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Temperature measurements by CARS and intrusive probe in an air–hydrogen supersonic combustion

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Abstract

Static and stagnation temperature measurements are performed by CARS and by an intrusive probe in a Mach 2 cylindrical jet of hydrogen, injected into a Mach 2 coflow of air. The single-shot CARS static temperature measurements are based on nitrogen. A stagnation temperature probe has been developed and tested. This method consists in identifying the transient regime of a thermocouple probe with a numerical prediction modeling the high speed effects on the probe recovery factor. The paper presents and discusses the comparison between the temperature measurements performed by the intrusive probe and the CARS non-intrusive techniques (1) at the inlet of the combustion chamber; (2) in the ignition zone of the hydrogen jet; (3) in the burnt gases. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Temperature measurements; Thermocouple; CARS; Supersonic flows; Combustion

1. Introduction

Renewed interest in high speed propulsion, based on the concept of SCRAMJET, restarted supersonic combustion studies. In the framework of the French Hypersonic Program, PREPHA, new test facilities were developed [1]. The scales of those facilities range from moderate ones, devoted to basic studies on the mixing and ignition of hydrogen in supersonic air flows, to large industrial facilities for validation of chamber concepts. The needs for non-intrusive diagnostics begin to be covered by various optical techniques such as Raman and Rayleigh scattering [2,3], CARS [4,5], and laser-induced fluorescence [6]. Those techniques can be implemented in specially designed facilities for basic research, but it is extremely difficult to use those diagnostics in large-scale industrial set-ups. Stagnation temperature probes [7] are necessary to measure the global performance of SCRAMJETS. After its development at CNRS/IMP, that probe has been tested in the ONERA supersonic combustion test facility because of its intermediate scale, limiting cost operation, and versatility allowing CARS temperature measurements. This paper presents and discusses the temperature measurements performed by those two complementary techniques in a Mach 2 supersonic reacting hydrogen–air flow.

2. Supersonic combustion experiment

The ONERA facility is devoted to the basic study of a supersonic reacting mixing layer [8] in order to establish a well-documented data base for the validation of the numerical techniques and the evaluation of the turbulent mixing and combustion models used in the CFD codes [9]. The aerothermochemical conditions of the air stream are close to those encountered in the combustion chamber of a SCRAMJET flying at Mach 6. Those conditions allow spontaneous ignition of the hydrogen. The growth rate of a supersonic mixing layer is in principle limited by compressibility effects [10,11]; the behavior of the mixing layer, in the reacting case, is

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Nomenclature

a	thermal diffusivity (m^2/s)
C_h	Stanton number
E	least-square coefficient (K)
F	view factor
h	enthalpy (J/kg)
h_c	convective heat coefficient (W/m^2 K)
M	Mach number
n	number of measurements
Nu	Nusselt number
P	pressure (Pa)
q_e	specific mass flow rate around the probe (kg/m^2 s)
q_m	average specific mass flow rate (kg/m^2 s)
r	recovery factor
Re	Reynolds number
S	surface or section (m^2)
t	time (s)
T	temperature (K)
u	velocity (m/s)
x	abscissa along a thermocouple wire
X, Y, Z	Cartesian coordinates in the supersonic combustor
ε	emittance
ϕ_{conv}	convective flux flow/probe (W)
ϕ_{rad}	radiative flux probe/environment (W)
γ	ratio of gas specific heats
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)

Subscripts

a	wire, far from the junction
aw	adiabatic wall conditions
c	chamber conditions
e	boundary layer outer edge
p	combustor wall
s	probe sensing element (thermocouple shield)
st	stagnation conditions
w	relative to a thermocouple equivalent wire

Superscripts

cal	model predictions
exp	experimental

investigated by means of optical diagnostics for detailed measurements of the aerothermochemical field. Thus, this simple and well-instrumented experiment has also been chosen for validation of new measurement techniques, such as the stagnation temperature probe.

A Mach 2 cylindrical hydrogen jet (exit diameter of 6 mm) discharges into a Mach 2 coflow of air (Fig. 1). The test section (overall length 870 mm) has first a constant section (45×45 mm^2) on a distance of 370 mm, and then slightly diverges (half-angle 1.15°) to avoid thermal choking. The Cartesian coordinates system (X, Y, Z) used for the presentation of the experimental results is given in Fig. 1. The experimental conditions are summarized in Table 1.

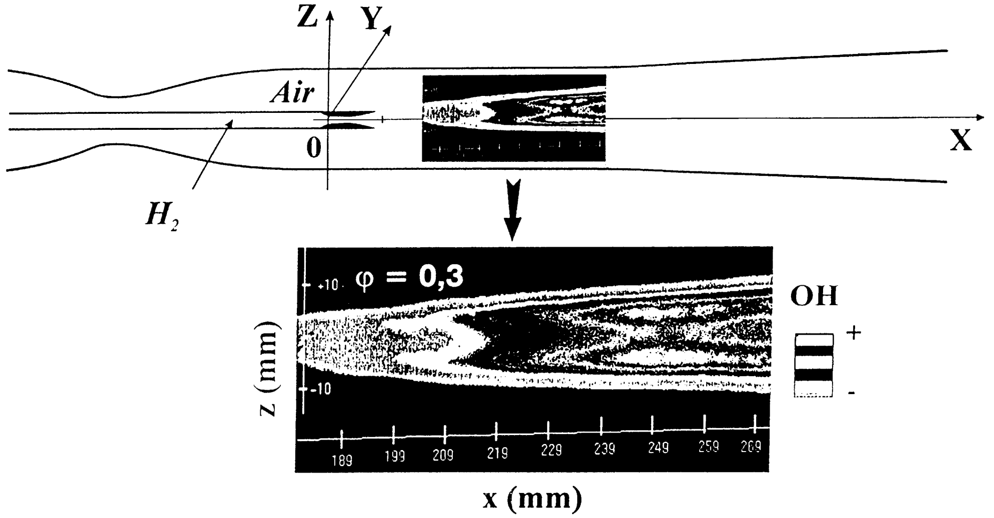

Fig. 1. Supersonic combustion experiment and visualization of the OH chemiluminescence.

Table 1
Experimental conditions

	Air	H_2
Mach	2	2
Total pressure (MPa)	0.72	0.68
Total temperature (K)	1800	300
Static pressure (MPa)	0.08	0.08
Static temperature (K)	1100	155
Velocity (m/s)	1336	1970

The incoming air is heated up to 850 K, by means of two heat exchangers and, then up to a stagnation temperature $T_{st} = 1800$ K with a hydrogen preburner. Stable supersonic combustion runs of 10 s duration are performed in that facility. Large fused silica windows allow optical accesses for single-point measurements. Those windows can be replaced by metallic plates that are used to set up Pitot pressure or stagnation temperature probes.

The OH emission of the flame has been imaged (Fig. 1) for $180 < X < 270$ mm and that global visualization allows to estimate the mixing and ignition length of hydrogen within the supersonic flow of air. Wall pressure P_p measurements, normalized by the total pressure P_{st}, confirm that heat release starts 240 mm downstream from the combustor inlet plane (Fig. 2). Consequently, the most interesting zones for the comparison between CARS temperature measurements and total temperature measurements probe are (Fig. 2):

1. The high temperature homogeneous non-reacting supersonic zone and the flame zone near the ignition region, that can be found at various heights Z in the plane $X = 242$ mm (location P1).
2. The high temperature burnt products at the exit of the supersonic combustor (location P2 at $X = 725$ mm).

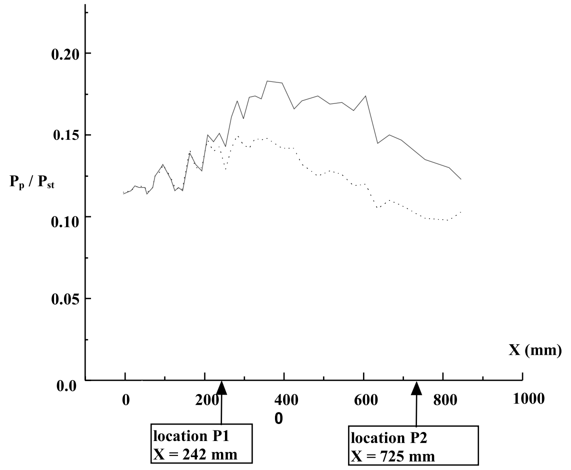

Fig. 2. Wall pressure measurements (--- without combustion; — with combustion) and measurement positions.

3. Stagnation temperature probe

3.1. General methodology

The presence of an intrusive probe perturbs the flow and, in the case of supersonic conditions, a reacting shock wave appears in front of the probe. Chemical reactions may occur in the boundary layer and on the probe surface (catalytic effects). It is well known that the heat transfer between the probe and the flow is dramatically influenced by these factors [12]. The stagnation temperature measurement is, therefore, difficult to validate in these conditions. For this reason we propose to test, in a first phase, the intrusive method in a low speed nitrogen thermal plasma flow (Mach number <0.05). This enables the Pitot method to be adjusted in more favorable non-reacting conditions. Moreover, as the stagnation and the static temperatures are very close for these conditions, we use an optical method to measure the static temperature of the plasma flow. The intrusive measurement can therefore be compared to an optical reference measurement.

The chosen optical reference method (described in detail in [13]) consists in identifying an experimental, partially resolved, molecular emission band by its calculation based on molecular theory. The CN violet emission system $B^2\Sigma^+ \rightarrow X^2\Sigma^+$ can be observed in our experimental conditions. The $(0,0)$ band is chosen to measure the CN rotational temperature which is considered to be equal to the plasma kinetic temperature.

3.2. Principle and description of the method

A bibliographical study suggests a spherical thermocouple probe for its adaptability and simplicity [14]. Its use in a steady-state regime in high temperature flows being impossible, we have developed a transient method which identifies the probe heating with a numerical calculation that accounts for the heat transfer between the probe and its environment (Section 3.3).

The temperature measured by such an intrusive method is the adiabatic wall temperature T_{aw} which may be different from the local stagnation temperature T_{st} because a part of the kinetic energy of the flow is not necessarily transmitted to the probe [15]. Another point to consider is the evaluation of the difference between T_{st} and the free-stream stagnation temperature which is the parameter of interest. A difference may occur if chemical reactions appear through the shock in front of the probe. Fig. 3 shows the principle of the intrusive method.

The measurement system (Fig. 4) is composed of the intrusive probe, three thermocouples and a jack driven motion system that introduces the probe into the flow. The stainless steel intrusive probe (40 mm long, 6 mm thick, 20 mm width) was designed to stand the supersonic flow. Three R thermocouples are settled into the

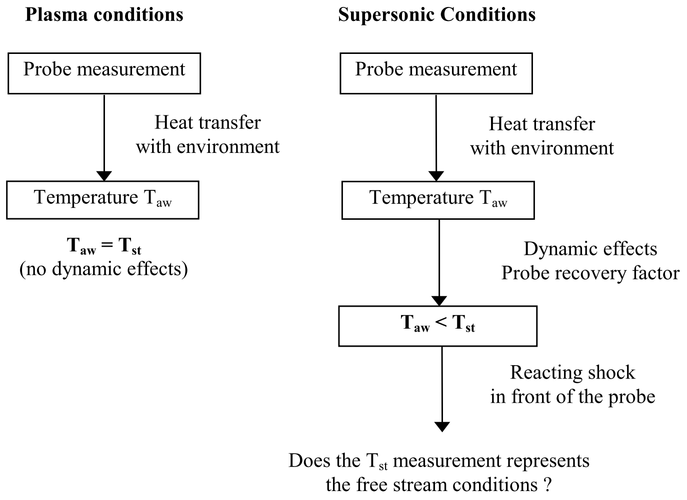

Fig. 3. Principle of the intrusive method.

probe and are maintained by 2 mm alumina tubings. By welding 0.5 mm diameter wires we obtained spherical junctions up to 1 mm in diameter. The probe is introduced into the flow for 0.2–0.5 s. The probe can be withdrawn if necessary once it has reached a maximum temperature or once a residence time has been obtained (fixed with an electronic clock). A 50 kHz high speed data logging system allows fast transient measurements with analogic/digital conversion. This enables us to reduce signal to noise ratio in severe industrial conditions where electromagnetic perturbations can occur. The distance between the probe and acquisition system is about 1 m, but the computer was set up 10 m farther, in the combustion facility control room.

Practically, depending on the temperature, the size of the probe, the heat exchange conditions, the residence time of the probe into the flow must be adapted. For example, typical 0.1 s residence time may be fixed for a 1 mm diameter spherical thermocouple probe in a Mach 2 air supersonic flow without combustion. In extreme conditions with combustion, this time may be reduced to 1 ms as convective heat exchanges between the flow and the probe become higher. The strategy adopted for all the experiments was to let the probe as long as possible

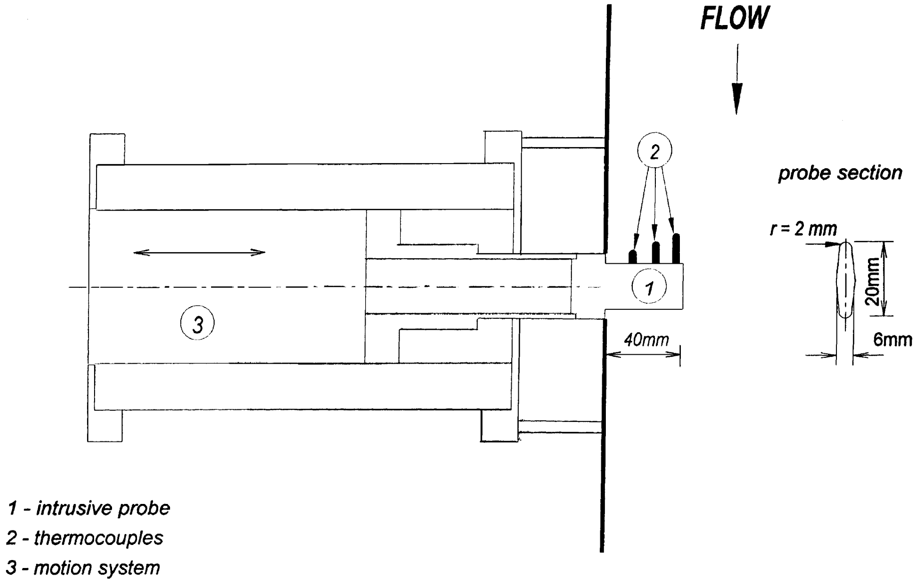

Fig. 4. Stagnation temperature probe.

in the flow as thermocouple probes are easy to construct. This is one of the main advantages that conduct us to the choice of this type of probes.

3.3. Description of the numerical model

An explicit finite-difference model is used to simulate the transient heating of a spherical thermocouple junction immersed rapidly in the flow. The model takes into account the junction geometry, thermophysical properties of the probe elements, conduction inside the probe, radiation with the environment and heat convection between the flow and the probe (see Fig. 5).

Several assumptions are considered to simplify the problem:

1. the thermocouple junction is spherical, with a uniform internal temperature T_s,
2. an equivalent wire (noted EW) at temperature T_w is used for calculations; it is a homogenous mixture of the two wires (equal to junction properties),
3. thermophysical properties are linear functions of the temperature,
4. the conduction in the equivalent wire is mono-dimensional and semi-finite,
5. the radiation of the gas is assumed negligible.

The following system is resolved for heat conduction:

$$\frac{\partial T_\mathrm{w}^\mathrm{cal}(x,t)}{\partial t} = a_\mathrm{w}\frac{\partial^2 T_\mathrm{w}^\mathrm{cal}(x,t)}{\partial x^2}$$

with the initial condition $t = 0$, $T_\mathrm{w}^\mathrm{cal}(x,0) = f(x)$ and with the boundary condition of a semi-infinite medium ($\lim T_\mathrm{w}^\mathrm{cal}(x,t) = T_\mathrm{a}$ when $x \to \infty$)

$$\phi_\mathrm{conv}(t) + \phi_\mathrm{rad}(t) = -\lambda_\mathrm{w}S_\mathrm{w}\frac{\partial T_\mathrm{w}^\mathrm{cal}(x,t)}{\partial x}(0,t).$$

The calculation is initialized by $T_\mathrm{w}^\mathrm{cal}(0,0) = T_\mathrm{s}^\mathrm{cal}(0) = T_\mathrm{s}^\mathrm{exp}(0)$, where $f(x)$ is the initial temperature in the wire and T_a is the ambient temperature of the wire far from the junction. The term ϕ_conv is used to introduce the adjustable parameter of the model, i.e., the adiabatic wall temperature T_aw. One of the following relationships can be used, either:

$$\phi_\mathrm{conv} = h_\mathrm{c}S_\mathrm{s}(T_\mathrm{aw} - T_\mathrm{s}) \quad \text{or} \quad \phi_\mathrm{conv} = C_\mathrm{h}\rho_\mathrm{e}u_\mathrm{e}S_\mathrm{s}(h_\mathrm{aw} - h_\mathrm{s}).$$

The convective heat transfer coefficient h_c is related to the specific mass flow rate q_e through classical correlations [20–22].

The radiative flux between the junction and its environment in the combustor is written under the following expression:

$$\phi_\mathrm{rad} = \varepsilon_\mathrm{s}\sigma S_\mathrm{s}\sum_{k=1}^{K}\varepsilon_{pk}F_k(T_{pk}^4 - T_\mathrm{s}^4),$$

where K surfaces of emittance ε_{pk} and temperature T_{pk}, with a view factor F_k, are considered. Two approaches are considered to determine the adiabatic wall temperature:

1. The temperature is obtained by identifying the transient response of the probe with the model calculation. A least-square method is used. The temperature T_aw is adjusted to minimize the term for a fixed specific mass flow rate q_e around the probe.

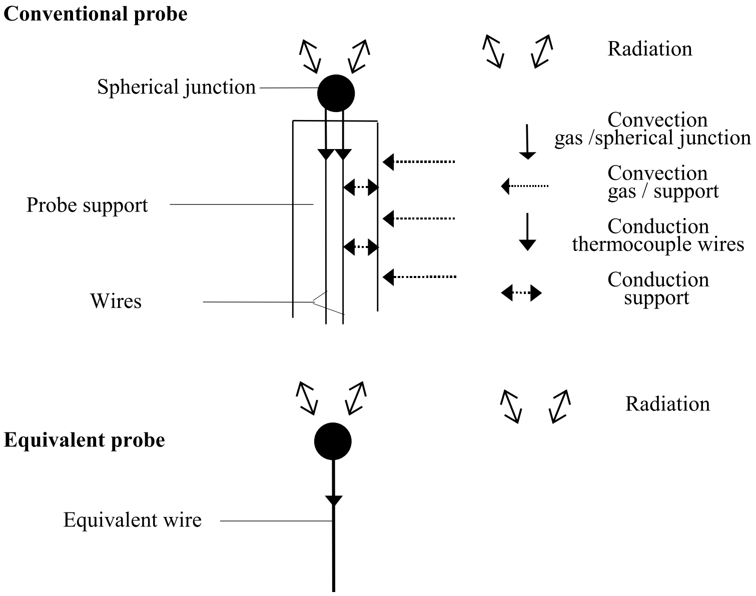

Fig. 5. Schematic of heat transfer between the probe and its environment: use of an equivalent probe concept for the intrusive method.

$$E = \sqrt{\frac{1}{n}\sum_{i=1}^{n}([T_{wi}^{\mathrm{cal}}]^2 - [T_{wi}^{\mathrm{exp}}]^2)}.$$

2. As supersonic combustion flows are generally stratified, it can be difficult to evaluate precisely the specific mass flow rate over the probe. This parameter is very important as it appears in most of the empirical correlations for the convective heat transfer. We have therefore developed another analysis method, extending the empirical correlations. Our new model consists in simultaneously determining the adiabatic wall temperature and one of the parameters representing the convective heat flux, q_e or h_c. Identification between the experimental and theoretical transient responses therefore requires two adjustable parameters. In this second approach we were able to determine [14] by minimization of the term E:

1. either adiabatic wall temperature T_{aw} and specific mass flow rate q_e,
2. or adiabatic wall temperature T_{aw} and convective heat transfer coefficient h_c.

3.4. Development of the probe in plasma conditions

The intrusive method has been validated in the non-reactive nitrogen thermal plasma facility [7]. Approach 1 is tested by evaluating the specific mass flow rate around the probe using the mass conservation equation in the chamber. The results (Figs. 6 and 7) correspond to those obtained using the CN rotational temperature (3% difference) in the range of validity of the optical reference method ($4250 < T < 4400$ K).

On the other hand, approach 2 did not give satisfactory results because temperature and specific mass flow rate were uncertain. The experiments showed that the thermocouple temperature (Fig. 6) was too far from its state of equilibrium for approach 2 to be applied.

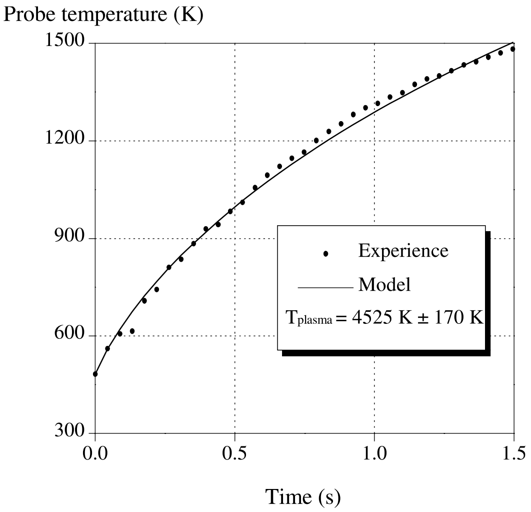

Fig. 6. Determination of the plasma temperature using the intrusive probe (method 1).

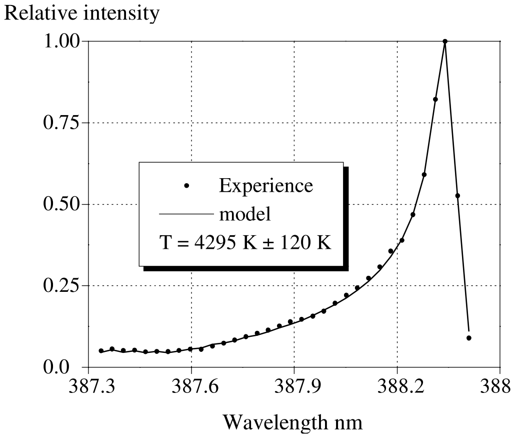

Fig. 7. Determination of the plasma temperature using the optical reference method.

4. CARS thermometry

Broadband nitrogen CARS thermometry is well adapted for time-resolved measurements in fluctuating media [16] and used with the following operating constraints needed by that specific experimental situation.

The optical arrangement selected for the measurement volume is planar BOXCARS. With 200 mm focal length lenses, we obtain the best spatial resolution available (1.5 mm × 20 μm) avoiding saturation effects [17] or breakdowns at the probe volume. The available energy at the probe volume decreases to 35 mJ for pump beam at 532 nm, 2 mJ for N_2 Stokes beam at 607 nm. A reference channel is used to produce a non-resonant CARS signal in argon taking into account the influence of shot-to-shot fluctuations of the energies, spectral modes, alignment of the pump and Stokes beams.

For accurate CARS temperature measurements in the flame, it is compulsory to discriminate the non-resonant contribution of the CARS signal, due to the water vapor content of the flow, from the resonant contribution. The non-resonant contribution is systematically canceled by the proper choice of the polarization of the exciting laser beams and by filtering the CARS signal [18].

CARS spectra were collected for different conditions of energy density at the measurement volume and on the windows in order to estimate the magnitude of saturation effects and the risk of damaging windows. The averaged spectrum (Fig. 8) obtained in the non-reactive supersonic flow, with focal length lenses of 160 mm shows a vibrational population $v = 1$ (vibrational tem-

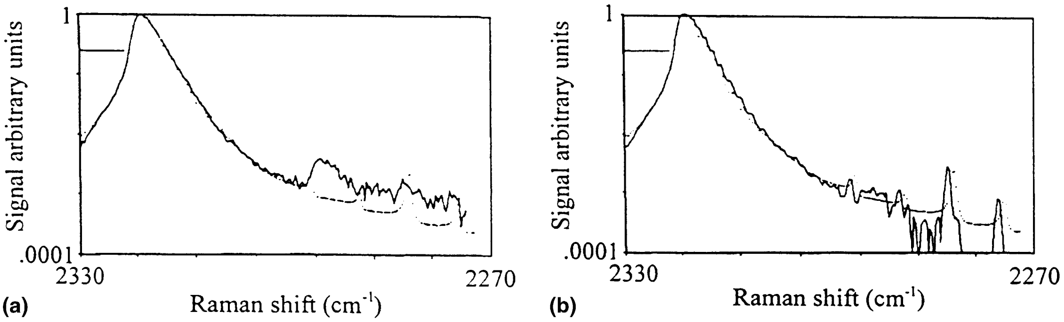

Fig. 8. Saturation effects on averaged CARS spectra at $T \sim 500$ K for different focal length lenses: (a) $f = 160$ mm; (b) $f = 195$ mm.

perature of 1000 K). The problem disappears when the energy density is limited by using focal length lenses of 200 mm instead of 160 mm. However, for both spectra, the processing routine returns a rotational temperature of 460 K, close to the one deduced from the spectrum in equilibrium. When processing theoretical spectra, the fitting error is very low (~1 K from ambient to flame temperature levels). Fig. 9 shows a rather noisy single-shot experimental CARS spectrum compared to a theoretical one and the calculated temperature is around 2150 K. Despite the high turbulent level encountered in the flow, the quality of the experimental spectrum is acceptable because the temperature measurements are based on the relative shapes of the N_2 CARS spectra and are not sensitive to variations of the signal intensity. The accuracy of the temperature measurements obtained in furnaces or laboratory flames is estimated ~15 K at room temperature and ~40 K at a flame temperature of 2000 K. In semi-industrial applications such as the present one, the accuracy is estimated at ~4% [19].

The CARS data acquisition rates (5 Hz) in our blow-down facility does not allow large numbers of single-shot temperature, even when repeating the supersonic runs at the same spatial location. For that reason, the averaged values of the temperature are calculated, on samples of 100 individual measurements, in the non-reacting case and 30–40 events for the reacting case.

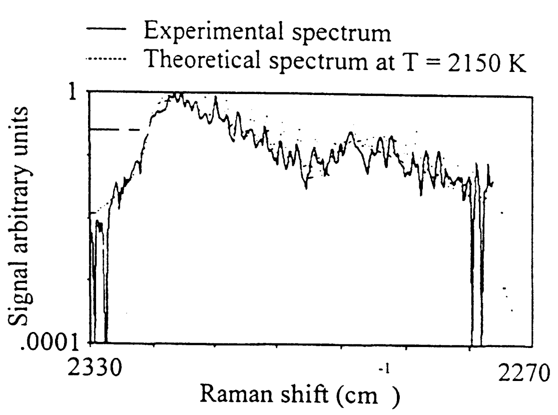

Fig. 9. Single-shot CARS spectrum in the supersonic combustion regime.

5. Development of the probe for supersonic conditions

CARS and intrusive probe measurements were performed in the non-reacting and reacting conditions.

5.1. Preliminary tests without combustion

We describe the methodology adopted to analyze the tests without supersonic combustion, at measuring point P1 ($Z = 12$ mm). In this case, a probe with only one type K thermocouple was used. The diameter of the spherical junction was 0.8 mm. We give results obtained for $T_{st} = 1790$ K. The average specific mass flux is equal to $q_m = 377$ kg/m^2 s. Three correlations are tested to calculate the convective heat flux between the probe and the flow: Sibulkin [20] (close to Fay and Riddell [12]), Mc Adams [21], and Ahmed and Yovanovich [22]. All these correlations require the local specific mass flow rate around the probe through a Reynolds number. The methods 1 and 2 are tested.

5.1.1. Method 1

Table 2 shows the results obtained for all three correlations, where q_e the specific mass flow rate is equal to q_m. Fig. 10 shows the type of comparison obtained. The Sibulkin correlation leads to better results. The measured temperature is obtained with 10% accuracy. The stagnation temperature of the flow is given by

$$\frac{T_{st}}{T_{aw}} = \frac{1 + ((\gamma - 1)/2)M^2}{1 + r((\gamma - 1)/2)M^2},$$

where the recovery factor r is around 0.7 [23]. A difference of about 3% is therefore obtained between temperatures T_{aw} and T_{st}.

Table 2
Determination of the adiabatic wall temperature

	Sibulkin [20]	Mc Adams [21]	Ahmed and Yovanovich [22]
$T_{st} = 1790$ K; $q_e = 377$ (kg/m^2 s)			
T_{aw} (K)	**1646**	**1792**	**2030**
E (K)	14.32	46.75	86.15
Re	7910–5610	7550–5375	7030–5065
h_c (W/m^2 K)	8550–11 300	6675–8325	4765–6225
Nu	107–92	79–64	51–44

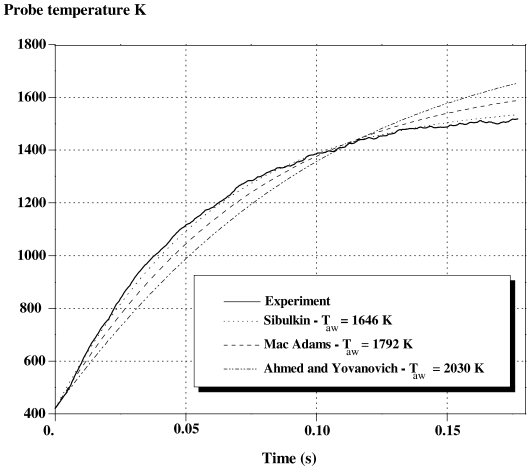

Fig. 10. Identification temperature experimental curve/model.

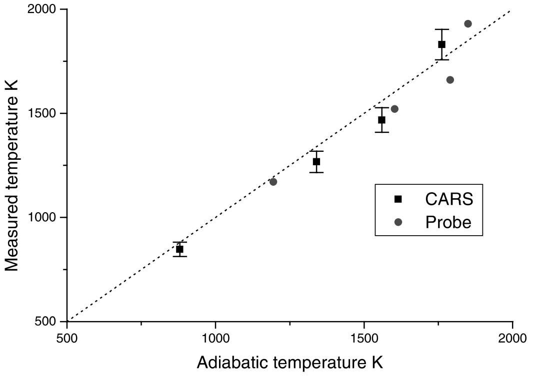

Fig. 11. CARS–probe temperature measurements comparison at location P1.

5.1.2. Method 2

Table 3 shows results obtained with this approach. The specific mass flow rate and temperatures obtained are realistic given the experimental conditions. By comparing all the tests we have shown that the Ahmed and Yovanovich correlation is not adapted to our experimental conditions [22]. Other studies, mainly based on the local specific mass flow rate measurement, should enable us to define the most appropriate correlation so that the convective transfer can be defined.

The CARS static temperature measurements are used to deduce the stagnation temperature knowing the Mach number profile and the thermodynamical properties of the flow ($\gamma = 1.27$). The standard deviation of the CARS temperature is around 114 K for an average value of 1150 K, and remains around 10% for the whole explored range: the statistical error on the averaged temperature due to the small size of the single-shot temperature sample is of the order of 1%. Fig. 11 presents the comparison between that estimation and the probe measurements, at position P1: the relative inaccuracy on the averaged temperature is around 4%. That last value is in agreement with the maximal inaccuracy, estimated of 10% for the relatively easy to use intrusive method.

5.2. Tests with combustion

As far as mixing is sufficient to provide CARS signals on nitrogen, transverse profiles of the temperature

Table 3
Determination of the adiabatic wall temperature and specific mass flow rate

	Sibulkin [20]	Mc Adams [21]	Ahmed and Yovanovich [22]
$T_{st} = 1790$ K; $q_m = 377$ (kg/m^2 s)			
T_{aw} (K)	**1610**	**1615**	**1608**
q_e(kg/m^2 s)	**455**	**702**	**1758**
E (K)	7.23	7.14	7.25
Re	9660–6850	14 895–10 570	37 360–26 505
h_c (W/m^2 K)	9295–12 290	9350–11 665	9275–12 095
Nu	118–101	118–96	117 –100

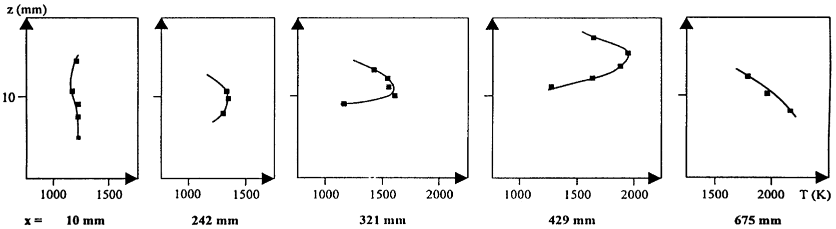

Fig. 12. CARS temperature profiles along the supersonic combustor.

Table 4
Results summary

	Approach 1 ($q_e = q_m$, T_{aw} (K))		Approach 2 (q_e constant, T_{aw} (K))		Approach 2 ($2h_c$ constant, T_{aw} (K))	T_{st} (K)
	Sibulkin [20]	Mc Adams [21]	Sibulkin [20]	Mc Adams [21]		
P1 Th1	–	–	–	–	685	**705 ± 70**
P1 Th2	2376	2700	–	–	–	**2780 ± 280**
P1 Th3	1808	1942	1881	1902	1936	**2000 ± 200**
P2 Th1	2415	2780	–	–	–	**2865 ± 285**
P2 Th2	No treatment was possible					
P2 Th3	No measurement (destruction of the thermocouple)					

(Fig. 12) were collected at $X = 10$ mm, $X = 242$ mm (position P1), $X = 321$ mm, $X = 429$ mm and at $X = 675$ mm (close to position P2). At $X = 242$ mm, the increase of 50 K, on the average measured temperature, when hydrogen is injected in the supersonic flow, confirms that there is no important heat release at that station (Fig. 2). On the contrary, high temperatures are found at $X = 675$ mm. The static temperature is around 2100 K in the region where the combustion efficiency is high.

The probe with three type R thermocouples (diameters between 0.5 and 0.7 mm) is used at both measuring points P1 and P2:

1. thermocouple Th1, on the burner axis ($Z = 0$);
2. thermocouple Th2, in the mixing layer ($Z = 8$ mm);
3. thermocouple Th3, in air outside the mixing layer ($Z = 16$ mm).

Both processing approaches have been tested in all cases [14]. Several examples of these results, summarized in Table 4, are given below.

5.2.1. Position P1, Th1

The temperature has been evaluated in the hydrogen jet by the method 2 (Fig. 13) where the convective heat transfer coefficient is adjusted. This choice has been made because it is very difficult to evaluate the chemical composition of the flow in this zone. The measured value of 705 K is consistent with limited H_2–air mixing leading to insufficient temperature levels for hydrogen ignition as shown by the pressure. That result was confirmed by H_2 CARS thermometry recent measurements [24] giving an averaged value of 717 K with a standard deviation of 153 K.

5.2.2. Position P1, Th2

In this situation we have shown that method 2 cannot be applied because the thermocouple was too far from its stationary state. However, approach 1 can be used by considering, as a first approximation, that the specific mass flow rate q_e is equal to q_m. Moreover, the gas composition is supposed to correspond to a completely

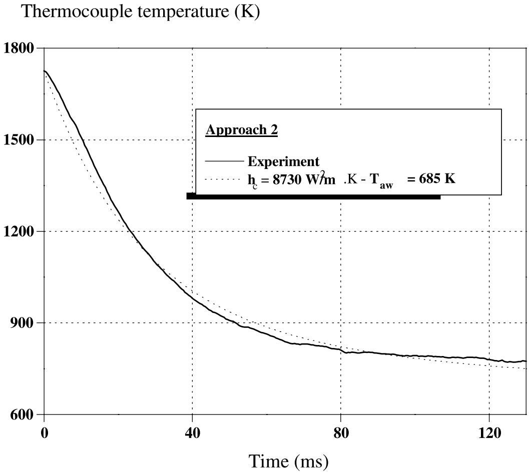

Fig. 13. Identification temperature experimental curve/model – point P1 – thermocouple Th1.

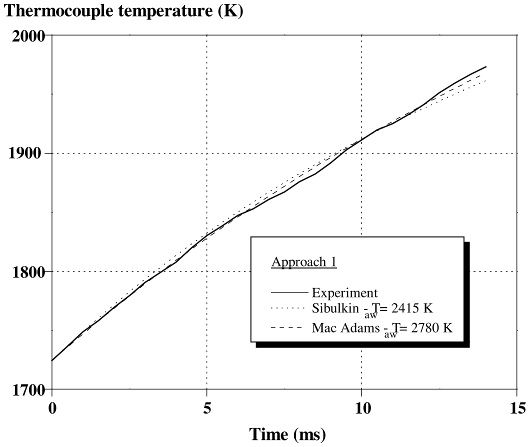

Fig. 14. Identification temperature experimental curve/model – point P2 – thermocouple Th1.

burnt premixture between air and hydrogen (temperature of 2780 K measured by the probe). But that hypothesis of mixing and complete combustion cannot be confirmed by CARS measurements (performed without intrusive probe). That apparent discrepancy can be explained by the behavior of the probe as a flame holder. The presence of the shock wave increasing locally the temperature will induce an early auto-ignition of the hydrogen–air mixture.

5.2.3. Position P1, Th3

The temperature level of 2000 K measured by the probe in the hot non-reacting gases is in agreement with the CARS measurements.

5.2.4. Position P2, Th1

According to the combustion analysis, the flow is not far from homogeneously burnt gases. In the divergent of the combustion chamber, the average mass flux is lower than its previous value of $q_m = 330\ \mathrm{kg/m^2\ s}$. The value of 2870 K given by the intrusive probe (Fig. 14) is reasonable, but more precise comparisons with the CARS measurements need further information on the local Mach number that are expected from planned laser Doppler velocimetry. An additional study for the P2, Th2 measurement is currently carried out in order to explain the observed transient heating, that may be due to catalytic effects on the thermocouple.

6. Conclusion

A stagnation temperature probe has been tested in a plasma flow and in a supersonic flow environment (non-reacting and reacting hydrogen jet in air). The comparison performed with emission and CARS spectroscopies gave the following conclusions. As a general rule, the Mc Adams [21] correlation leads to better results for processing the probe measurements. Those measurements compare fairly well in the case of non-reacting flows. For reactive flows, the use of the intrusive probe should be limited to completely reacted flows due to the probe playing a flame holding role when reactions are not complete. That intrusive instrument can provide valuable evaluation of combustion efficiency at the exit of SCRAMJET combustion chambers, when the use of more sophisticated methods such as laser diagnostics is impossible.

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