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A NEW FACILITY FOR HYPERSONIC FLOW SIMULATION DRIVEN BY A HIGH VELOCITY OXYGEN FUEL GUN

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Abstract

The paper reports on the development of a new Vacuum High Velocity Oxy Fueled Facility (V-HVOF) for Aerothermodynamic and Propulsion applications. The related setup comprises unique equipment designed to test candidate materials for thermal protection systems and mimic experimentally conditions corresponding to hypersonic sustained flow. We illustrate critically the underlying principles, along with a focused description of the various facility subsystems, their interconnections and the specific procedures to be used to overcome some of the inherent complexities embedded in the overall theoretical and technical architecture on which the facility relies. Its performances are finally presented in relation to some prototype applications, together with the indication of the related limits, advantages and possible directions for future improvements.

Keywords: Aerodynamics, Hypersonic Flow, Experimental Facilities and Techniques.

1. Introduction

Plasma guns used in the context of thermal spray applications are often engineered versions of similar devices originally designed for the analysis of aerospace problems, such as those related to planetary entry and the related testing of Thermal Protection Systems (TPS) [1]. For these cases the plasma gun is particularly relevant because it couples the reliability of an industrial device with the desired operating conditions, i.e. very high temperatures and very low pressures of the considered gas (heated by the electric arc).

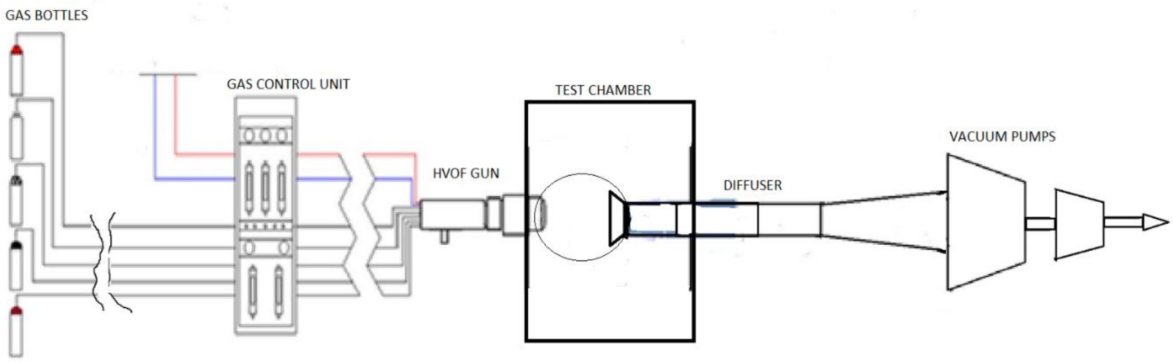
Nowadays, however, new applications, emerging in the specific fields of aerothermodynamics and propulsion require (a) lower temperatures and higher pressures with respect to those generated by plasma torches, (b) different process gases (typically methane or hydrogen) and (c) different operational modes (e.g., combustion in place of an electric arc).

All these requirements call for the design and development of new facilities, and the present study may be regarded as a relevant effort along these lines. In particular, here, we describe the development of a new V-HVOF system (where the acronym stands for "Vacuum High Velocity Oxy Fueled Facility") based on a High-Velocity Oxygen Fuel (HVOF) torch, operated in a manual mode, that exhausts into a low pressure ambient. Unique properties of this facility are its ability to further expand the flow, reduce the very strong noise from the torch itself and, last but not least, the possibility to use the HVOF gun in a particular functional mode (the so-called IDLE mode) by which the overall gas consumption can be reduced drastically.

2. Experimental Apparatus

Figure 1a shows the overall V-HVOF system.

(a)



(b)

Figure 1 – Picture (a) and Layout (b) of the V-HVOF system.

The related gas system consists of a Gas Supply System and a Gas Control Unit (Fig. 1b). Accordingly, the main facility components can be listed as:

1. Gas Supply System
2. Gas Control Unit
3. Cooling System
4. Hybrid HVOF gun
5. Test Chamber
6. Diffuser (Cooling and Exhaust System)
7. Vacuum Pump System

2.1 Gas Supply System

The details of the gas supply system are shown in Fig. 2.

In the related "Spraying" mode, nitrogen is used as a carrier gas for the powder feeder, whereas in the “No Spraying” mode, nitrogen is used only to prevent melting of the powder injector.

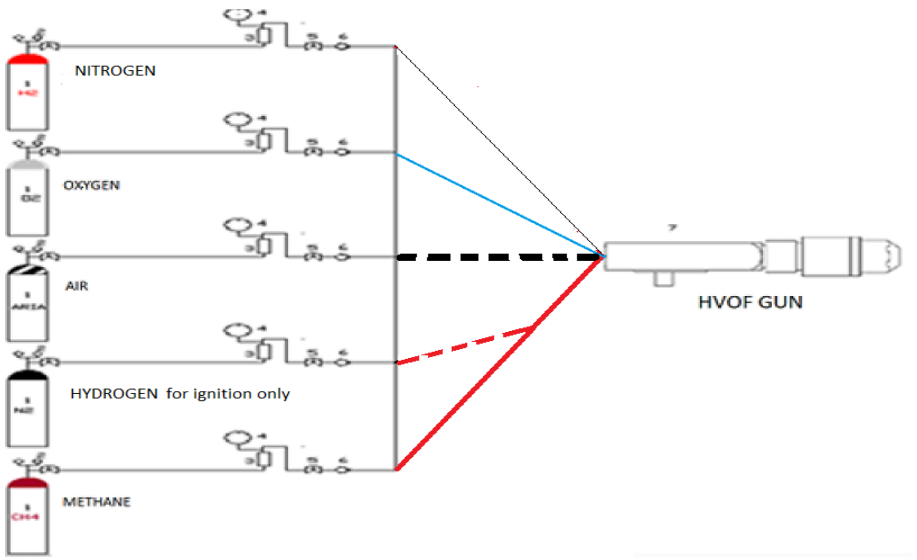
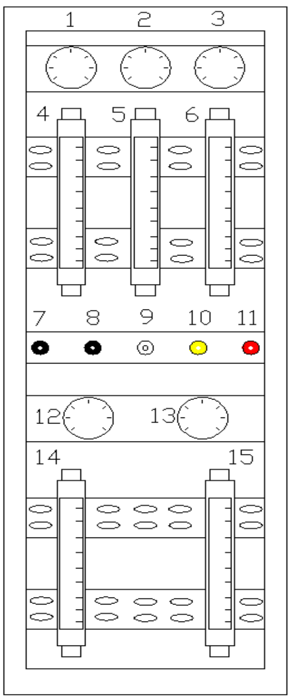


Figure 2 – Layout of the gas supply system.

The requirements for Nitrogen are approximately 18 NLPM at 12 bar, while those for oxygen and hydrogen are 340 NLPM at 12 bar and 4 - 8 NLMP at 10 bar, respectively. Air is used both as an oxidant in the combustion process and as a cooling gas for the torch; the corresponding requirements are 439 NLPM at 7 bar. For methane the requirements are approximately 200 NLPM at 7 bar The mass-flow rates of the gases are measured and controlled by the flow meters of the Gas Control Unit (Sect. 2.2).

2.2 Gas Control Unit

A sketch of the Gas Control Unit is shown in Fig. 3, with some relevant details being made evident through the associated legend.



1. Air pressure gauge
2. Oxygen pressure gauge
3. Methane pressure gauge
4. Air flow-meter
5. Oxygen flow-meter
6. Methane flow-meter
7. Air control Knob
8. Nitrogen control knob
9. Oxygen control knob
10. Hydrogen control knob
11. Methane control knob
12. Nitrogen pressure gauge
13. Hydrogen pressure gauge
14. Nitrogen flow-meter
15. Hydrogen flow-meter

Figure 3 – Gas Control Unit - Front Panel

2.3 Cooling System

A complete HVOF installation obviously also requires plant facilities to supply and control cooling water. In our case the cooling water requirements are:

- Drinking water quality or better.
- Maximum inlet water temperature: 23°C
- Minimum water flow: 9.5 l/min.

The related cooling water system layout is presented in Fig. 4.

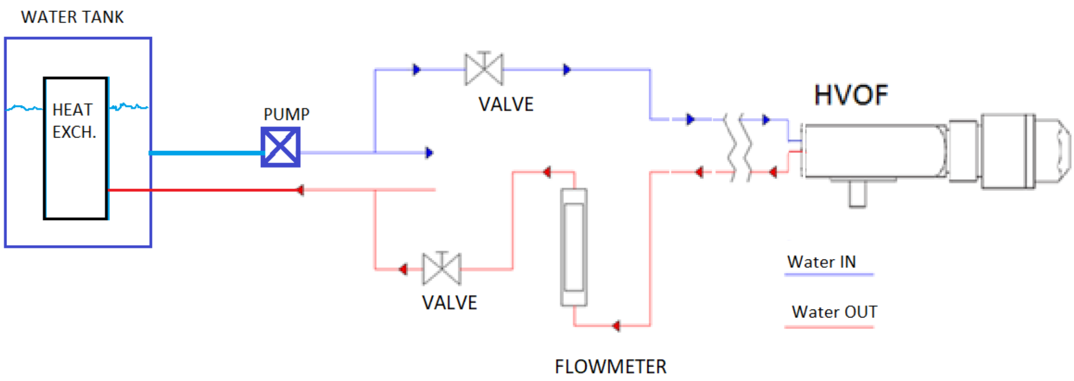


Figure 4 – Layout of the cooling water system.

2.4 HVOF Gun

The Sulzer-Metco Diamond Jet (DJ) 2700 has been chosen as HVOF gun (the reader being referred to Figure 5 for a detailed sectional drawing of the gun).

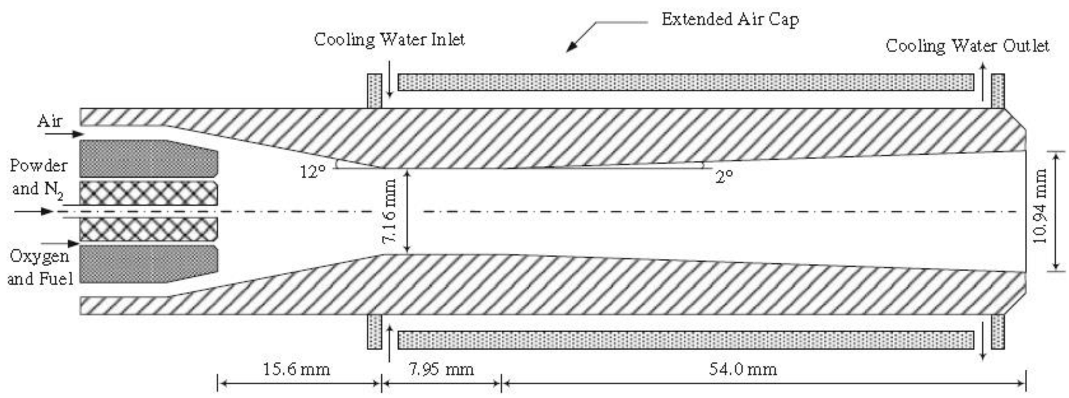


Figure 5 – Diamond Jet Hybrid Thermal spray torch.

The DJ gun relies on a combination of oxygen, fuel and air to produce a high pressure annular flame, which is characterized by a uniform temperature distribution. In this process, the premixed fuel gas (typically methane, propylene or hydrogen) and oxygen are fed from the annular gap to the air cap, where they react to produce high-temperature combustion products. The exhaust gases, together with the air injected from the annular inlet orifice, expand through the nozzle to reach a supersonic state. The air cap is cooled by both water and air to prevent it from melting (see Fig. 6).

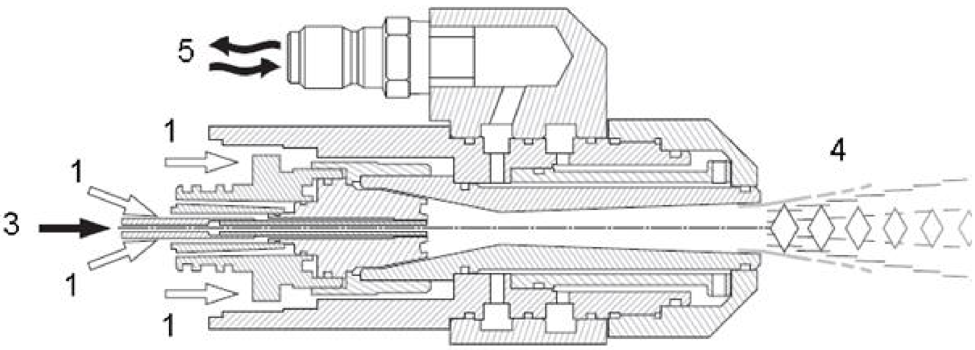


Figure 6 – Cross section of the Diamond jet Hybrid gun DJ 2700

A water circuit is used to support the air cooling process (Fig. 7). Air (1) circulates between the air cap body and the air cap, and around the nozzle assembly. Water (5) circulates through the water adapter to cool the air cap. Figure 7 shows the full cable assembly on the HVOF torch.

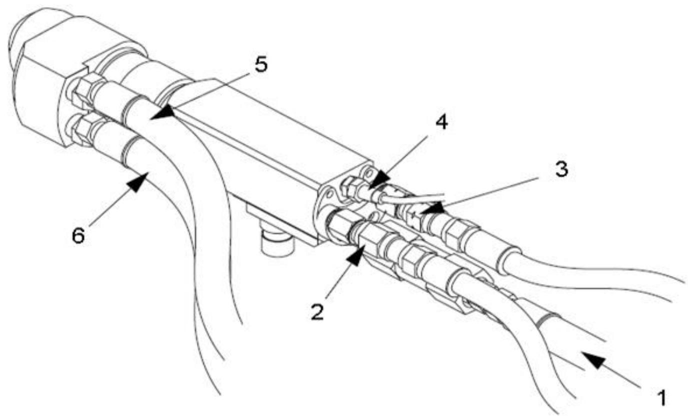


Figure 7 – Cable Assembly (1. Air, 2.Oxygen, 3.Fuel, 4.Powder, 5. Inlet water, 6. Outlet water).

2.5 Test Chamber and Diffuser

The test chamber is a iron cylinder with a diameter of 600 mm (Fig. 8), flanged at the ends and hosted inside the first section of the supersonic diffuser (Figs. 9(a) and 9(b)).

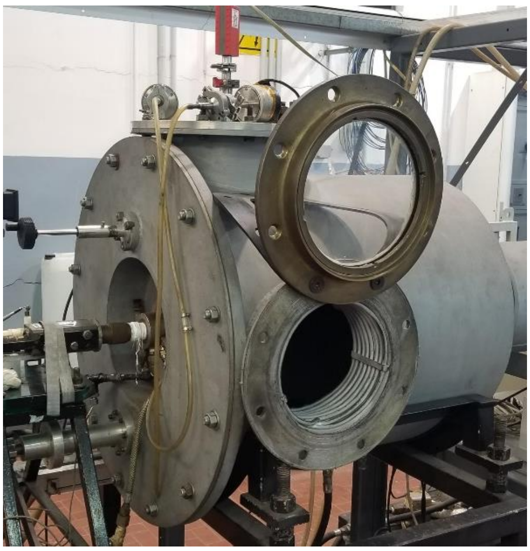
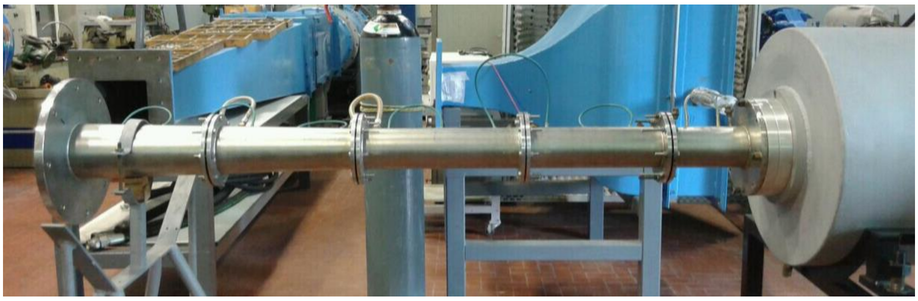


Figure 8 – Vacuum Test Chamber.



(a)

(b)

Figure 9 – Diffuser: (a) lateral view, (b) first section.

2.6 Vacuum Pumps

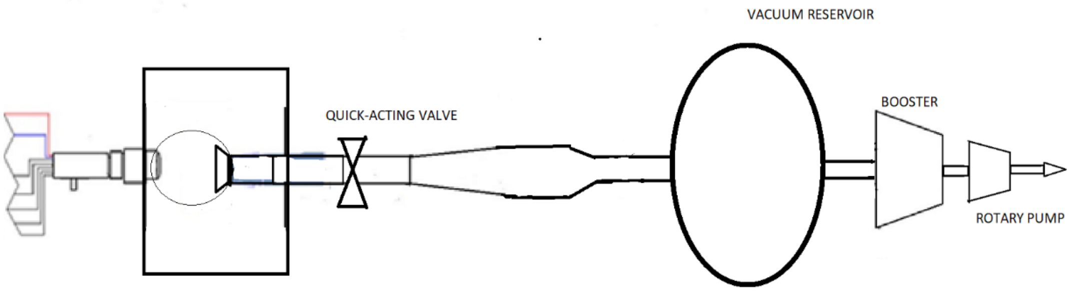
Multiple choices are possible in terms of vacuum pump to be associated with the Gun. The available variants and the related volumetric rates are listed below:

R1) Rotary Pump Stokes Microvac 212H (220 m^3/h)
R2) Rotary Pump Edwards E2M275 (292 m^3/h)
B1) Booster General Engineering HGMB 1300 (2220 m^3/h)
B2) Booster Edwards EH 4200 (4200 m^3/h)

It is also worth noting that possible combinations of these are:
R1 + B1
R1 +B1 + B2
R1 // R2
R2 + B2
(R1 // R2) + B1
(R1 // R2) + B1 + B2
Where the symbols // and + stand for pumps in parallel and pumps in series, respectively.

2.7 Vacuum Tanks

The HVOF gun can process up to a maximum of ~1000 NLPM (60 m^3/h) of gas in the operating mode called "Full Flow". The gas flow rate can be reduced to a minimum of ~400 NLPM (24 m^3/h) in the "Idle" mode. With such flow rates, in order to produce Mach numbers in the hypersonic range, the facility relies on the presence of a tank inserted on the process line between the diffuser and the vacuum group (see Fig. 10a). The used tank has a capacity of 4.5 – 6.5 (m^3), while the most effective or relevant vacuum pump combination is R1 // R2, see Fig.10(b).



(a)

(b)

Figure 10 – Vacuum System: (a) Tank, (b) Rotary pumps.

The “Full Flow” volume flow rate (1000 NLPM) corresponds to a mass flow rate of 0.020 kg/s. Starting from an initial tank pressure of 1 (mbar) and considering that in the Full Flow condition the pressure at the nozzle exit is 0.7 bar, the mass increase corresponding to a pressure increase of 0.7 bar (Dp = 709 – 1 = 708 mbar) can be estimated as:

$$DM = (V/RT) \times Dp = (6.5 /500/350) \times (70800) = 2.63 \text{ kg} \quad (1)$$

(assuming that the combustion products have a “R” constant of 500 J/kgK and that gas temperature in the tank has decreased to 350 K)

Key observations about these processes can be summarized as follows. Up to the pressure of 0.7 bar, the flow is expected to expand correctly, beyond this value, it will over-expand. During the tank filling time, about 130 (s), the flow is expected to pass from a condition with Mach = 7.6 (at pt /p ~ 7000) to a condition with Mach = 2.2 (at pt /p = 10). Some additional relevant theoretical considerations about the existence of a constant pressure phase (time-independent Mach number), albeit short, to be used as Run Time, are reported in the next section; while the reader is referred to Sect. 4 for the outcomes of practical tests and experimental verification of such principles.

3. Modeling the Facility Flow Process

Roughly speaking, the major physicochemical processes involved in the HVOF process are:

- Transformation of chemical energy into thermal energy through combustion;
- Conversion of thermal energy into kinetic energy of the burning gases induced by the nozzle.

These phenomena occur simultaneously and make the fundamental modeling of the HVOF process an essentially difficult task. The gas evolving in the HVOF gun should be considered as a fully compressible and reacting flow characterized by turbulence and a complex hierarchy of subsonic/sonic/supersonic transitions. As an example, Fig. 11 shows the temperature contour in the combustion chamber of the Diamond Jet 2700 gun, as calculated by means of a commercial CFD code (the treatment of related mathematical/numerical details is beyond the scope of the present work; the examples shown in Figs. 11 and 12 being included solely to support reader's understanding of certain processes). The outcomes of these numerical simulations are particularly instructive as they show that the hot flame is surrounded by the cooling air, which protects the hardware from being overheated. The next figure of the sequence (Fig. 12) provides the contours of static pressure in the external gas field. The significance of this figure resides in its ability to make evident that the pressure gradually decreases from 7.6 bar in the combustion chamber to 0.69 bar at the exit of the nozzle. Since this pressure is smaller than the ambient pressure, the flow is under-expanded and adjusts to the ambient pressure by a series of shock waves (which are indeed usually observed during operation of this facility).

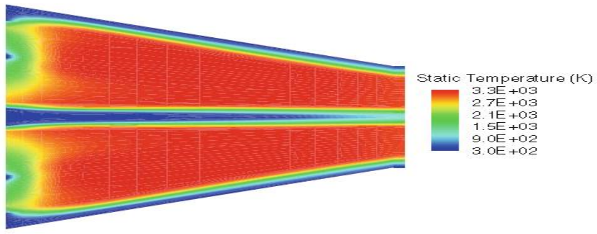


Figure 11 – Contour of static temperature in the combustion chamber.

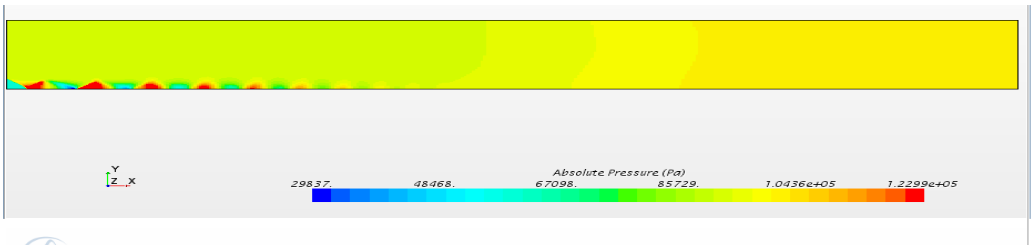


Figure 12 – Contours of static pressure in the external field.

Given these premises, the following assumptions are used here to elaborate a relevant theoretical model:

- instantaneous equilibrium at the entrance if HVOF gun;
- frozen, isentropic flow during passage through the nozzle;
- all of the oxygen coming from the air participates in the combustion reaction;
- all gases obey to the ideal gas law;
- the combustion gases behave as a perfect gas during isentropic compression and expansion, and the specific heat ratio is nearly constant.
- the effects of friction and cooling water along the nozzle are negligible, so that the laws of isentropic flow apply.

Moreover, considering that the gas residence time in the combustion chamber (convergent section of the nozzle) is much longer than that in the subsequent sections, it is also reasonable to assume that the reaction occurs primarily in the combustion chamber. In turn, this can be modeled in the framework of a global one-step equilibrium chemistry approach (namely the CEA code developed by NASA [7]).

Using the mass flow rates of oxygen and fuel as input parameters, the chamber pressure can be determined in a relatively straightforward way. More specifically, given the oxygen and fuel flow rates, a tentative combustion pressure can be assumed; the CEA code can be used accordingly to calculate the equilibrium composition and temperature in the combustion chamber; the total mass flow rate at the throat of the nozzle can then be determined; finally, the combustion pressure has to be adjusted until the discrepancy between the calculated and the specified total mass flow rates falls under a user-specified tolerance (iterative process).

The expression to determine the total mass flow rate in the HVOF gun can be cast in compact form as :

$$\dot{m} = \frac{p_o}{\sqrt{T_o}} A_{th} \sqrt{\frac{\gamma M_{pr}}{R_g} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}} \quad (2)$$

where:

- A_{th} is the cross-sectional area at the throat,
- R_g is the molecular gas constant,
- M_{pr} is the average molecular weight of the combustion products,
- T_0 is the stagnation temperature in the combustion chamber,
- p_0 is the stagnation pressure in the combustion chamber.

This equation clearly reveals that the mass flow rate and the combustion pressure are interrelated, which explains why the combustion pressure should be determined in the frame of an iterative procedure.

4. Characterization of Atmospheric Pressure Tests

In the light of all the arguments provided in the preceding sections, the logical sequence of steps to be used to assess the facility performances in the case of tests performed at atmospheric pressure can be listed as follows. Using the simple flow model described in Sect. 3, the total and static pressure can be determined (as quantitatively substantiated in Fig. 13) along with the total and static temperature (Fig.14) versus mass flow rate for some typical operating conditions (total mass flow rate). Furthermore, the main combustion products of the HVOF gun can be calculated as a function of the static/adiabatic flame temperature ratio using the aforementioned CEA code [7] (Fig. 15).

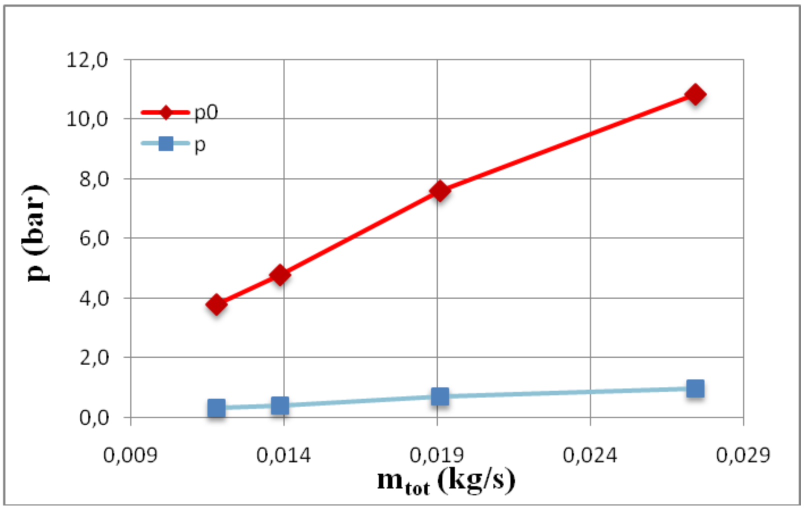


Figure 13 – Total and static pressure vs mass flow rate (tests conducted at atmospheric pressure).

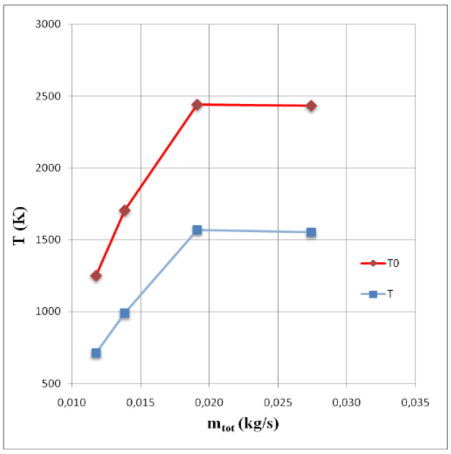


Figure 14 – Total and static temperature vs mass flow rate.

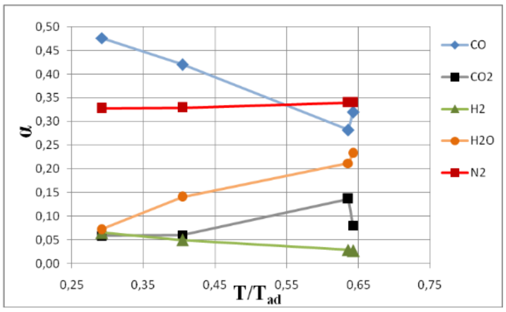


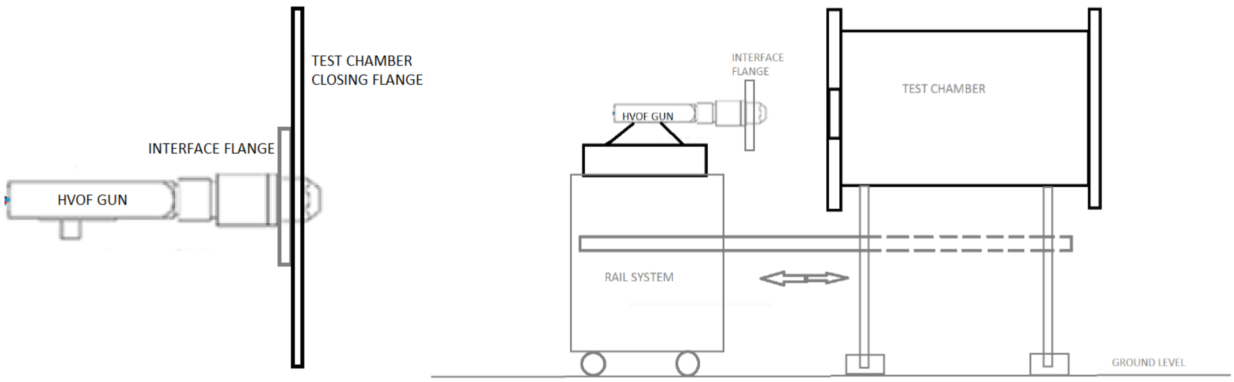
Figure 15 – Combustion products vs temperature ratio.

5. Preliminary Tests at Sub-atmospheric Pressure

As discussed extensively in earlier sections, the HVOF gun is equipped with its own supersonic nozzle, by which a Mach 2.2 flow at atmospheric pressure can be obtained. However, since it is impossible to ignite the HVOF gun under vacuum, the only practical way to operate this system consists of igniting the gun at atmospheric pressure and then inserting it into the vacuum test chamber. From a purely theoretical standpoint this is allowed by the well-known inability of pressure disturbances to propagate in the upstream direction in a supersonic flow field.

In order to verify this procedure, two “ad hoc” mechanical parts were prepared:

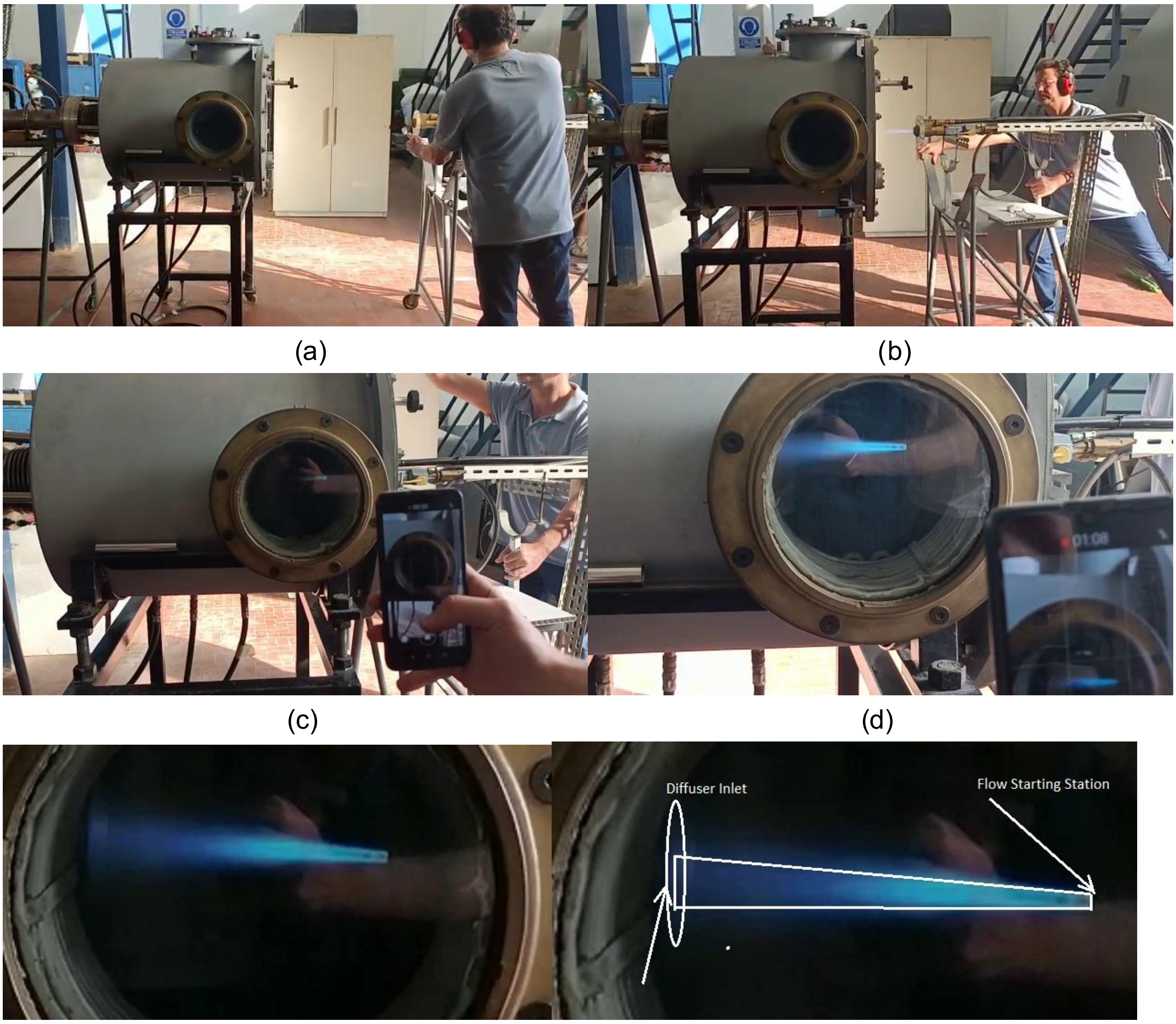
- a connection flange between the HVOF gun head and the test chamber closing flange, Fig. 16(a);
- a support trolley for the HVOF gun, equipped with a rail device, Figure16(b), in order to bring the gun head into the test chamber.



(a) (b)

Figure 16 – Provisions for HVOF operation under vacuum: (a) interface flange, (b) rail system.

Some preliminary tests were carried out accordingly. These tests, conducted using only rotary vacuum pumps, were successful, Fig. 17(a – d).



(a) (b)

(c) (d)

(e) (f)

Figure 17 – Facility Operational Procedure:
(a) Ignition at ambient pressure – (b) Inserting the Gun in the Test Chamber
(c) Starting the Vacuum Pumps – (d) Flow Expansion Stage
(e) Close view of the jet –(f) Geometrical approximation of the flow.

As explained above, this experimental campaign was conducted essentially to verify the practical applicability of the proposed procedure, i.e. 1) ignition at atmospheric pressure, 2) subsequent insertion of the lit gun into the test chamber and finally 3) activation of the vacuum pumps. As a concluding remark for this section, however, we wish to highlight that through a geometrical analysis of the flow expansion process (a kind of reverse engineering, see Fig 17 (e-f)), we could even estimate the Mach number at the diffuser inlet ($\cong$4.5), this being much larger than that obtained for atmospheric pressure conditions ($\cong$2.2). Unfortunately, we could not evaluate the uncertainty associated with such a prediction due to the lack of a concurrent measurement of the pressure in the test section (which plan to do in the near future).

6. Applications

As the reader might have realized at this stage, since the HVOF thermal spray system displays interesting thermo-kinetic properties, it could be used for different aerospace applications, such as aerothermal testing, aeropropulsion testing, or as a heat source for a combustion-heated facility, just to cite a few. A relevant example along these lines (Combustion-heated Facility) is described in the remainder of this section. The HVOF can indeed be used as source for a combustion-heated facility to simulate hypersonic conditions. In this specific case, obviously, the requirements of the facility naturally stem from the flight corridor of the considered (future) hypersonic vehicle, see Figs. 18 and 19.

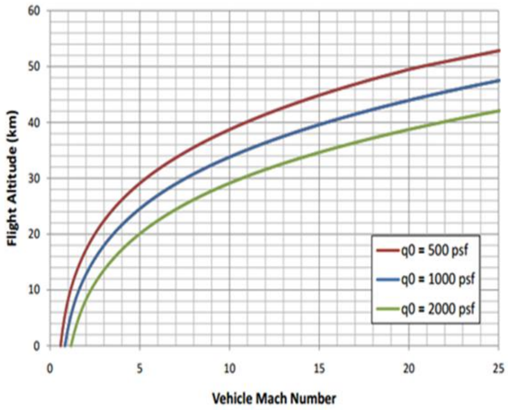


Figure 18 – flight altitude VS Mach number.

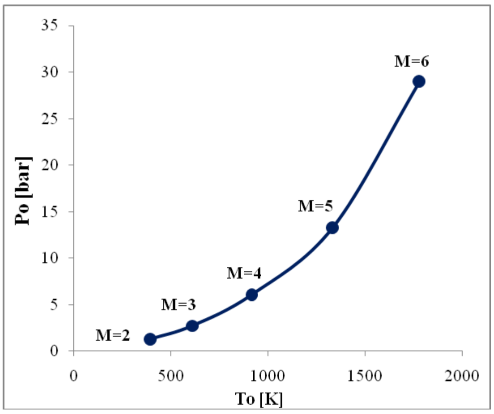


Figure 19 – total pressure VS total temperature.

For fixed flight conditions, the corresponding pressure and temperature can be obtained through the standard atmosphere tables. Moreover, the isentropic equations allow the calculation of the total pressure and temperature to be attained in the wind tunnel; as an example, to simulate a Mach number spanning the interval from 2 to 6 at a flight altitude between 13 and 27 km, the required total pressure would range between 1.3 and 29 bar.

The flow configuration or topology for the proposed facility is shown in Fig. 20; hot combustion gases leaving the HVOF gun enter a mixing chamber, where oxygen is added thereby producing a second combustion stage. Finally, cold air is mixed with the hot flow to reach the target stagnation conditions (pressure and temperature).

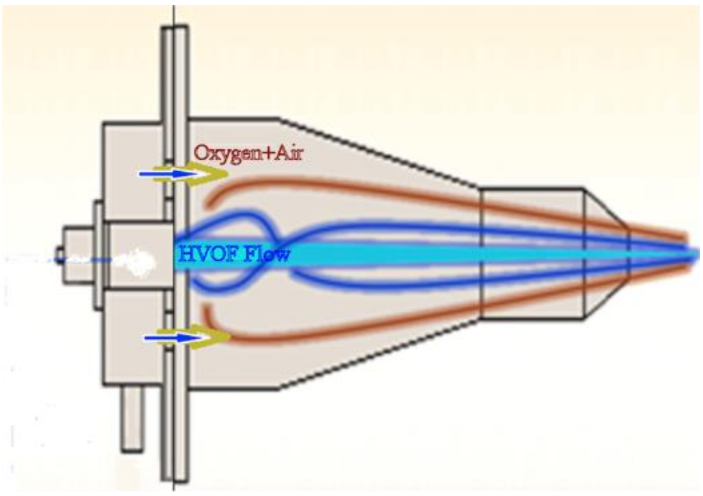


Figure 20 – picture of the Heat Source for the Combustion-heated Facility.

Considering a typical operating condition of the HVOF gun, namely (see table 1):

Table 1

Test	p (bar)	T (K)	qO_2 (NLPM)	qCH_4 (NLPM)	qAir (NLPM)	qN_2 (NLPM)	Oxi/ Fuel	m_{tot} (kg/s)	H_{ch} (MJ/KG)
STAR3	10.85	298.15	450	300	660	27	3.76	0.029	7.002

The output (nozzle exit) for this condition is (Table 2):

Table 2

Test	ρ (kg/m^3)	T_0 (K)	γ	C_P (J/kg K)	XCO	XCO_2	XH_2	XH_2O	XN_2
STAR3	1.04	2433	1.23	2380	0.219	0.035	0.258	0.249	0.233

As explained above, oxygen is added in the proper percentage to nitrogen (oxygen mass flow rate of 10 g/s); as a result, further combustion is enabled with hydrogen and carbon oxide, leading to the following conditions:

Table 3

Test	*P* (Bar)	T_0 (K)	R (J/kg K)	αCO	αCO_2	αO_2	αH_2O	αN_2	αOH
STAR3+O_2	1.0132	2773	446.1	0.106	0.259	0.060	0.294	0.241	0.032

In the next stage, air is added to obtain the target stagnation conditions:

Table 4

Test	*P* (Bar)	T_0 (K)	R (J/kgK)	αCO	αCO_2	αO_2	αH_2O	αN_2	αOH
STAR3+ O_2 + Air	1.0132	2773	446.1	0.106	0.259	0.060	0.294	0.241	0.032

after a number of calculation attempts, see Fig. 21, the final result reads:

P_0 = 7 bar; T_0 = 789 K (3)

this condition for the facility is compatible with a stable operation for the HVOF gun and is representative of Mach 4 operation.

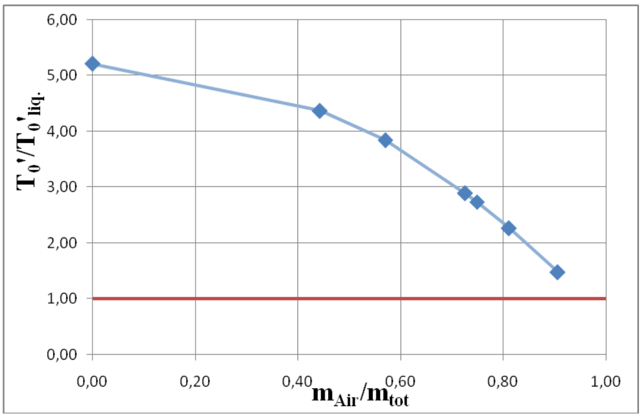


Figure 21 – calculation attempts to match air flow.

7. Conclusions

A High-Velocity Oxy-Fuel (HVOF) gun, i.e. an industrial device that can generate a supersonic flame through high efficiency combustion of a methane-oxygen-air gas mixture, has been used to simulate a range of flow temperatures, pressures and chemical compositions relevant to sustained hypersonic flight experimental simulation.

The principles driving the choice of the HVOF torch, related flow models, laboratory-scale set-ups and preliminary tests have been critically discussed with an eye on possible applications. Such preliminary results are promising and may regarded as a first step towards the implementation of a future larger-scale research program building on such initial findings.

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9. Copyright Statement

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