29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

MECANISM OF FLAMEHOLDING IN PLASMA-ASSISTED SUPERSONIC COMBUSTOR

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Keywords: *supersonic combustion, flameholding, plasma assistance, two-zone mechanism*

Abstract

This paper is focused on the study of mechanisms of plasma impact on flameholding in a confined supersonic flow. Fuel (gaseous hydrogen or ethylene) was injected through five circular orifices all in a row across the span and inclined at 25° from the normal in the upstream direction. The combustion process was initiated and sustained by near-surface electric discharge. The row of electrodes was placed 15mm upstream of the row of injectors, each injector is in line with an electrode. A two-zone mecanism of flameholding was observed: i) so called "cold" combustion takes place in the first zone, where plasma-induced fuel conversion and relatively small heat release occurs, ii) common "hot" combustion proceeds in the second zone, where combustion is completed or almost completed with high level of heat release. The following step of this study is spreading out JIHT-RAS approach of plasma assistance to the new supersonic combustor of ONERA, where higher incoming air flow temperature can be reached. Preliminary experimental results without plasma assistance at ONERA's facility and the design of a new plasma/injection module are presented.

1 Introduction

Air-breathing high speed propulsion demands leaving classical jet engines to more efficient propulsion. For flight over Mach 5-6, a promising way is a scramjet propelled vehicle. In these conditions, air entering in scramjet combustor is hot (static temperature between 600K and 1200K) and fast-flowing (typically from M=2 to M=4, which corresponds to a 1300-2000m/s velocity range). The residence time in combustor is short, making it difficult to achieve injection, mixing and burning of the fuel. Moreover optimizing the geometrical configuration for a chosen Mach number of operation leads to degrade performance for both lower and higher values of Mach numbers. Improving the overall capability of scramjets with fixed geometry of the duct could be achieved using extra methods such as, for instance, staged fuel injection, forced flameholding at low temperature (e.g. plasma assisted combustion).

During the last decade, different research teams investigated the ability of plasma discharges to extend a scramjets operating range to off-design values of Mach numbers for fixed geometry scramjet flowpaths [1]-[3]. Prospectively the use of this method might lead to a reduction of total pressure losses under non-optimal conditions, an enhancement of operation stability and, consequently, to the extension of the air-breathing corridor of scramjet operability [4], as illustrated in Fig.1. PWT-50H facility of Joint Institute for High Temperature Russian Academy of Science (JIHT-RAS) was designed to investigate the combustion plasma assistance in high speed flows. PWT-50H facility has been extensively used since many years, with a wide variety of test conditions, the variable parameters being pressure, air temperature, electrode/injector/test section arrangement, and used fuel. Based on these results, key mechanisms of this assistance have been elucidated.

The purpose of this paper is to present some relevant experimental results obtained at JIHT-RAS facility, and to suggest how to adapt the related approach to the new LAERTE-LAPCAT2 facility of ONERA [5],[6], where total temperature, pressure and tests duration are more representative of flight conditions.

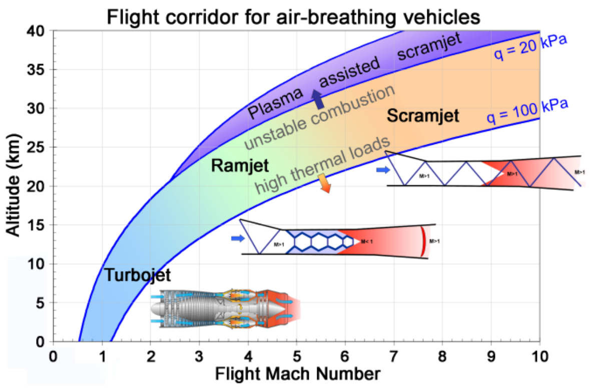


Fig.1 Air-breathing engines operation depending on flight conditions (altitude, flight velocity and related dynamic pressure q)

2 Experiments at PWT-50H Facility of JIHT–RAS

2.1 PWT-50H facility

The experimental facility PWT-50H of JIHT-RAS ([1],[2]) is used for exploring the ignition and flameholding. Hydrogen or ethylene fuel can be injected directly into the supersonic air flow M=2 from the combustion section wall. Combustor’s cross-section is 72×72mm^2. Experimental conditions are: static pressure P_{st} = 0.013–0.020MPa, total temperature of airflow in the range T_0=300–750K (two-stages electric + burner preheater), air flow rate is in the range 0.6–0.9kg/s, fuel mass flow-rate (hydrogen or ethylene) in the range 0.1–6g/s, discharge power W_{pl} = 1–10kW, test duration < 0.5s. A principal layout of the facility and the test section arrangement are shown in Fig.2.

In the present study, the fuel is injected through 5 circular orifices (diameter d = 3,5mm) all in a row across the span and inclined at 25 degrees from the normal in the upstream direction. The row of injectors is 15mm downstream from the row of electrodes, just downstream of the ceramic block; each injector is in line with an electrode in the configuration that includes 5 electrodes.

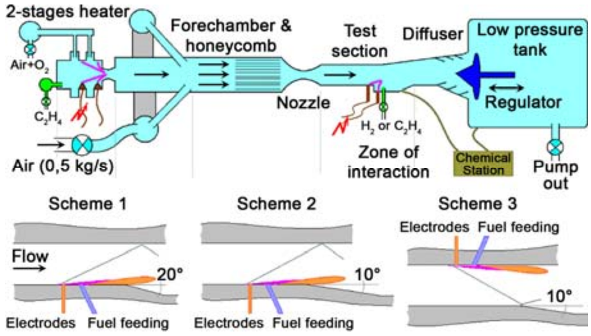


Fig.2 Layout of the facility PWT-50H. Three main schemes of the test section arrangement

The fuel mass flow rate was balanced between the orifices using a fuel plenum. Fuel injection was started prior to the discharge initiation and was switched off after completion of the discharge. Typically, the fuel injection continued 10–20ms after the discharge to observe whether the flame was held or extinguished. The facility is equipped with pressure transducers (16 points), a Schlieren system, a Schlieren/streak-camera system, devices for optical and spectroscopic observations, current-voltage sensors, Tunable Diode Laser Absorption Spectroscopy (TDLAS) of water vapour, station of chemical analysis of exhaust gases, and some others.

2.2 Discharge characterization

The major properties of the near-surface quasi-DC electrical discharge were described in papers [7],[8]. The discharge appears in the form of oscillating plasma filaments. Initial electrical breakdown occurs not far from the electrodes location. The individual filaments are blown down due to main flow at velocity a bit less than the core value. The frequency of oscillations depends on flow speed, inter-electrodes gap, and parameters of power supply (10–30kHz in the most cases). The regulation of power release in a range W_{pl} = 3–17kW was performed by means of electrical current change I_{pl} = 2–20A.

At low current, the discharge is unstable, while at high current, electrode erosion is significant.

Temperature measurements based on optical emission spectroscopy of the N_2 second-positive system (i.e., $C^3\Pi \rightarrow B^3\Pi$ emission) yield a rotational temperature of T_g = 3500±300K, independent of the power release from the discharge under conditions of this experiment. Typical oscillogram is shown in Fig.3.

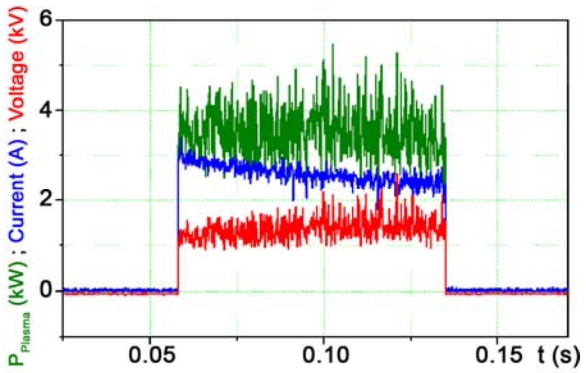


Fig.3 Typical oscillogram for high-voltage discharge operation.

2.3 Experimental results

The principal results of the study of plasma-assisted flameholding in high-speed flow can be found in publications [8]-[11]. Ignition and flameholding were realized for H_2 and C_2H_4 fuelling on a plane wall by using a transversal electrical discharge at relatively low power deposition (< 2% of flow enthalpy). The power threshold was measured to be W_{pl} < 3kW for a hydrogen flameholding, and $W_{pl} \geq$ 4kW with ethylene. The combustion efficiency was estimated to be around 0.9, for both hydrogen and ethylene. The ignition effect of the gas discharge was compared for different levels of the power, power density, and reduced electrical field (characterizing the departure from equilibrium for the discharge). It was found that the effectiveness of the flameholding is determined primarily by the level of power deposition, and secondarily by the power density. In this experiment the effect of reduced electrical field was not an important factor.

In comparison with hydrogen fuelling, a main difference with ethylene fuelling was that thermal choking was not observed, even at the maximum discharge power of W_{pl} > 10kW. Furthermore, the completeness of the ethylene combustion decreases with increased fuel mass flow rate. Another important feature was established in the tests, which can be formulated as following statement: “no discharge = no combustion” for all conditions and fuels tested. Moreover, switching off the discharge promptly leads to flame extinction. Plasma generation in the flow results not only in the heat and active species production, but also in the modification of supersonic flow structure, including induced boundary layer separation, vorticity, etc. The plasma and the recirculation zone are interdependent, which leads to a self-adjustment loop: the plasma modifies the chemistry, which in turn modifies the heat release, which in turn modifies the recirculation zone location, which in turn modifies the plasma parameters, and so on, Fig.4. This feedback is an important feature of active flame control by electrical discharges.

2.4 TDLAS technique and measurements

Tunable Diode Laser Absorption Spectroscopy (TDLAS) is a widely used spectroscopic technique for the detection of various parameters of the combustion products zones [10],[12]. This technique provides remote, non-perturbing measurements of the parameters of a hot zone with time resolution in the range of μs to ms depending on the specific experimental conditions. The technique is usually based on the measurements of the ratio of the absorption line intensities of a test molecule. If Boltzmann distribution of the energy levels is established, the ratio of the line intensities depends only on the kinetic temperature of the object.
Molecular water was used as a test molecule. Water vapor is one of the major combustion products and key indicators of the extent of combustion and is therefore widely used as a tracer of combustion processes in mixed gas flows. Initially, the optimal TDLAS strategy was developed in laboratory experiments with stable conditions in an evacuated cell filled with the air. Molecular water was used as a test molecule. Water vapor is one of the major combustion products and key indicators of the combustion extent. It is therefore widely used

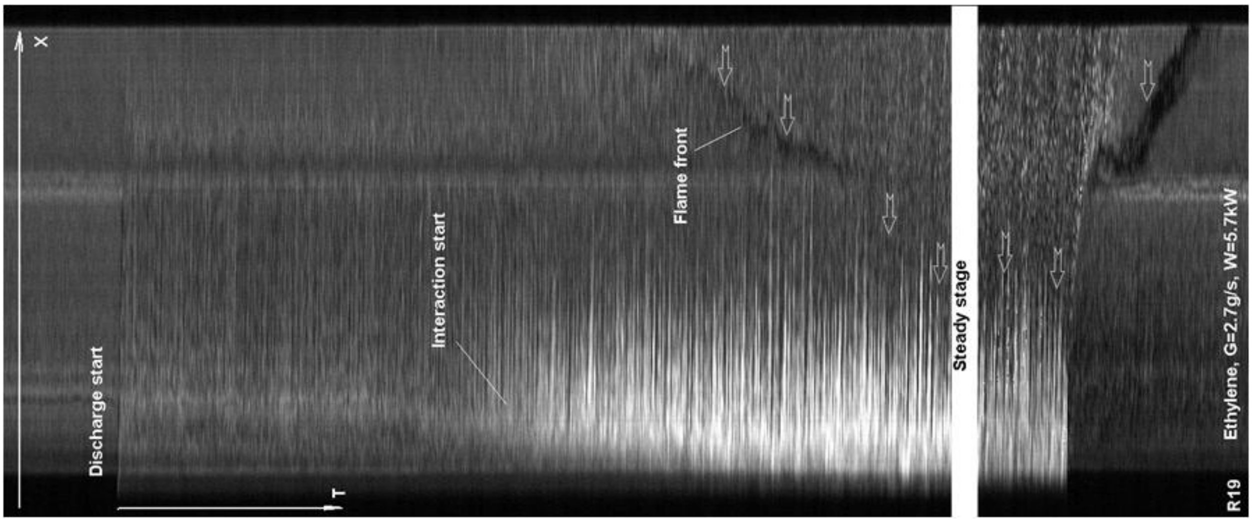


Fig.4 Schlieren-streak recording showing plasma/flame interaction

as a tracer of combustion processes in mixed gas flows. Initially, the optimal TDLAS strategy was developed in the laboratory experiments with stable conditions in an evacuated cell filled with the air. The optimized and validated version of the TDLAS technique was then applied to the measurement of the temperature, total gas pressure, and H_2O concentration in a plasma-assisted supersonic combustion flow.

The selection of the specific spectral lines was dictated by several reasons: the energies of low levels should be different, the lines should be reasonably resolved and the spectral interval should be free from lines of other gas components. The following H_2O absorption lines were selected: 7189.344cm^{-1} (E'' = 142cm^{-1}), 7189.541cm^{-1} (E'' = 1255cm^{-1}), 7189.715cm^{-1} (E'' = 2005cm^{-1}). All lines could be recorded in a single scan of the laser wavelength across a $\Delta\lambda\sim$ 1cm^{-1} spectral interval.

The laser beam was routed to the chamber via a 22 m-long single-mode fiber (core diamater 9μm). The optical path inside the test chamber was 7cm. The laser beam probed a cross-section of about 2mm within the combustion zone. The collimator of the signal beam was fixed in an optical head, which was solidly mounted at the input window flange of the chamber. The head could be precisely translated in x-y directions and angularly aligned.

The TDLAS measurements were fulfilled in typical operation modes: plasma power was W_{pl} = 8kW, hydrogen mass flow rate was G_{H2} = 0.3g/s, and the ethylene G_{C2H4} = 0.8g/s. The absorption spectra are shown in Fig.5-a for “cold” and “hot” conditions. They were averaged over 30 scans. In some cases a high signal-to-noise ratio enabled spectral fitting with fewer averaged scans. In reality the observed fluctuations of gas parameters are strong, especially in the vicinity of the fuel injection. Fig.5-b and 5-c give some impression on the combustion dynamics: i) 2D image of TDLAS spectra before and after combustion;

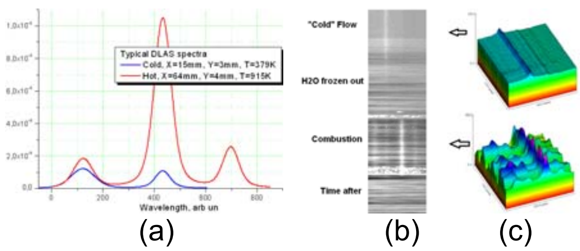
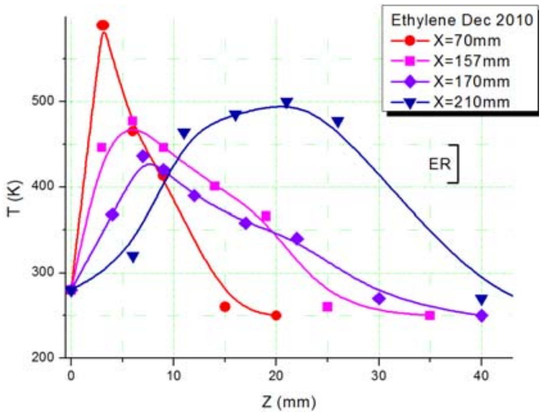


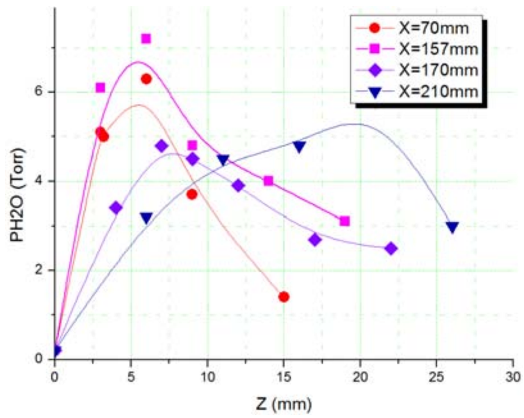
Fig.5 Typical absorption spectra of water vapors for two zones of flowfield (a). Samples of real spectral distribution (b, c).

ii) related 3D reconstruction of spectra at appropriate time.

The temperature distribution along the combustor obtained as a result of such fitting is shown in Fig.6-a. Each point in the figure was obtained in individual run of the facility. The values of the temperature inferred from both slopes coincide reasonably well. The water vapor partial pressure measured in a parallel way is presented in Fig.6-b. The uncertainty of the temperature evaluation associated with the experimental errors and fitting procedure was estimated basing on the results database. We assume that during one scan (about 830µs) the temperature is constant. The estimated precision (statistical error) of the temperature measurements was σ = 40K.



(a)



(b)

Fig.6 Temperature (a) and H_2O vapor pressure (b) distribution measured by TDLAS in plasma-assisted combustion zone for ethylene-air pair. X axis is along the flow direction. Z is the distance from the wall.

2.5 Two-zone mechanism of plasma-assisted supersonic combustion

To explain the above observations, the following two-zone mechanism of the plasma assisted flameholding [11] was proposed (this scheme reflects the two-stage ignition process mentioned in some last publications [13]-[16]). The idea may be briefly described as follows: for hydrocarbon fueling at low initial temperatures, flame stabilization by non-equilibrium plasma occurs by means of a two-step process. During the first step, the “cold” combustion takes place: the plasma induces active radicals production and so-called “preflame” (or fuel reforming in terms of Stanford’s team), and may be simplified as production of H_2, CH_2O, and CO. This zone does not experience significant temperature and pressure increase, even if a bright luminescence can be observed. The lengths of the first zone in our tests measured by the schlieren and schlieren-streak technique were usually in the range of 50mm to 150mm, corresponding to the range of 0.1 to 0.3ms of the induction time.

This “preflame” or “cool flame” initiates (under favorable conditions) the second step of normal “hot” combustion, characterized by high temperature and pressure rise. Under some conditions the multistage combustion is observed without plasma of electrical discharge [17]. But at the plasma assisted combustion the kinetic mechanism of ignition looks to be principally multistage process (at least, two-stage), as it is pointed in some last publications, for example in [18]. At the same time a validation of the two-stage mechanism of the plasma-based flameholding requires detail information on the spatial distribution of the gas parameters in zone of combustion. Current work contributes the data to elucidate this problem.

3 Extension of the test conditions with LAERTE-LAPCAT2 facility of ONERA

3.1 LAERTE-LAPCAT2 facility

Extending experiments conducted at PWT-50H facility to more representative of scramjet flight conditions (higher air temperature and static pressure, longer test duration) will be done at ONERA's LAERTE facility. The supersonic combustor (Fig.7 to Fig.9), recently built within LAPCAT2 European program [5], is fed with hot vitiated-air (heating by H_2/air combustion, O_2 mol fraction kept at 21% by upstream extra injection of oxygen). Total temperatures up to 1800-1900K can be obtained and the total pressure can reach 1.0-1.2MPa.

This facility is operated in the blow-down mode, the test section working as a heat-sink. A overall duration of a test run is around 1 minute but the useful duration, i.e. at required temperature, lasts between 5 and 15 seconds, depending test combustion (no water-cooling of the combustor).

Permanent diagnostics include total pressure (P_0) and total temperature (T_0) measurements (3 thermocouples at different radial positions) and 124 wall pressure transducers scanned at 10Hz (Scanivalve) and distributed along the combustor. Pressure sensors have been calibrated.

The combustion chamber is made of a Copper alloy. The inner walls include a 0.3mm thick ZrY_2 deposit (thermal barrier). The combustor width is constant (40mm) and its inlet height is 35.4mm.

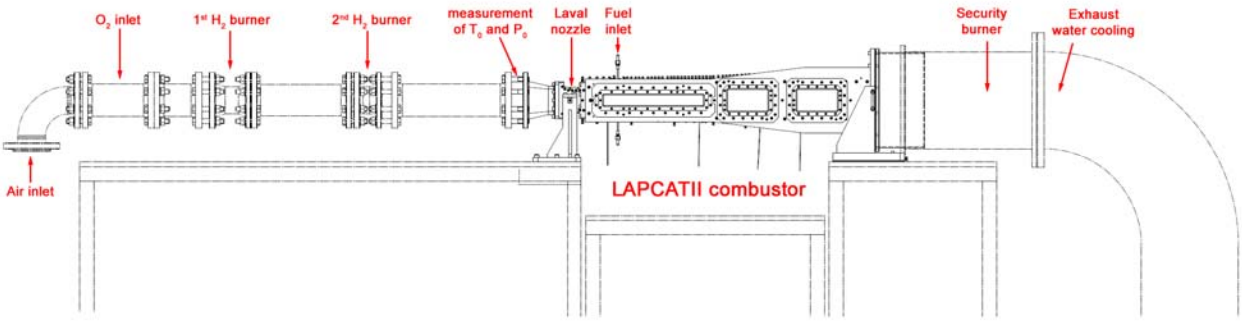


Fig.7 Schematic of the LAERTE-LAPCAT2 facility

Fig.8 LAPCAT2 supersonic combustor in LAERTE Facility

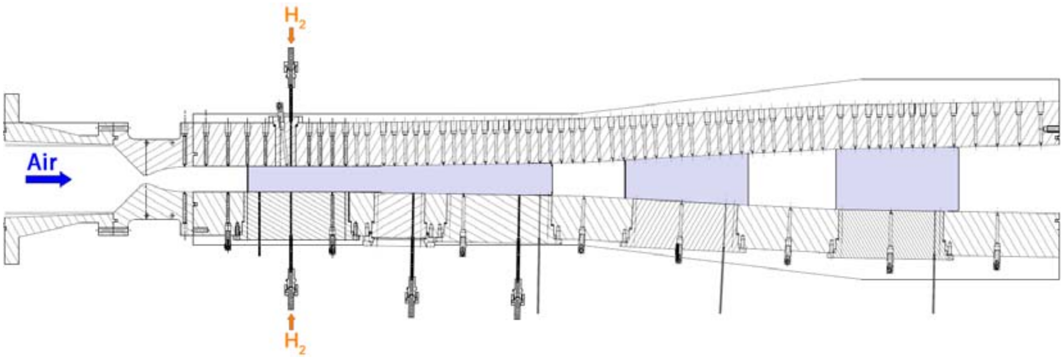


Fig.9 Schematic of the LAERTE-LAPCAT2 combustor showing optical accesses and pressure measurements location

The combustor contains 4 successive sections: the first one has a constant cross-section, the following sections have 1°, 3° and 1° of diverging half angles respectively to avoid thermal choking. The overall length of the combustor is around 1257mm. Large fused silica windows can be placed at different locations of the test section, allowing optical access for either single-point measurements (CARS, LIF, TDLAS…) or imaging techniques (fast-camera imaging, schadowgraph technique, schlieren technique, PLIF…).

The combustor can be fueled with pure hydrogen or a mixture of hydrogen and gaseous hydrocarbons (methane, ethylene, propane…). Fuel is injected though a 2mm diameter hole. Injection can be achieved at x=200mm (upper and/or lower wall), x=368mm, 513mm or 698mm (lower wall). Pressure and temperature of the fuel are measured 104mm upstream from the injection point.

Two Laval nozzles are available, making it possible to feed the combustor with a M=2.0 or 2.5 air flow. For this study, only M=2.0 Laval nozzle was used. The outlet of combustor is connected to a 400mm diameter exhaust pipe where the pressure is around 0.1MPa.

For $P_0 \geq 0.9$MPa, air flow is supersonic up to the exit of the combustor. Fig.10 presents the profiles of Mach number, static temperature and static pressure along the combustor.

For $P_0 < 0.9$MPa, the transition from supersonic to subsonic occurs within the combustor and pressure increases up to 0.1MPa (pressure level in the exhaust pipe).

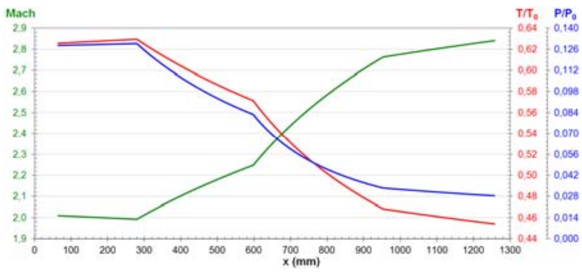


Fig.10 Evolution of Mach number, static temperature and static pressure along the combustor (non-reacting case with a fully supersonic flow)

3.2 Supersonic combustion in LAERTE facility

Experimental results for LAERTE-LAPCAT2 combustor presented here were obtained for a total pressure of 0.4MPa. Transition from supersonic to subsonic flow occurs then around x=800mm. The effect of air temperature on the supersonic combustion was investigated. The Table 1 (below) sums up the test conditions. Fig.11 presents the images of H_2 combustion in

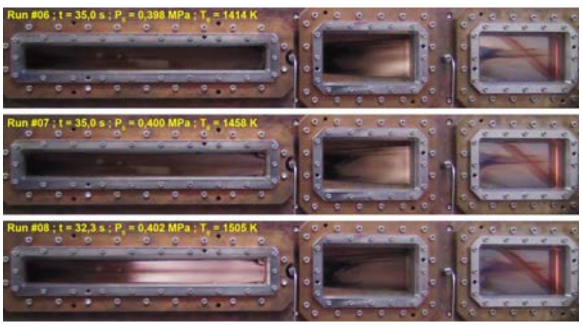


Fig.11 Total air temperature impact on H_2 combustion in LAERTE-LAPCAT2 combustor (P_0 = 0.4MPa; E.R. = 0.15, flow direction from the left to the right)

Table 1 Typical flow conditions

Total pressure		P_0 = 0.4 MPa	
Total temperature		T_0 = 1414 K	T_0 = 1505 K
Freestream Conditions	Mach number	M_∞ = 2.01	
	Pressure	P_∞ = 0.051 MPa	
	Temperature	T_∞ = 891 K	T_∞ = 956 K
	Density	ρ_∞ =0.188 kg.m^{-3}	ρ_∞ =0.175 kg.m^{-4}
	Velocity	U_∞ = 1209 m.s^{-1}	U_∞ = 1253 m.s^{-2}
Vitiation Air	Air flow rate	m_{air} = 270 g.s^{-1}	m_{air} = 256 g.s^{-2}
	Oxygen flow rate	m_{O2} = 52.9 g.s^{-1}	m_{O2} = 57.1 g.s^{-2}
	Hydrogen flow rate (heating burner)	m_{H2} = 4.34 g.s^{-1}	m_{H2} = 4.68 g.s^{-2}
	Total air flow	$m_{v\,air}$ = 328 g.s^{-1}	$m_{v\,air}$ = 318 g.s^{-2}
	Mole Fraction	X_N$_2$ = 0.604	X_N$_2$ = 0.586
		X_O$_2$ = 0.210	X_O$_2$ = 0.210
		X_H$_2$O = 0.178	X_H$_2$O = 0.197
		X_Ar = 0.007	X_Ar = 0.007
	Adiabatic index	$\gamma_{v\,air}$ = 1.291	$\gamma_{v\,air}$ = 1.285
Fuel flow rate		m_f = 1.53 g.s^{-1}	m_f = 1.47 g.s^{-2}
Equivalence ratio		E.R. = 0.15	

the supersonic combustor. We can conclude from these images that: i) for T_0 = 1414K, no combustion is observed in the supersonic region (left window), ii) for T_0 = 1458K, a weak light emission (cool flame?) is observed in the last third of left window, iii) for T_0 = 1505K, supersonic combustion is evident.

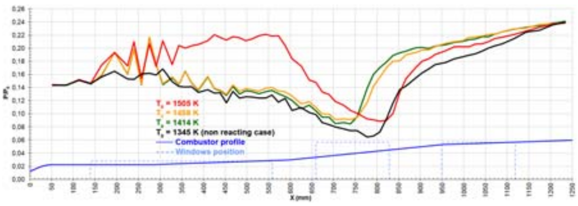


Fig.12 Pressure profile along the combustor – Effect of air temperature on H_2 combustion (P_0 = 0.4MPa; E.R. = 0.15)

Pressure profiles along the combustor, presented in Fig.12, confirm this trend as a tiny pressure increase is observed in the supersonic region (x < 750-800mm) for T_0 = 1458K, whereas a strong increase of pressure due to supersonic combustion occurs between x= 350mm and x= 800mm for T_0 = 1505K.

Further experiments will be conducted in the coming months with H_2 + CH_4 fuel mixture instead of pure H_2, as plasma assistance is actually prone to significantly improve the combustion of hydrocarbons/air mixtures (production of H_2, CH_2O and CO in the cool flame region).

LAERTE-LAPCAT2 facility is now fully operational to study supersonic combustion. The next step is to manufacture a plasma/injection module to investigate the ability of discharges to initiate supersonic combustion at lower incoming temperature.

3.3 Design of a plasma/injection module for LAERTE-LAPCAT2 combustor

A plasma/injection module has been designed for LAERTE-LAPCAT2 combustor. It will be implemented by removing a side window and replacing it by a dielectric material containing a set of electrodes and wall injection holes. With the conditions of use previously presented, the related static pressure is 0.057MPa. For T_0 = 1000K to 1500K, local density will be range between 4.1×10^{18}cm^{-3} and 6.3×10^{18}cm^{-3} (0.16 to 0.26 times the density at standard pressure and temperature conditions).

A key point to successfully observe an effect of the plasma is to allow the good mixing of fuel and air. For this purpose, a multi-point injection is preferable [18]. Moreover, to allow pre- and post-injection discharges, high voltage electrodes are proposed.

This module will be manufactured during the course of 2014 and first tests are expected at the end of the same year.

4 Conclusions

Based on the results of the experimental study carried out at PWT-50HG facility of Joint Institute for High Temperature Russian Academy of Science (JIHT-RAS), the principles of supersonic flameholding and combustion control by plasma of electrical discharge were identified. We can formulate them as follows:

i) the local boundary layer separation is created by the combination of a near-surface electrical discharge and fuel jets applying the flush-mounted electrodes and fuel orifices;

ii) the plasma generator and fuel injector are gathered under one single unit utilized for fuel ignition, flameholding, and combustion control;

iii) the location of this unit along the duct, its activation and switching off, and the magnitude of input parameters are chosen based on maximal engine efficiency and controlled by active feedbacks.

Two-zone mechanism of flameholding was observed in the plasma-assisted supersonic combustion experiment: i) so called “cold” combustion takes place in the first zone, where plasma-induced fuel conversion and relatively small heat release occurs, ii) common “hot” combustion proceeds in the second zone, where combustion is completed or almost completed with high level of heat release. To prove such a mechanism of combustion the diode laser absorption spectroscopy (TDLAS) was applied for the remote measurement of temperature, total pressure and concentration of water vapor. The comparison of these data with results of visualization and pressure records allows considering the two-zone mechanism of plasma assisted combustion as very consistent.

As the new LAERTE-LAPCAT2 supersonic combustor of ONERA is now fully operational, further experiments will be achieved at higher pressure and temperature, and with longer test durations to evaluate the relevance of this strategy under extended flight conditions.

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