzles and electrodes are inserted so that they are flush with the surface to avoid disturbing the flow and generating undesirable shock waves. Fuel is injected through two nozzles—the first, or secondary, upstream oblique nozzle generating a subsonic jet and the second, or primary, transverse nozzle 26-mm downstream of the oblique nozzle, generating a sonic jet. The oblique jet nozzle is inclined at 30° from the surface normal toward the downstream direction. Fuel injection is controlled by two valves for independent determination of flow rates. In general, a much larger portion of the fuel is injected through the transverse sonic jet nozzle. The cathode and the anode are positioned 10 and 16 mm, respectively, downstream of the oblique jet nozzle.

III. RESULTS

The jet in crossflow model is tested at the following two different pure-oxygen crossflow conditions: 1) Mach number $M = 1.7$ and 900-K static temperature and 2) $M = 2.3$ and 1300-K static temperature. These two crossflow conditions are distinguished by their differing abilities to support flame propagation into the supersonic free-stream flow. At the higher crossflow speed and temperature, the higher pressure and temperature behind the shock wave induced by the fuel jets can enhance ignition and flame propagation. At $M = 1.7$, the jet flame is not able to be ignited even with the application of the USRD, although excited OH radicals are detected in the region adjacent to the plasma discharge. An $M = 2.3$ crossflow is capable of autoigniting jet flames when the jet-to-crossflow-momentum ratio J exceeds two.

Fig. 3 shows the representative images of intrinsic OH emission in an $M = 1.7$ oxygen crossflow taken $1 \mu\text{s}$ after the USRD pulse. The spontaneous fluorescence of the USRD is not seen in the image due to its short lifetime (~ 20 ns); however, time-average photographs of the discharge indicate that it is observed to be a streamer of approximately 1 mm in diameter (spanning 6 mm between the electrodes) extending up to 2 mm above the surface. The calculated static pressure and temperature are approximately 25 kPa and 900 K, respectively. Fig. 3(a) is taken with only the upstream hydrogen jet injection. The momentum ratio of the upstream jet is approximately $J = 0.1$. In contrast, Fig. 3(b) and (c) shows the corresponding images of OH emission (side and top views, respectively), when

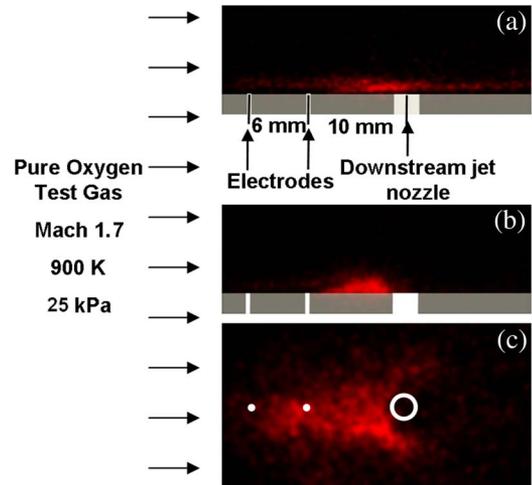


Fig. 3. Pulsed-discharge-induced excited OH emission images with $M = 1.7$, $T = 900$ K pure-oxygen crossflow. (a) Side view when an upstream subsonic hydrogen ($J \sim 0.1$) jet is injected. (b) Side view and (c) top view when both of the upstream ($J \sim 0.1$) and downstream ($J \sim 2$) hydrogen jets are injected.

both the upstream and downstream hydrogen jets are activated. The momentum ratio of the downstream jet is $J = 2$. At a momentum ratio of $J = 0.1$ for the upstream jet, the jet flow is in the subsonic jet regime, and this ratio is found to maximize the OH emission intensity. Spontaneous OH emission is not observed at $1 \mu\text{s}$ after the USRD pulse with ratios $J > 0.2$. In both cases [Fig. 3(a) and (b)], the excited OH emission appears to be strongest very near the wall surface downstream of the electrode pair. The radicals do not penetrate deeper into the crossflow because the upstream hydrogen jet momentum ratio is too low. It is noteworthy that no OH emission is detected without the USRD. We therefore attribute this emission to excited OH that is produced as a result of plasma excitation and convected by the flow, as the excited $A^2\Sigma^+$ state has a relatively long lifetime. We cannot rule out the possibility of the production of an initial flame kernel; however, ground-state OH is not detected far from the surface by PLIF imaging under these conditions, confirming that a flame has not propagated into the free stream.

We therefore conclude that the OH radicals seen in emission are produced by the USRD from the oxygen crossflow mixed primarily with hydrogen supplied through the upstream jet nozzle. In Fig. 3(a), we see that in the absence of a downstream jet, the radicals spread over a wide range far downstream of the electrodes, while a stronger and narrower OH emission region is observed between the electrode pair and the downstream jet nozzle [see Fig. 3(b)] with both of the jets activated. Fig. 3(c) confirms that the downstream jet blocks the crossflow and provides a small recirculation region in front of the bow shock induced by the jet.

The higher enthalpy crossflow ($M = 2.3$ and $T = 1300$ K) enhances the downstream jet flame ignition and flame propagation but only under nonequilibrium plasma activation. Fig. 4 shows the typical OH PLIF images of ground-state OH radicals taken in the absence of a USRD pulse [Fig. 4(a)] and $1 \mu\text{s}$ after a USRD pulse [Fig. 4(b)] under these higher enthalpy conditions. We estimate that the ratio of energy deposition by the USRD

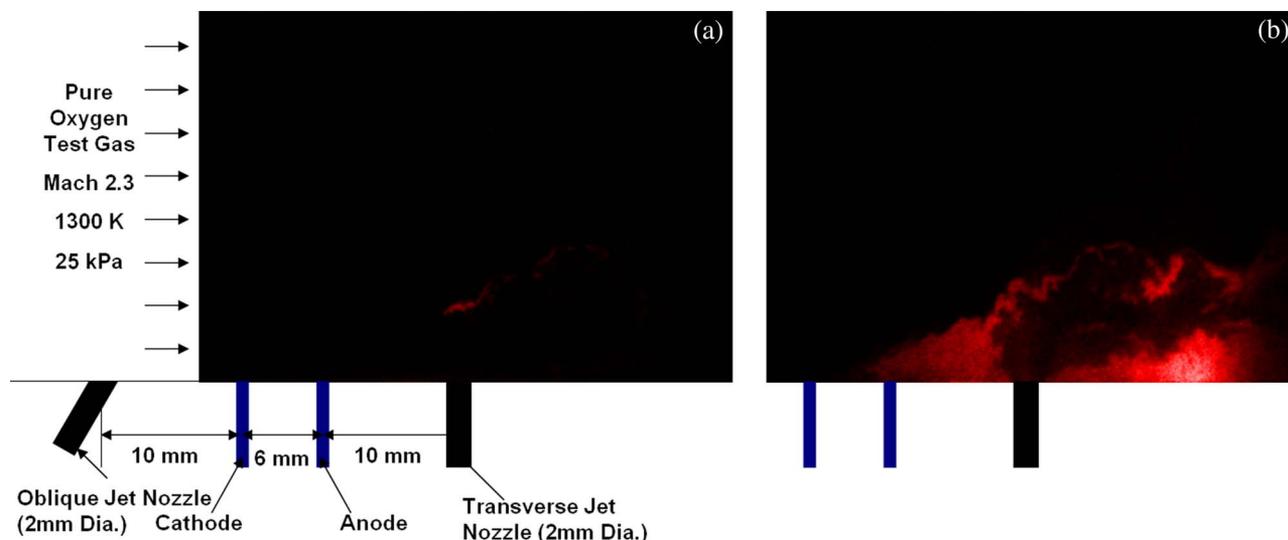


Fig. 4. OH PLIF images taken (a) without and (b) with the pulsed discharge.

to the total crossflow enthalpy is approximately 10^{-6} . In both cases, both the upstream and downstream hydrogen jets are activated with corresponding jet momentum ratios $J = 0.1$ and $J = 2$, respectively. We see that a small fragmented OH region is apparent on the windward side of the main jet [see Fig. 4(a)], suggesting the presence of a weak autoignited downstream jet flame. In contrast, in the presence of the USRD, there is a more intense OH region distributed over a wider area in both the windward and leeward sides of the downstream jet, confirming the existence of a stronger jet flame that appears to propagate into the supersonic crossflow. Clearly, the ignition and stabilization of this flame are only achieved by the use of the USRD under these flow conditions. Recall that from the emission studies shown in Fig. 3, the presence of the downstream jet served to produce a region rich in plasma-activated species just upstream of, and around, this fuel jet. Examining the PLIF images of Fig. 4, we see that combustion is clearly taking place in this region and that the flame extends well into the free stream, suggesting that this region in front of the bow shock may serve to pilot the resulting jet flame.

Based on the lower heating value of the hydrogen fuel, we estimate that only one part in 10^5 of the fuel's energy release is used by the USRD to ignite the flame (assuming that the fuel is completely consumed). The fraction of the discharge-deposited energy that is used in dissociation and production of radicals depends on the characteristics of the discharge. The reduced electric field of the USRD is approximately 300 Td, resulting in an electron temperature (in an equimolar H_2/O_2 mixture) of 8 eV, as estimated from the electron energy distribution function (EEDF) derived from the solution of the Boltzmann equation using the commercially available Boltzmann solver BOLSIG [20]. The method of Penetrante *et al.* [21] with available dissociation cross sections and the EEDF provides initial yields of dissociated species. If these species are produced within the discharge volume of approximately 6 mm^3 during the duration of the discharge pulse by electron impact dissociation, the dissociation rate coefficients and resulting radical concentrations permit an estimate of the electron number density during

the discharge pulse, which we calculate to be approximately 10^{18} m^{-3} .

The nature of the postdischarge flow field and its interaction with the associated shock structure is believed to play an important role in the flame ignition mechanism. A superposition of typical pulsed Schlieren images with the PLIF ground-state OH images of Fig. 4 assists in trying to understand this relationship by revealing interesting flow features. These superimposed images are shown in Fig. 5. Fig. 5(a) combines a typical Schlieren image with the PLIF image (discharge off) of Fig. 4(a), while Fig. 5(b) combines the same Schlieren image with the PLIF image (discharge on) of Fig. 4(b).

We see from Fig. 5(a) that there is evidence of an autoignited flame just behind the bow shock where we expect the pressure and temperature to be elevated by the shock wave. Note, however, that there is no detectable OH in the leeward side of the jet where the fuel and crossflow are expected to be relatively well mixed in the jet wake [22]. It seems that despite this autoignition behind the bow shock, the flame is marginally stable and does not propagate into the free stream to consume a significant fraction of the jet fuel. This is contrasted with the case in the presence of the discharge, as shown in Fig. 5(b). In the presence of the USRD, we see that the flame is autoignited behind the bow shock, but it is attached to the strong combustion region in front of the bow shock, and we also find that there is evidence of even stronger OH signals in the leeward side of the jet in comparison to the windward side, signifying the presence of combustion in the jet wake. The results of the discharge-off case indicate that the autoignition is triggered by the shock wave, and it is very likely that even with the discharge plasma activation, the strength of the shock may be an important parameter in determining autoignition conditions. As mentioned previously, the shock wave raises the temperature and pressure, notably in the region adjacent to the boundary of hydrogen and oxygen in the windward side. As important, the USRD triggered pilot in the recirculation region in front of the bow shock appears to penetrate across the shock wave into this marginally autoignitable mixture and seems to

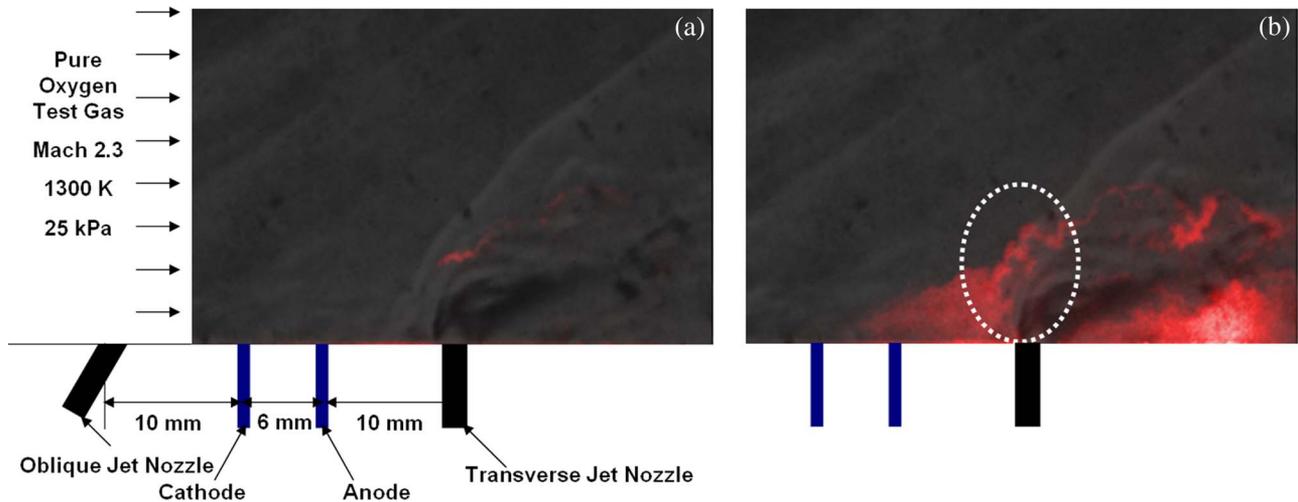


Fig. 5. Schlieren images overlapped with the OH PLIF images: (a) Without and (b) with the pulsed discharge.

be directly connected to the postshock jet flame [see the region highlighted by the white circle in Fig. 5(b)]. It is also possible that the strong combustion occurring in the leeward side of the jet is also partially dependent on the production of this plasma-activated pilot flame, as the species in this upstream region can flow around the bow shock [see Fig. 3(c)] and can also traverse the shock and flow around the jet to penetrate into the hydrogen/oxygen mixture in the leeward side.

Clearly, the composite images of Fig. 5 indicate an important interplay between the chemistry of the plasma-activated flow and the complex jet flow field, which needs further study for optimization. Future experiments will further examine the benefit offered by this USRD plasma in igniting and sustaining these jet flames under conditions of marginal stability. Important issues to be addressed include a study of the postdischarge flow region composition (e.g., are stable intermediate species playing an important role in the piloting of the combustion in the bow shock region) and a detailed survey of flame stability limits and how these are dependent on jet flow properties.

IV. CONCLUSION

This paper describes recent studies of pulsed nonequilibrium plasma activation of jet flame ignition in supersonic crossflows. The nonequilibrium plasma is produced by repetitive pulses of 7-kV peak voltage, 20-ns pulsewidth, and 50-kHz repetition rate. A combination of subsonic and sonic hydrogen jets is injected into a pure-oxygen supersonic free-stream flow under conditions ranging from $M = 1.7$ to 2.3. Unlike previous methods of stabilizing combustion in supersonic flows, no use of wall cavities or abrupt geometric changes in the channel wall are used to generate recirculation regions. Here, the fuel injection nozzles and electrodes are flush with the surface of a flat sharp-leading-edge plate that is oriented to be parallel to the flow to minimize stagnation pressure losses associated with generated shock waves. We describe a configuration combining an upstream subsonic oblique jet and a downstream sonic transverse jet that serves to provide flow conditions for jet flame ignition. The flow pattern and shock waves induced by the dual hydrogen jets are characterized by Schlieren imaging.

PLIF and emission spectroscopy are employed for imaging the distribution of OH radicals and confirmation of jet flame ignition by the plasma. It appears that the upstream subsonic jet produces an oxygen/hydrogen mixture that, when activated by the plasma, is convected toward the downstream main sonic jet, interacting with the bow shock formed by this jet to produce a combustion region that pilots the formation of a jet flame, even under conditions of marginal stability. We find that ignition is easier at higher Mach numbers (e.g., $M = 2.3$ as opposed to $M = 1.7$), as the postshock conditions play an important role in the autoignition process and in the combustion of entrained oxygen/hydrogen in the wake region of the primary fuel jet.

Future experiments will focus on carrying out an extensive survey of the combustion stability limits and on extending combustion to lower static temperature and lower Mach numbers by further optimizing the interaction of the USRD with the two fuel jets. An important element in future studies includes the development of an understanding of the postdischarge chemistry and its role in piloting the combustion process.

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