Plasma-enhanced mixing and flameholding in supersonic flow

Alexander Firsov\textsuperscript{1}, Konstantin V. Savelkin\textsuperscript{1}, Dmitry A. Yarantsev\textsuperscript{1} and Sergey B. Leonov\textsuperscript{1,2}

\textsuperscript{1}Joint Institute for High Temperatures, Russian Academy of Sciences, 125412 Moscow, Russia
\textsuperscript{2}Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA

The results of experimental study of plasma-based mixing, ignition and flameholding in a supersonic model combustor are presented in the paper. The model combustor has a length of 600 mm and cross section of 72 mm width and 60 mm height. The fuel is directly injected into supersonic airflow (Mach number $M = 2$, static pressure $P_{st} = 160–250$ Torr) through wall orifices. Two series of tests are focused on flameholding and mixing correspondingly. In the first series, the near-surface quasi-DC electrical discharge is generated by flush-mounted electrodes at electrical power deposition of $W_{pl} = 3–24$ kW. The scope includes parametric study of ignition and flame front dynamics, and comparison of three schemes of plasma generation: the first and the second layouts examine the location of plasma generators upstream and downstream from the fuel injectors. The third pattern follows a novel approach of combined mixing/ignition technique, where the electrical discharge distributes along the fuel jet. The last pattern demonstrates a significant advantage in terms of flameholding limit. In the second series of tests, a long discharge of submicrosecond duration is generated across the flow and along the fuel jet. A gasdynamic instability of thermal cavity developed after a deposition of high-power density in a thin plasma filament promotes the air–fuel mixing. The technique studied in this work has weighty potential for high-speed combustion applications, including cold start/restart of scramjet engines and support of transition regime in dual-mode scramjet and at off-design operation.
1. Introduction

The effective operation of high-speed air-breathing engines (ram- and scramjets) over a wide range of flow parameters (velocity and altitude) is one of the most technically difficult challenges in design of hypersonic vehicles. The promising approach is a scramjet having flexible gasdynamic configurations that meets a number of extremely challenging technical issues: materials, gears, etc. Commonly discussed trade-off assessment consists of a fixed geometrical configuration based on some ‘characteristic’ Mach number of operation and a control system augmenting a poorer performance for lower and higher values of Mach number, especially for ram/scram transition mode [1–3]. To improve the overall capability of a scramjet with fixed duct geometry at variable conditions, some methods could be applied such as a staged fuel injection, additional mechanical flameholding, or electrical discharge as an ignitor and flameholder. The main advantage of plasma application for control of fuel ignition/combustion is due to non-equilibrium, non-uniform and transient nature of electrical discharges, which deliver a synergy with thermal effects (heating) owing to essentially nonlinear behaviour of induction time versus gas temperature. Those properties may also be of critical importance under non-premixed flow conditions, enhancing air–fuel mixing in compressible flows [4–8]. Three main ideas underlie the concept of plasma-assisted combustion: the gas heating/non-equilibrium excitation by the discharge, fuel–air mixing enhancement owing to gasdynamic instability generation, and control of flow structure in the vicinity of the reaction zone. Sections 3 and 4 consider the experimental data emphasizing the details of plasma-flow–fuel interaction.

A number of experimental studies have been performed to demonstrate the electrical discharge capability for the fuel ignition under conditions typical for scramjet operation [9–11]. In most of those experiments, a modification of supersonic duct geometry was used, such as a backward facing wall step or a contoured cavity, and plasma was used as an igniter of a combustible mixture in a low-speed flow region. At the same time, previous experiments using an alternative configuration, where an electric discharge was sustained over a plane wall [12,13], demonstrated feasibility of plasma application as an effective flameholder in a supersonic combustor, without relying on mechanical obstacles. The last approach is particularly considered in this work. Over the years, a main benefit of plasma application was expected owing to highly non-equilibrium chemical kinetics, which helps to reduce plasma power for fuel–oxidizer mixture ignition [5–7,14–16]. There was shown a dramatic reduction of ignition time up to orders of magnitude at premixed conditions, including a specifically important for scramjet technology range of gas temperature, \( T_0 = 500–900 \) K. Despite very promising capability, such an approach looks to be a little impractical for high-speed engines with a direct fuel injection. In most conditions, a main limiting factor is a rather slow mixing, resulting in strong gradients of fuel–oxidizer ratio across a combustion chamber.

Mixing enhancement by plasma is the second principal focus of this work. In practical schemes of non-premixed flow, the combustion and mixing develop simultaneously affecting each other [17–19]. In general, the molecular diffusion and the kinematic stretching of fuel–oxidizer interface are responsible for the mixing process. However, the molecular diffusion is a rather slow process and the mechanism of interface stretching, natural or artificial, is only enable to provide a fast enough mixing in compressible flow. Both direct and indirect mechanisms of plasma-flow interaction may be responsible for the mixing boost. First, plasma-based heating generated in the flow acts as a ‘gradual’ obstacle, generating a vortex flow similar to a Karman vortex trail [20]. A body force generation due to electrical current in an external magnetic field (magnetohydrodynamics mechanism) affects the flow structure and mixing accordingly [21,22]. Another direct plasma effect is caused by strong modulation of power deposition in the electric discharge, which results in boundary layer or shear layer tripping, depending of the discharge location. An indirect mechanism of mixing enhancement is realized through the Richtmyer–Meshkov instability, occurring in flows with non-collinear gradients of density and pressure [23]. This leads to formation of deterministic vortex-dominated flows and, subsequently, to small-scale perturbations resulting in accelerated interface stretch and turbulent kinematic mixing. The most
challenging issue in this case is a right location of typically non-uniform discharge in a shear layer between a fuel jet and surrounding airflow [24].

A novel pattern of plasma–fuel interaction is examined in this paper comparing with previously tested configurations, where plasma was generated in air in front or behind of the fuel injection [12,13,25]. In the current scheme, electric discharge partially locates inside of an injection orifice, chemically preprocessing the fuel and accelerating the mixing owing to introduction of strong thermal inhomogeneity into flowfield. For future research such an approach looks to be quite promising to promote mixing and flameholding in a supersonic combustor.

2. Experimental apparatus and diagnostics

The experiments were performed in a supersonic blow-down wind tunnel PWT-50H [12,13], a schematic of which is shown in figure 1. In the present configuration, the test section operates as a supersonic combustor, with the fuel injectors and electrical discharge generator flush-mounted on a plane wall [20], as shown tentatively in figure 1b. The coordinate system $X, Y, Z = 0$ is placed at fuel injector exit. The combustor cross section is $D_y$ (width) $\times$ $D_z$ (height) $= 72 \times 60$ mm, with a length of $D_x = 600$ mm. To avoid thermal choking during fuel ignition, the test section has a $10^\circ$–$15^\circ$ expansion angle downstream of the injectors $x = 40–60$ mm on the opposite (bottom) wall, to the cross section of $D_y \times D_z = 72 \times 72$ mm. The experimental conditions are as follows: initial Mach number $M = 2$; static pressure $P_{st} = 160–250$ Torr; stagnation temperature $T_0 = 300$ K; air mass flow rate $G_{air} = 0.6–0.9$ kg s$^{-1}$; fuel (ethylene) mass flow rate $G_{C_2H_4} = 1–8$ g s$^{-1}$; duration of steady-state aerodynamic operation $t \geq 0.5$ s. The global equivalence ratio (ER) alters in the range of ER $= 0.02–0.15$, while the local value is rather variable in zone of interaction.

The test section of PWT-50H high-speed combustion facility is equipped with three pairs of 100 mm diameter quartz 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 of plasma–fuel-flow interaction. 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 [25]. Instrumentation includes the pressure measuring system, the schlieren system, UV/visible optical emission spectrometer, current and voltage sensors, TDLAS apparatus for water vapour temperature/concentration measurements, five-component exhaust flow chemical analyser, high-speed cameras and operation sensors.

Three basic schemes of injectors and plasma generators arrangement were examined, as shown in figure 2:

- Scheme 1: electrodes located upstream of the fuel injectors. Plasma is generated mostly in air and then interacts with injected fuel [12].
- Scheme 2: electrodes located downstream of the fuel injectors. Electrical discharge is generated in non-uniform air–fuel composition [25].
- Scheme 3: the electrical discharge collocates with the fuel jet [26].

In the first two patterns, the fuel is injected through five circular ($d = 3.5$ mm) orifices all in a row across the span, as is shown in figure 2b. The row of injectors is located at 20 mm downstream of the first row of electrodes and 30 mm upstream of the second one. The direction of fuel injection is normal to the wall. Typically, the duration of the discharge was about 100 ms. Fuel injection was started 20 ms after the discharge initiation. The fuel injection continued 10–20 ms after the discharge to observe whether the flame was held or extinguished. In the third scheme four injection-ignition modules (PIMs) are installed in the combustor on the same wall. The fuel injectors have the same diameter and geometry as in schemes 1 and 2. The high-voltage electrode (anode) is integrated into the fuel injector to ensure significant impact of the discharge on the fuel-flow prior to its injection into the main airflow. The custom-made power supply used in the present experiments is designed to operate with a steep falling voltage–current characteristic and
Figure 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 is shown by a rectangle in the top wall of the test section. (Online version in colour.)

Figure 2. Schematic of three basic layouts of fuel injectors and electrode arrangement (a). Three-dimensional view of two insertions used in test (b): left image is for scheme 1 and scheme 2; right image is for scheme 3. (Online version in colour.)

individual control of each output channel. Control of output power is performed by varying the internal resistance of the power supply. Despite large magnitude of high-frequency oscillations, the time-averaged power values are quite stable and repeatable from run to run.

The facility is equipped with the static pressure scanner NetScanner 9116 with 16 static pressure sensors, B1–B16, stagnation pressure sensor \( P_{\text{Pitot}} \), pressure in vacuum tank \( P_{\text{P}} \). Schlieren visualization was used as the main tool to study dynamics of the flow structure modification during fuel ignition induced by the plasma. The high-resolution schlieren system uses a high-power pulsed diode laser (pulse duration \( t_{\text{exp}} = 100 \text{ ns} \), frame rate up to 5000
frames per second) and framing camera Basler A504K (frame rate up to 1000 frames per second synchronized with the diode laser). Emission spectra of the plasma luminescence were recorded by a Lot-ORIEL spectrometer with Andor CCD camera (spectral range $\lambda = 200$–$1200$ nm). The spectral dispersion is 0.035 nm pixel$^{-1}$, and the spectral resolution is $\Delta \lambda \sim 0.13$ nm. The spectroscopic system collects plasma emission from a cylindrical volume aligned in the $Y$-direction from window to window and with diameter of 10 mm.

3. Ignition and flameholding experiment

(a) Near-surface quasi-DC electrical discharge characterization in high-speed flow

Typical photographs of the discharge appearance, taken during operation in scheme 1 and scheme 3, without and with fuel injection, are presented in figure 3. In scheme 2, the discharge without injection looks very similar to scheme 1. A hydrocarbon fuel injection leads to significant increase of discharge luminescence in zones of interaction, mostly because of strong CN and C2 molecular bands amplification. Total discharge power in all cases was $W_{pl} = 6$–$24$ kW. The discharge voltages were oscillating because of variation of discharge filament lengths, within a range of $U_{pl} = 0.7$–$2$ kV. The volt–ampere characteristic of the discharge has a stepwise shape: at fixed parameters of electrical circuit and airflow the discharge current remains roughly constant [13]. The average power is regulated by means of variation of the discharge average current within a range of $I_{pl} = 1.5$–$7$ A for each electrode or PIM. Prior to fuel injection, the discharge power is distributed equally between the electrodes. A simple estimation shows that for the typical tests the discharge power presents a small fraction of the thermal power released at fuel combustion, $W_{pl}/(h \times GC_{2}H_{4}) \leq 10\%$, decreasing down to a few per cent at optimization. Note that an apparatus, similar to one described in this paper, is unlikely to be used at operation with so low an overall ER but mostly as a flameholder or chemical reactor in engine with much higher thermal release.
Figure 4. Optical emission spectrum taken in scheme 3 from the ethylene–airflow–plasma interaction region. The spectrum incorporates seven overlapping spectra, taken separately at the same conditions. Discharge current $I_{pl} = 2–4$ A, ethylene injection jet $G_{C_2H_4} = 0.5–1$ g s$^{-1}$ from each module in $M = 2$ airflow, $P_a = 180–220$ Torr. Major emission lines and bands are labelled. (Online version in colour.)

The detailed data for the discharge in modes 1 and 2 are presented in [12,13,20]. For scheme 3, the discharge dynamics is described in the following way. In the beginning of plasma filament development, breakdown occurs along the flow inside the injector and a short gap between the injection orifice and a grounded metal wall upstream of the injector. After this, the filaments are blown away by the flow downstream of the injector, terminating to the grounded wall downstream of the ceramic inserts, shown in figure 2. After this occurs, the plasma filaments extend downstream over a distance up to 100 mm, close to the surface of the ceramic insert. The location of filament termination at the grounded wall oscillates at a frequency of $F = 10–20$ kHz. The filament behaviour changes after fuel injection. Specifically, plasma emission intensity increases and the plasma filaments move away from the surface. Operation characteristics of individual PIMs depend to some extent on whether the adjacent modules are powered or not, especially for the side modules.

A composite optical emission spectrum of the plasma, taken by integrating the emission from the area of plasma–fuel-flow interaction, $X = 20–30$ mm, $Y = 0–10$ mm, is displayed in figure 4. Analysis of the spectrum shows that in the presence of the hydrocarbon fuel, three different types of species are detected: hydrocarbon/carbon fragments, chemical reaction products resulting from interaction of hydrocarbon plasma and air, and excited air species (mainly $N_2$). Species with highest emission intensity include atomic hydrogen, carbon and oxygen (O atom triplet line at $\lambda = 777$ nm outside of the spectral range of figure 4), hydrogen molecule $H_2$, as well as $C_2$, CN, OH and CH radicals. Neglecting continuum luminescence, the molecular bands of CN violet system, and $C_2$ Swan bands dominate in acquired visible–UV emission. These spectra indicate intense chemical transformations in the flow, including generation of active radicals in electronically excited states. The emission spectra were used to evaluate plasma parameters in a zone near the base of the fuel injection jet. Second positive system of molecular nitrogen, $N_2 (C^3 \Pi_{u}, v' = 0 \rightarrow B^3 \Pi_{g}, v = 0)$ band at $\lambda = 337.1$ nm, was used to infer the rotational–translational temperature in the plasma [27], $T_r = 3000 \pm 500$ K, which is strongly weighted towards the peak temperature in the plasma filament. The H atom Balmer series lines are very intense, with the $H_\alpha$ line at $\lambda = 656.3$ nm being the strongest in this case. Electron density in the plasma was extracted from $H_\alpha$ spectral line shape [28,29], since Stark effect is the dominant mechanism of line broadening at the present conditions. Electron density near the base of the fuel injection jet is inferred to be $n_e = (4.5 \pm 1.0) \times 10^{15}$ cm$^{-3}$. 

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log (intensity), arb. units

wavelength (nm)

Graph with emission lines and bands labeled.
Figure 5. Normalized wall pressure $P_{st}/P_{\infty}$ distribution at plasma-assisted combustion. (a) For scheme 1 and scheme 2. Total discharge power $W_{pl} = 9–12$ kW. (b) Scheme 3, total discharge power $W_{pl} = 16–18$ kW. Numbers in the legend indicate ethylene mass flow rate $G_{C_2H_4}$ in g s$^{-1}$; points labelled ‘flow’ taken without fuel injection, with the discharge turned off; points labelled ‘dis’ taken without fuel injection, with the discharge turned on. (Online version in colour.)

(b) Experimental results on plasma-assisted combustion: effect of fuel mass flow rate and discharge power

Typical wall pressure distributions are presented in figure 5a for schemes 1 and 2, when the electrode system and fuel injectors are not combined into a single module. The discharge generation without fuel injection slightly affects the pressure distribution, increasing the pressure in immediate vicinity of electrode system. When the fuel injection is turned on, the pressure elevates slightly in zone near (downstream) injector for the first scheme and close to plasma area for the second scheme. This elevation is associated with the fast reactions of fuel partial oxidation by atomic oxygen O. Other branches of reaction are related to electronically/vibrationally excited nitrogen ($N_2^*$) and other active species generated in air plasma.

In the case of the second scheme, the highly reactive species and radicals, such as H, CH, C$_2$H$_3$, are involved also in the initial fast chemical processes. The products of those fast plasma–chemical reactions are accumulated in associated separation bubble and then are blown down by a core
flow. Main chemical power release occurs after fuel mixing with a core air on the second stage of combustion [12], rather downstream of the place of plasma generation. In figure 5, this zone is located at \( x > 120 \) mm. The schlieren image in figure 6a depicts this zone very well; it is labelled as the ‘flame front’. At relatively low plasma power \( W_{\text{pl}} < 8 \) kW, the second stage of combustion may not be realized at all. Two effects are responsible for this: (i) insufficient fuel activation by the discharge and (ii) insufficient fuel–air mixing enhanced by the plasma. Numerical modelling [30], including plasma–chemical kinetics and mixing processes, indicates that the second effect may be dominant.

At ‘optimal’ conditions for scheme 2, the zone of intensive chemical reactions moves upstream and stabilizes near the plasma location. This regime is seen in figure 5a for ethylene mass flow rate \( G_{\text{C}_2\text{H}_4} = 2.1 \) g s\(^{-1}\). It appears in significant increase of the wall pressure at coordinates between \( x = 30 \) and \( x = 40 \) mm. When the flame front is stabilized (during steady-state flameholding), the combustion process progresses slowly in the axial direction, owing to gradual mixing of fuel and air. Chemical energy release during combustion elevates the pressure and forms a wedge-shape combustion zone, with its average angle increasing as combustion intensifies. The attached oblique shock-wave angle increases accordingly. It should be noted that this zone is observed at operation on scheme 1 as well; but the electrical power for this effect to appear has to be rather high, \( W_{\text{pl}} > 20 \) kW. If \( G > 3 \) g s\(^{-1}\), the zone of high-energy release moves down.

The second series of experiments was performed on ethylene ignition and flameholding by means of the electrical discharge collocated to the fuel injection jet, described above as scheme 3 [26,31]. The following test parameters have been varied: (i) fuel injection flow rate, within a range of \( G_{\text{C}_2\text{H}_4} = 1–8 \) g s\(^{-1}\) and (ii) discharge time-averaged current (i.e. discharge power). First of all, it has been determined that ignition and flameholding are observed over a much wider
range of parameters compared to previously tested configurations on schemes 1 and 2, both with upstream and downstream location of the electric discharge relative to fuel injection port. Pressure distributions measured along the test section are plotted in figure 5b versus fuel mass flow rate. At high enough values of discharge power and fuel injection mass flow rate, a significant increase of wall pressure is observed over a wide range of fuel-flow rates. In lean mixtures, ignition is detected downstream, as far as \( X > 250 \text{ mm} \) from the location of the plasma–airflow–fuel injection interaction region (this is not visible in the schlieren images). As the fuel injection flow rate is increased, the flame front moves forward and gradually occupies the entire combustor downstream of the injector location. Operating at fuel mass flow rate above \( G_{\text{C}_2\text{H}_4} \approx 6 \text{g s}^{-1} \) may lead to thermal choking in this combustor geometry. At higher temperature of air the thermal choking should be observed with a greater fuel mass flow rate. Increasing the duct expansion angle may resolve this problem.

Typical schlieren images of flow structure during combustion are shown in figure 6a,b for schemes 1 and 3, correspondingly. In the case of scheme 1, the oblique shock wave, originating at plasma generator, reflects from the bottom wall and impinges the fuel jet. Another shock wave from the wall ramp impinges the mixing layer of fuel and air that is visible in the second windows. In the case of scheme 3, the oblique shock wave, originating at fuel injector and plasma generator, interacts with expansion fan and compression wave generated by the duct expansion on the bottom wall of the test section (see figure 6b), and then impinges the mixing layer between the fuel jet and the core flow. Flow separation near the side wall at the PIM location is evident. An increase of fuel mass flow rate would result in separation bubble moving upstream, thus increasing the oblique shock-wave angle, and eventually leading to thermal choking of the duct.

The other side of electrical discharge effect on combustion is enhancement of air–fuel mixing in high-speed flows. Two regions of the flow field, labelled as A and B in figure 6b, are of particular interest. In region A, shock waves caused by the test section wall imperfections and originating upstream of the field of view interact with the fuel jet with a high density gradient, caused by plasma-induced non-uniform heating. In region B, the shock wave is caused by the wall wedge and is amplified by a strong shock coming from the PIMs. At the beginning of PIM operation, this shock impacts the heated near-wall fuel jets, thus enhancing the mixing processes.

Figure 7 demonstrates a remarkable difference between the performance of the three schemes applied for plasma-based ignition and flameholding under conditions of low gas temperature, non-premixed composition and low overall ER \( \ll 1 \). Scheme 1 exhibits more effective ignition at low fuel-flow rates, \( G_{\text{C}_2\text{H}_4} < 2 \text{g s}^{-1} \). The last configuration, scheme 3, however, shows much better performance at higher values of the fuel injection, \( G_{\text{C}_2\text{H}_4} > 2 \text{g s}^{-1} \), where scheme 1 is limited to partial oxidation with fairly insignificant increase of pressure. To interpret this difference, two key factors need to be pointed out: (i) in scheme 1, the discharge was sustained in air, while in scheme 3 it is sustained in the fuel (inside the injection orifice) as well as in the fuel–air mixture and (ii) the flow structure in scheme 3 is significantly different comparing with scheme 1. Specifically, near-surface quasi-DC discharge used in scheme 1 produces a 'closed' flow separation zone (a separation bubble) downstream of the discharge, with high concentrations of chemically active species, such as atomic oxygen (O) and electronically/vibrationally excited nitrogen (\( N_2^* \)). The fuel, after being injected into this zone, has sufficiently long residence time to mix with plasma-activated air and ignite. After ignition, the volume of this zone increases and forms an extended subsonic flow zone without obvious reattachment downstream. At further increase of fuel injection a local concentration of the fuel in separation zone exceeds the rich limit of ignition. In contrast to this pattern, in scheme 3 the discharge is localized along the fuel injection jet, which generates reactive species and radicals, such as H, CH, \( \text{C}_2\text{H}_3 \), etc. by electron impact, and enhances mixing by convecting the unstable plasma filament with the injection jet. Based on the present results, it appears that plasma filament convection with the flow becomes significant only at sufficiently high fuel injection speed, comparable with the main airflow velocity.
Figure 7. Comparison of pressure data depending on fuel mass flow rate, obtained for the configuration with discharge generation upstream of the fuel injector, downstream of the fuel injector, and for collocated scheme. Flow parameters ($M = 2$, $P_{st} = 150–200$ Torr) and discharge power ($W_{pl} = 12–18$ kW) are similar in all cases; axial location $X$ is measured from the fuel injection cross section. (a) Location of measuring points in proximity of fuel injector $x = 40–50$ mm; (b) in downstream zone $x = 175–190$ mm. (Online version in colour.)

(c) Data on tunable diode laser absorption spectroscopy measurements

TDLAS measurements were performed in typical operation modes: $M = 2$, $P_{st} = 150$ Torr, plasma power was $W_{pl} = 10–16$ kW, ethylene mass flow rate was ‘optimal’ for each operation scheme: $G_{C_2H_4} = 1.3–1.6$ g s$^{-1}$ for scheme 1, $G_{C_2H_4} = 1.8–2.1$ g s$^{-1}$ for scheme 2 and $G_{C_2H_4} = 2–2.5$ g s$^{-1}$ for scheme 3. The data on $Z$-distribution of gas temperature in cross section $x = 130$ mm are shown in figure 8. The spectral interval of a single diode laser (DL) scan was about 0.9 cm$^{-1}$. Four absorption lines fall within the interval. Depending on the temperature of the probing zone relative intensities of the lines vary significantly. The details of data processing algorithm are described in [32] and references therein. Each point in the figure was obtained in an individual run of the facility. The accuracy of measurements could be estimated in $\Delta T = \pm 30$ K at $T > 300$ K. Note that the measured temperature is line-averaged on the DL beam pass from wall to wall. In the case of non-homogeneous distribution of gas parameters in reacting zone, a contribution
of each individual area is weighted in accordance with water vapour concentration. It makes an estimation of maximal values of gas temperature to be a non-trivial problem.

The result of measurements indicates substantial difference in maximal value of temperature and a hot zone thickness depending on applied scheme of plasma-flow–fuel interaction. In the case of upstream plasma generation, the reaction zone is thin in \( Z \) direction comparing with schemes 2 and 3. The maximal value of the \( Y \)-averaged gas temperature is also much lower in this case. The distribution patterns are also different. Scheme 3, where plasma collocates with the fuel injection jet, demonstrates the highest amplitude of gas temperature and a rather thick hot zone in \( Y \) direction. Qualitatively, similar result was obtained for a water vapour concentration distribution measured by TDLAS.

4. Mixing enhancement experiments

In this section, a problem of the mixing enhancement is explored owing to a mechanism of gasdynamic instabilities developing at decay of after-discharge channel. It was mentioned in the Introduction that such a mechanism is one of several direct and indirect ones that could be realized at interaction of electrical discharge with a high-speed flow. The described mechanism is based on an experimentally proved fact that a strongly turbulent gas motion develops in a cooling post-discharge channel [33–35]. In experiments with a pulse sub-microsecond filamentary discharge [36–38], it has been shown that there is one more, much faster, mechanism of the after-spark channel expansion. In such specific mode, the expansion is driven by high-velocity radial jets formed during the after-spark channel cooling. The second important feature of the short-pulse long spark is a high selectivity of the discharge localization in medium with gradient concentration of different components [24]. The discharge position is detected right in mixing layer of some pairs of gases involved. Finally, it was demonstrated that the discharge channel position can be effectively tailored by a little energy beam of a femtosecond laser [39].

Recently, the mixing intensification in high-speed flow due to filamentary discharge generation was experimentally proven by means of analysis of flow disturbances and measurements of local fuel concentration by method of probe breakdown fluorescence [40].

The triggered pulse discharge is generated by means of the specially designed power supply based on a Tesla coil with impulse excitation [37,38]. An important feature of the power supply is the rapid voltage rise, \( \frac{dU}{dt} > 2 \times 10^{11} \) V s\(^{-1}\). Tests were performed in ambient conditions and in a high-speed flow at the following parameters: air pressure \( P = 1 \) bar at \( M = 0 \) and \( P = 0.2\)–0.8 bar at \( M = 2\)–0.3; inter-electrode gap \( d = 30\)–80 mm; discharge main pulse duration \( \tau = 30\)–80 ns;
Figure 9. Schlieren images of gasdynamic instabilities developed due to pulse discharge generation in ambient air at $U_{\text{max}} = 90\,\text{kV}$, $I_{\text{max}} = 1.5\,\text{kA}$. (a) Time delay $t \approx 1\,\mu\text{s}$; (b) time delay $t = 100\,\mu\text{s}$; (c) time delay $t = 1\,\text{ms}$. 'SW'—position of shock wave; 'DCh'—interface of residual thermal cavity expanded after the electrical discharge. (Online version in colour.)

maximum voltage $U_{\text{max}} = 80–120\,\text{kV}$; maximum current $I_{\text{max}} = 1–3\,\text{kA}$; maximum power release $W_{\text{max}} = 20–110\,\text{MW}$; energy deposition in a single-pulse mode $E_d = 1.0–2.7\,\text{J}$. Instrumentation includes test chamber with variable gas pressure and gas composition, supersonic wind tunnel PWT-50 with a set of sensors, voltage and current probes. A set of schlieren images were acquired with spatial resolution of 0.2 mm and a temporal resolution of 0.1 $\mu\text{s}$. The discharge duration is rather short compared with the gasdynamic processes occurring after the pulse. The gas movement after high-energy density deposition appears to be unstable and goes through several stages [36]. On the first stage ($t < 50\,\mu\text{s}$), the channel looks quite classical: cylindrical thermal cavity and shock wave running away. Note that even in the early stage small-scale instabilities of the discharge channel were observed (figure 9a). A working hypothesis of the origin of these perturbations is of an electromagnetic nature due to interaction of high electric current with the azimuthal magnetic field.

At $t = 80–150\,\mu\text{s}$ the shape of the after-spark channel occurs intensely unstable (figure 9b). The physical mechanism of this instability was considered in [38,41]: cooling of the axial zone leads to the pressure decrease with sequential gas reverse movement. Such a movement is unstable owing to the Rayleigh–Taylor mechanism [34,41]. The estimation of the instability development time $t \approx 100\,\mu\text{s}$ appears in a good agreement with the experimentally observed value.

The analysis of experimental data taken in ambient air and in high-speed flow returns a not obvious result concerning the size of disturbed zone: its value is several times bigger than it should be in accordance with laminar or turbulent diffusion mechanisms [40–42]. This happens because of generation of intensive lateral jets on the last stage of expansion followed by fast turbulization of the gas in significant volume, comparable to the gap distance, as is shown in figure 9c.

The fast jet generation on a time scale $t = 10^2–10^3\,\mu\text{s}$ is of major importance for a suggested mechanism of the mixing intensification. The mechanism of jet origination is in strong asymmetry of the discharge shape at long enough plasma filament. At concave sides of the plasma channel, the shock-wave propagation results in strong compression followed by strong rarefaction behind the shock. At convex sides, the shock wave is diverging, and thus is characterized by smaller compression followed by weaker rarefaction when compared with the concave sides. As a result, a pressure gradient builds up, with pressure decreasing from convex to the opposite concave sides. This causes jet formation outside of the concave regions, with the general direction of jets from concave to convex. Typically, the velocity of gas movement measured in jets decreases from $V \approx 300\,\text{m s}^{-1}$ at $t = 100\,\mu\text{s}$ down to $V \approx 100\,\text{m s}^{-1}$ at $t = 300\,\mu\text{s}$. The processes mentioned above are well illustrated in [41,42]. Note that no jets are observed when the peak power is lower than 10 MW.

It was found experimentally that the discharge closely follows a boundary between two gases in most of the cases at the air–fuel–plasma interaction (see [35,38] and references therein). This
effect has been called ‘the effect of specific localization’ [43]. The explanation of this fact includes the idea that the discharge localization is managed by the rule of minimal electrical field, required for the discharge maintenance, along the line of breakdown. It can be supposed that the discharge ‘prefers’ the path in the fuel, oxidizer or between them depending on conditions and the phase of discharge development. If the medium is non-homogeneous, the favoured path may not be the shortest one. Tests and computational analysis of plasma properties in fuel–air (C2H4–air in this particular case) mixtures of various compositions demonstrate [35,42,44] that the best conditions for discharge development may be realized in the air–fuel mixture but in air or in fuel.

Special tests were arranged to prove the effect of discharge specific localization in high-speed two-component flow [42]. The experimental approach includes the following key points: supersonic duct-driven airflow \( M = 0.3 \) and \( M = 2.5 \); direct wall injection of gaseous fuel or model gas; and transversal short-pulse repetitive electrical discharge, crossing air–fuel–air zone. Experimental scheme is shown in figure 10a. Jet of secondary gas was injected from the wall through a \( D = 4 \) mm orifice with sonic velocity. The grounded electrode was combined with the nozzle. The ‘hot’ high-voltage electrode was installed on the opposite wall of the duct slightly downstream in respect of the grounded one. Injected gases were of different density, namely: C2H4 (fuel), CO2 (model of a heavier fuel and product) and He (model of hydrogen).

Schlieren photos in figure 10b–d demonstrate CO2 jet in flow, discharge operation without CO2 jet, and the discharge with jet under conditions of subsonic flow (the result in supersonic flow was qualitatively the same). It is clearly seen that discharge breakdown occurs along the jet. Localization of the discharge’s filament may vary from run to run in the experimental mode without jet, but it does not vary significantly in different runs with jet injection.

5. Conclusion

Mixing, ignition and stabilization of combustion in supersonic flows are the problems of major fundamental and applied importance in the development of hypersonic vehicles. Utilization of electrical discharges is the promising approach for the fuel–oxidizer mixing at direct fuel
injection into combustion chamber and for the stabilization of supersonic combustion flame front. Being compared with basic scramjet’s layout, the scheme with plasma assistance delivers more freedom in choice of geometric configuration owing to replacement of mechanical flameholder with a highly effective electrically driven apparatus. The concept of plasma-assisted combustion includes not only accelerating ignition but also mixing enhancement when operating at non-premixed conditions, and flame stabilization (flameholding).

The paper discusses the experimental results on plasma-assisted supersonic combustion and flameholding that have been recently obtained at high-speed combustion facility PWT-50H, using flush-mounted installation of discharge modules. The comparison of previously used schemes with upstream and downstream generation of plasma in respect of fuel injection place and the novel scheme of a combined electric discharge/fuel injection module, with the high-voltage electrode placed inside the fuel injection orifice, is depicted in this work. In the last scheme, called scheme 3, after breakdown is achieved, the discharge current path follows the fuel injection jet due to convective entrainment of the plasma by the flow. The axial part of the plasma filament is localized inside the fuel–air mixing layer. The plasma filaments are extended by the fuel injection flow, penetrate into the main airflow, and terminate far downstream, which is critically important for fuel–air mixing acceleration. Stable flameholding has been observed over a wide range of fuel injection mass flow rates. Critical importance of plasma module and combustor geometry, as well as of key operation parameters such as total discharge power, \( W_{pl} > 10\, \text{kW} \), and fuel mass flow rate, \( G_{\text{C}_2\text{H}_4} > 1 \, \text{g s}^{-1} \), has been demonstrated. Finally, the new scheme demonstrates a significant advantage in terms of flameholding limits, compared with previously tested configurations.

The air–fuel mixing intensification by a long spark discharge of sub-microsecond duration generated in free stream \((M = 0.3–2.5, \text{ static pressure } P = 100–250 \, \text{Torr, discharge energy approx. } 1 \, \text{J pulse}^{-1})\) has been considered as an effective method of mixing intensification in compressible flow. Experimental results demonstrate generation of turbulent and directed motion in the after-spark channel that can essentially enhance the rate of fuel-gas mixing within a high-speed combustor. The effect of specific localization of the filamentary discharge in a mixing layer of two-component flow is of major importance for an implementation.

The use of plasma technology may potentially lead to reduction of total pressure losses when operating the combustor under non-optimal conditions, enhancement of operation stability and, consequently, expanding the air-breathing corridor of ramjet/scramjet operation range. It is also important that the present experiments illustrate possible ways for further improvement of this technique, including the use of contoured injector orifices for supersonic injection and a power supply with a modified voltage–current characteristic.

**Authors’ contributions.** A.F. performed simulations and the data processing; K.S. prepared and conducted most experiments, D.Y. was responsible for measurements and diagnostics and S.L. planned the experiments, processed the data and drafted the manuscript.

**Competing interests.** We declare we have no competing interests.

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