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Development of a Probe for Particle Collection in High-Temperature, Supersonic Flow: Conceptual and Detailed Design

Stefania Carlotti[⋆†], *Alessandro Ferreri*[⋆], *Riccardo Bisin*[⋆], *Filippo Maggi*[⋆],
Luciano Galfetti[⋆], *Dominik Saile*[⋆⋆], *Ali Gülhan*[⋆⋆], *and Tobias Langener*[⋆⋆⋆]

[⋆]*Politecnico di Milano, Milan, Italy, Dept. Aerospace Science and Technology, SPLab, Via La Masa 34*
stefania.carlotti@polimi.it · alessandro.ferreri@mail.polimi.it · riccardo.bisin@mail.polimi.it ·
filippo.maggi@polimi.it · luciano.galfetti@polimi.it

[⋆⋆]*German Aerospace Center DLR, Supersonic and Hypersonic Technology Department, Germany, Cologne, Linder Hohe*
dominik.saile@dlr.de · ali.guelhan@dlr.de

[⋆⋆⋆]*ESA, Noordwijk, The Netherlands, Aerothermodynamics and Propulsion Analysis Section (TEC-MPA), Keplerlaan 1*
tobias.langener@esa.int

[†]Corresponding author

Abstract

An intrusive technique for the collection of the condensed combustion products in the proximity of the rocket nozzle is proposed. In particular, a supersonic probe able to withstand the harsh environment of a plume was sized to handle a progressive deceleration and cool down of the exhaust gas, preventing from liquid particle breakup. The task was achieved by diluting the swallowed flow with a cold inert gas and quenching the suspended particles using a liquid spray in a specific chamber. Preliminary tests performed in the supersonic wind tunnel at DLR confirmed the quality of the collection device.

1. Introduction

Solid Rocket Motors (SRMs) are a mature thermochemical propulsion technology, made appealing by their simplicity and low cost. Since they provide very high thrust levels, high thrust-over-weight ratios, high volumetric specific impulse, they are the main propulsion units for launch boosters or atmospheric launcher stages. Moreover, compactness, reliability and readiness make the SRMs a good choice for military missions. The addition of aluminum powder to solid propellants is a common practice to improve the performance of SRMs and suppress high enthalpy instability. Although difficult to ignite, aluminum has a high enthalpy of reaction, allowing a higher increase of the flame temperature with respect to the average molecular mass of products, and, hence, an increase of the gravimetric specific impulse. However, the incomplete combustion of aluminum reduces the combustion efficiency if particulate residence time is too short, leading to the formation of condensed (solid or liquid) combustion products (CCPs). The presence of CCPs in the rocket exhaust plume is detrimental in terms of performance and pollution. Reydellet[22] estimated that about 10% of the ideal specific impulse is lost in a solid rocket motor and, out of this amount, about 1/3 to 2/3 is due to two phase losses. In fact, during nozzle expansion, the thermal and kinetic inertia of the large condensed particles lead to a warmer and slower flow with respect to the ideal gas-only case, yielding to two-phase flow losses, resulting in about 3-5% of specific impulse losses attributed to multiphase flow.[20] Moreover, the climatological impact of the plumes has to be considered. In fact, alumina particulate contribute among others to radiation from the plume and the reactivity and lifetime of alumina in the atmosphere needs to be further studied.[5]

In the past decades great effort was put for the collection of combustion products in the vicinity of the burning surface.[2,12] Such practice can be performed by burning propellant strands in quench bombs. The incipient formation of metal agglomerates after the release from the propellant can be characterized. However, in a real motor the condensed particles experience a variety of phenomena while they are carried through the nozzle by the gaseous mixture.

In the convergent portion of the duct the streamlines tend to cross each other and agglomerates merge, incrementing their average size. The maximum acceleration of the gas occurs at the throat. Here the velocity gradient can be so high

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that the critical Weber number of the liquid droplets is reached, leading to particle breakup. The condensed combustion residues eventually enter the divergent portion of the nozzle, where coalescence due to impacts prevails. Both kinetic and thermal inertia are functions of the particle size, which changes significantly through the nozzle. That is, the morphology of the agglomerates at the burning surface is not sufficient to fully understand their effect on the rocket motor performance and the environmental pollution of the plume.[8]

The EMAP (Experimental Modeling of Alumina Particulate in Solid Booster) project, a collaboration between the European Space Agency (ESA), the German Aerospace Center (DLR), Swedish Defense Research Agency (FOI), and the Space Propulsion Laboratory (SPLab), which is part of the Department of Aerospace Science and Technology (DAST) of Politecnico di Milano, aims at characterizing the rocket exhaust plume from a sub-scale SRM, resembling the exhaust conditions of Ariane 6 boosters. The motor is fired in a supersonic wind tunnel to simulate the flight status of the launcher at an altitude of approximately 4-5 km. The objective of the activity is to gain a comprehensive overview of the statistical development of the particle distribution, experimentally characterizing the flow and the condition of the alumina particulates starting upstream of the nozzle inlet to the nozzle exit. Hence, the large uncertainty in building up a picture of the alumina behaviour in the nozzle and of the state, size and distribution of alumina in the plume could be overcome. Additionally, one of the objectives of the EMAP activity is the development of new or the improvement of existing measurement techniques for the use in solid rocket motor plume experiments.
In this scenario, an innovative intrusive technique shall be implemented by SPLab-POLIMI, to collect the agglomerates in the proximity of the rocket nozzle. The present work presents the conceptual design of such innovative sampling system.

2. Literature Survey

2.1 Condensed Combustion products

In the group of the condensed combustion products from a solid propellant we can distinguish the group of smoke oxide particles (SOP), and the agglomerates. Both groups take part in the primary smoke of a plume and derive from a different way of combustion of the metal. The agglomerate is originated by a heterogeneous oxidation of the metal particle while travelling in the core; the SOP is caused by the gas-phase combustion of the metal drop. The size of the SOP fraction is conventionally located in the sub-micrometric range. Its composition is mainly oxidized metal and carbonaceous soot, featuring a bimodal distribution. Agglomerates are drops containing a mixture of the metal and its oxide. They can have a multimodal distribution depending on their chemical composition, combustion process and propellant formulation.[1,9,18,21]
Metal agglomerates feature different steps in their lifetime:

- at the release of the burning surface (incipient agglomeration);
- in the core flow, after possible breakup immediately after emission from the burning surface;
- at the inlet of the nozzle throat (the result of core flow evolution for all agglomerates at any section);
- at the exit of the convergent-divergent nozzle, after breakup and growth.

The agglomerate release from the burning surface represents the initial condition of its evolution throughout the rocket. A characterization of just-released CCPs by the propellant can be carried out from burning of strands in combustion vessels and quenching appropriately the agglomerate.[2,11,13] The study also collected several literature sources regarding pressure dependence of CCP size, showing an increment of mean size as the pressure grows in the combustion chamber. Typical behavior can be observed in Figure 1.
When agglomerate burns inside the core of a rocket, it is subjected to several effects. The agglomerate, after the release from the burning surface, is still rich of metal and further oxidizes in the core of the rocket, till it reaches the nozzle. At the instant of release from the burning surface and in the nozzle it is subjected to viscous stresses which overcome the critical Weber number of the metal drop, leading to atomization with adverse effect on the pressure which reduces the velocity in the core flow.[18] The fact that the agglomerate can be atomized just after the release from the burning surface favors the combustion of the metal itself and the global efficiency. Atomization depends on combustion chamber pressure and L/D geometric ratio. The SRMs with low L/D ratio are prone to generate larger agglomerates with potential release of unburned metal.[18]
Inside the nozzle, condensed products undergo further modifications. Particles are trailed by the accelerating flow but feature a velocity and thermal lag. A relative velocity is generated between gas and particles. If the behavior of a single droplet is considered, particles find the conditions for breakup both in the convergent (subsonic) and in the

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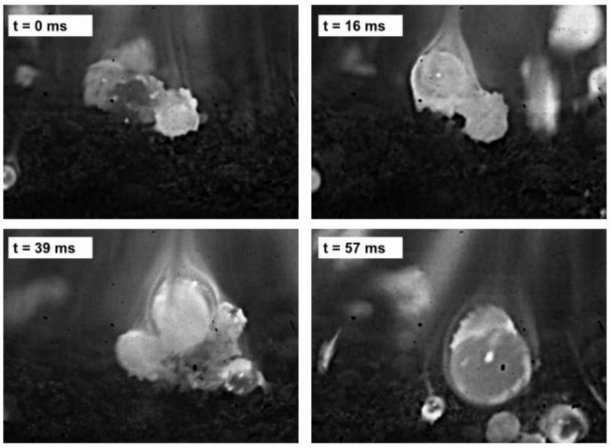

Figure 1: Typical aggregation-agglomeration process at the propellant surface for a HTPB/Al/AP formulation. Courtesy of.[17]

divergent (supersonic) section.[6] The Weber number of particles rapidly increases in the proximity of the nozzle throat, reaching the critical limit for breakup. Collection from plumes[14] revealed that the size of the agglomerates is expected to increase as the throat diameter is incremented. Otherwise, if a cloud of particles is considered, turbulent mixing and differential velocity between particles of different size generate the conditions for growth due to collision,[19] in particular in the convergent part.

2.2 Collection Technique

CCPs collection from the nozzle gives an insight into the agglomerate evolution that takes place in the exhaust gases before exiting the rocket. These techniques are useful to evaluate the two-phase flow losses, the combustion inefficiency, the particulate radiant heat transfer, the particulate acoustic damping, and, the rocket plume structure.[7,20] The collection of condensed combustion products during rocket tests is a particularly difficult task because of the extremely high flow temperature and velocity in the proximity of the rocket nozzle. According to Kessel,[15] placing the collecting system well behind the rocket nozzle, where the flow has become slower and colder after expansion, would be ineffective since the exhaust particles may react with air and depart the exhaust stream before capture. Therefore, collection shall take place preferably near the rocket nozzle, meaning that high temperature and velocity have to be dealt with. According to,[15] collected particle size did not depend on combustion chamber and nozzle exit pressures, metal particle size before combustion, propellant composition, expansion ratio, and residence time.

In the past decades, authors main ideas consisted in the use of an impinging surface, capable of capturing the particles in some different ways.[3,7] This kind of collection assumes that the morphology of the impinging particles is not altered by the impact with the capturing surface and the sample, though limited, is a representation of the total particle population. However, Brown and McArty[3] pointed out that the possible effect of shock waves and particle growth in the exhaust plume, leading respectively to liquid particle shattering and coalescence, were not taken into account. In other cases, operators tried to collect as much material as possible by enclosing the rocket in collection systems or by operating suction devices with particle extraction features.[10,24] The tank collection method gave a measure of the detailed size distribution averaged over the duration of firing,[24] highlighting that the particle size distribution is pressure-dependent when aluminized propellants are used (i.e., lower chamber pressure resulted in smaller particles). On the other hand, aluminum particle size and aluminum percentage in the propellant formulation had no effect on particle size distribution. Some patents[4] with the scope to remove solid pollutants from rocket plumes were produced in the past. Such systems handled the full plume of the rocket and performed a particle-gas separation by using liquid quenching and filtering. This approach features some advantages such as the capability of managing the full plume amount, resulting in better representation of the particle statistics. However, the size of the apparatus is large compared to the tested rocket and were not conceived to maintain the properties of the collected material. Kessel[15] studied several devices (subsonic and supersonic) having the capability of particle capturing by means of suction or ingestion. The capability of supersonic ingestion was always considered an added benefit since the absence of a bow shock at the front of the probe could avoid particle deviation and alteration. As a drawback of such configurations, these devices are capable of managing a limited mass flow rate and collect particles after filters. Moreover, the sampling is local and is prone to localized effects, being the plume non homogeneous.

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3. Concept Development

3.1 Design Issues and Requirements

The general requirement consists of the development of an experimental capability to analyze the condensed combustion products exiting from the nozzle of a metalized solid rocket motor. Critical aspects of the environment and the design are hereby highlighted.

- the probing device has to survive to a severe environment and at the same time it should supply a representative data set of the probed particles. The drawbacks of dealing with a supersonic hot flow make the design and operation of the instrument quite sensitive to deviations from nominal behavior. A possible solution could be to locate the probe far downstream from the nozzle exit, i.e. 60 to 120 exit diameters from the rocket motor. The flow is cooler and slower thanks to mixing with ambient air.[7] However, the complex phenomena that occur when the rocket exhaust plume mixes with air, namely, shock waves and chemical reactions with oxygen,[25] do not guarantee that the collected particles are representative of nozzle exhaust. Moreover, according to Kessel,[15] condensed particles might depart from their original track as the plume mixes with air. Expected properties of exhaust rocket core flow expanded through a nozzle, using a shifting equilibrium expansion model, are listed in Table 1.
- the supersonic medium in which the CCPs are suspended is likely to generate a bow shock in front of any object placed in the wake. Hence, the collection in the plume can be subjected to particle alteration if bow shocks at the front section, internal shocks, and velocity gradients are generated while the particles are still in liquid form. Strong mitigation should avoid particle break up during collection due to strong deceleration, requiring to maintain the particle Weber number below the critical threshold (20-30). Considering the necessity of a collection at the nozzle exit, it is possible that particles are still in liquid form. If aluminum droplets are in the flow, the metal melts at 933 K which is much lower than expected gas temperature. Even in case of alumina droplet, the melting point is around 2300 K. Moreover, since particles feature a non-negligible thermal lag with respect to gas phase, real temperatures may be higher. Hence, any strong shock should be delayed until the flow is sufficiently decelerated and cooled down to have solid particles inside.
- the probe should be a small system, easy to handle from the point of view of the size but the capturing process must ensure that the collected particles are representative of the global population, even in case of treatment of only a part of the plume.
- the collection methodology should enable the characterization of particle without chemical alteration, featuring an inert collection medium.

3.2 Probe Design

The concept development focused on the merging between the supersonic probe patented by Kessel[15] and a gas scrubber by Carns et al.[4] The former enables to swallow a localized hot supersonic flow in proximity of the nozzle and slows and cools it down by means of a cold gas. The latter gathers all the particles that come out of the rocket nozzle, but it is a much larger system. This is a problem not only from the point of view of the test chamber size available, but also because of the large mass flow rate to deal with. In fact, if the pressure inside the tank increases too much, the flow will choke leading to the formation of undesired shock waves. This problem can be overcome by generating a flow that moves in the same direction as the exhaust plume by means of a fan. This solution cannot be considered since large mass flow rates are involved. In addition, the collecting tank[4] injects a quenching liquid in normal direction with respect to the supersonic flow. This would generate a bow shock wave[26] which could break the particles.[23]

The probe will be inserted in the rocket plume and will act as a collector of the exhaust gases while the scrubber will act in a separation chamber, where particles will be segregated from the gas using liquid sprinklers spraying the quenching medium. An heat resistant inlet tip swallows the exhaust flow in proximity of the nozzle. After deceleration

Table 1: Theoretical exhaust condition. Propellant wt.% is AP 68%, Al 18%, HTPB 14%. (Cea code by NASA).

M, [-]	**P, [bar]**	**T, [K]**
3.23	0.53	2226.7

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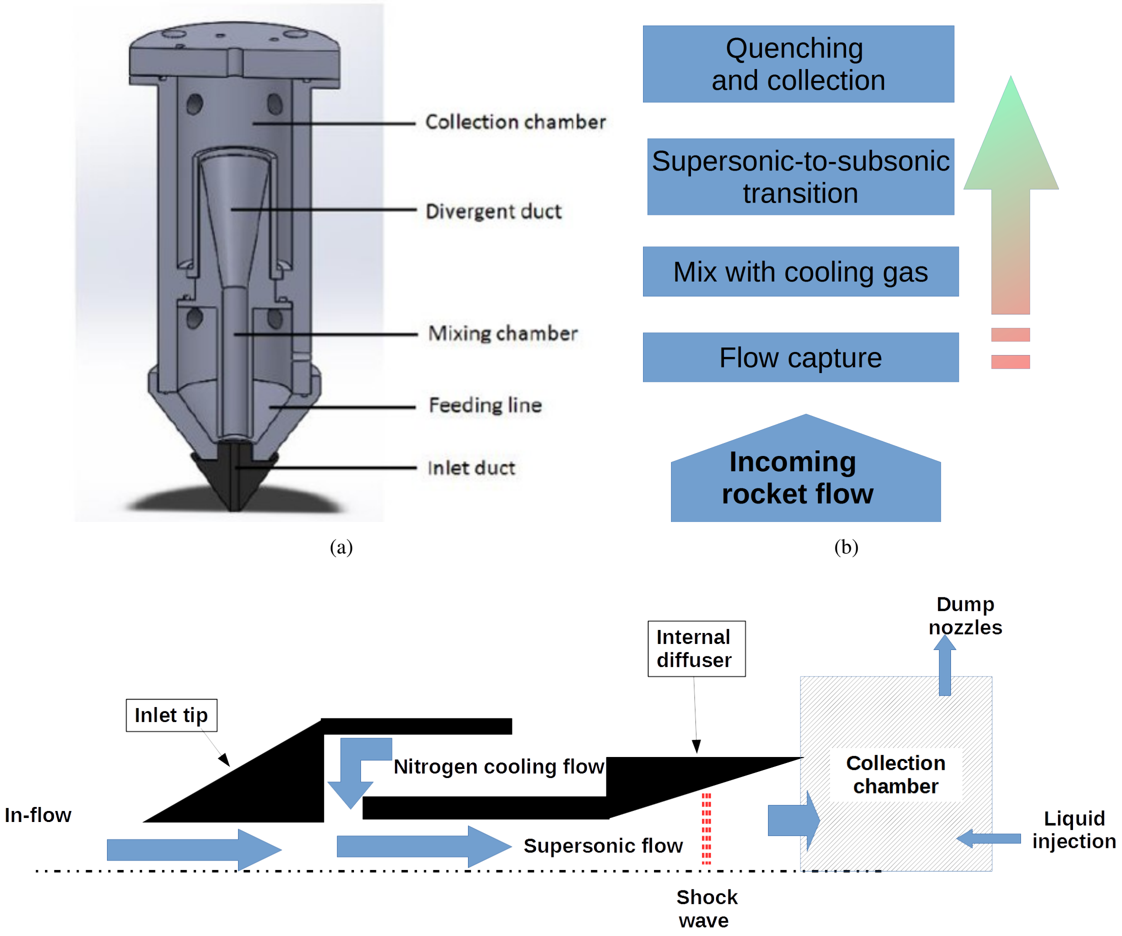

(a)

(b)

(c)

Figure 2: SPLab supersonic probe: (a) construction scheme; (b) logical work flow; (c) internal scheme of probe design concept.

and cooling by supersonic mixing with a cold inert gas, the supersonic-to-subsonic transition occurs in a divergent channel by means of a shock wave. The location is defined by the downstream pressure. Exiting the divergent, a quenching spray captures the particles, whose temperature across the shock wave is increased, and stores them in a pressure-controlled tank. The probe is assembled vertically, with the flow coming from the bottom. The schematic mechanical drawing and the flow chart of the design are shown in Fig. 2(a) and 2(b). A feasibility study of this system was performed building a numerical model based on the Shapiro method and normal shock wave theory. Refer to Maggi et al.[16] for further details.

The tip must withstand a stagnation temperature of about 3400 K. Graphite is considered for construction and thermal analysis guarantees its survivability, even though the high temperature reached during the operations may suggest a replacement of the component every one or two tests (lasting up to 1 s). The inlet diameter of the tip is set to 0.5 cm, to guarantee a sufficient amount of condensed combustion products entering the probe. The duct shall be as short as possible for two different reasons: firstly, the deceleration of the flow in the inlet duct makes the temperature increase in a significant way; secondly, the turbulent boundary layer growth together with a shock-train system may reduce the effective cross-section area up to a point where the flow becomes choked and a bow shock wave develops in front of the probe tip. This "unstart" of the probe will no further allow the representative collection of the alumina particle. The operational scheme of the probe is shown in Figure 2(c). The inlet shape must prevent a bow shock. Hence, the external surface of the inlet tip should have an inclination ensuring an attached shock. An inclination of 34° was selected (shock inclination is easily derived) for construction reasons. Moreover, since, according to,[15] a bow shock wave would form in front of the collection system if rounded nose is used, a sharp inlet angle was manufactured.

Several approaches were modeled to decelerate and cool down the supersonic hot exhaust flow containing the condensed combustion products. It seems to be impossible to simultaneously decrease Mach number and temperature of the flow by varying the cross-section area of the duct, since while temperature decreases the Mach number increases

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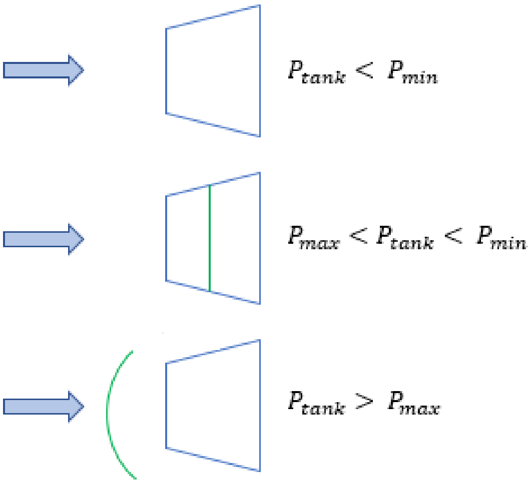

Figure 3: Position of the shock wave inside a divergent duct as a function of the back-pressure.

and the subsequent shock wave causes a strong temperature jump. If the temperature of the particles before the shock wave is compatible with the requirements, extremely high values are obtained afterwards. Decreasing the temperature by means of a cooling jacket yields the same results. The Mach number increases, thus one or more shock waves would be necessary to decelerate the flow, leading to a temperature rise and possible particles alteration. The only approach that allows decreasing Mach number and temperature at the same time seems to be a mixing between the exhaust gas and a cold inert gas. However, according to,[15] complex phenomena are involved in the process, such as boundary layer growth and formation of oblique shock waves. It is extremely important to avoid the choking of the flow caused by merging of different boundary layers or stagnant presence of the cooling inert gas inside the mixing chamber, leading to the generation of a bow shock wave in front of the probe. Hence, the mass flow ratio between the ingested flow and the coolant flow, the initial velocity and temperature of the coolant flow have to be critically chosen throughout a feasibility study: refer to.[16] The former can be controlled if the channel has a divergent shape while the latter can be prevented by injecting the dilution gas at high speed. Radial injection, and hence a radial mixing, was selected as the solution to achieve the best mixing (see Fig. 2). During the design phase, the coolant gas was assumed to enter a stagnation chamber and reach the sonic condition in correspondence of the area entering the mixing duct. Hence, a brief expansion assures a supersonic flow when encountering the ingested one. The Mach number shall approach unity in such a way that the subsequent normal shock wave in the divergent will not cause undesired temperature jumps. Temperature shall be lower than 933 K before the shock wave to avoid particles melting and breakup.

In order to generate the shock wave the probe is linked to a tank, whose pressure is selected in such a way that the discontinuity is generated as close as possible to the throat to avoid flow acceleration in the divergent duct. The inlet conditions of the divergent correspond to the conditions at the end of the mixing chamber. The minimum and maximum values of the tank pressure P_{tank} that guarantees the presence of a normal shock wave inside the divergent duct can be easily computed. The highest value P_{max} is the one that generates the shock wave at the probe inlet, equal to the value of pressure at the end of the duct. If the tank pressure is higher the shock wave is pushed outside of the probe. The minimum value of pressure P_{min} can be obtained by expanding the supersonic flow through the divergent duct and then placing a shock wave at the end of the duct and it is equal to the value of pressure after the shock wave. If the pressure tank is lower than the minimum pressure but at the same time larger than the pressure reached by the flow through isentropic expansion P_{iso}, the flow is over-expanded and oblique shockwaves will form after the duct. If the tank pressure is lower than the isentropic pressure, the flow is under-expanded and it will keep expanding beyond the duct through Prandtl-Meyer expansion fans. The shock wave will be somewhere in the divergent if the tank pressure is comprised between the minimum and the maximum pressure. The concept summary is shown in Figure 3.

In order to achieve the pressure design value, the collection chamber is provided with a convergent nozzle that is chocked under nominal conditions, meaning that the flow is sonic in correspondence of the minimum cross-section area and, most importantly, the mass flow rate is constant. It is reasonable to assume that the collection chamber is initially filled with air at ambient pressure (no outflow through the nozzle). When sampling begins, the exhaust

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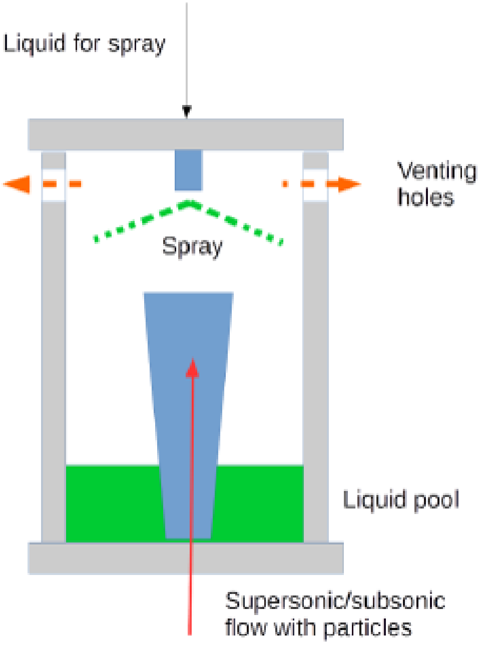


Figure 4: Schematic functioning of the injector.

plume diluted with nitrogen enters the collection chamber, mixing with ambient air. Since the initial value of the back-pressure is 1 atm no shock wave is present and the slightly over-expanded flow accelerates to high supersonic speed in the divergent before entering the collection chamber. The collection chamber pressure rises because of the swallowed mass, therefore air starts spilling from the convergent nozzle. At the beginning of pressurization the outlet flow rate is lower than the inlet one, since the chamber pressure is still low. However, due to the positive net mass variation within the volume, pressure keeps rising. At a certain point the back-pressure becomes sufficiently high to generate a normal shock-wave at the end of the divergent, and as it keeps increasing the discontinuity moves upstream to the design position. When the nominal value is reached, the shock wave is where it is supposed to, and outflow and inflow match.

During the design phase the desired pressure is fixed in order to trigger the onset of a shock wave inside the divergent of the probe. The higher is the pressure, the closer is the shock wave to the beginning of the divergent. Such condition ensures a less strong shock, since the flow will accelerate in the divergent, till the supersonic regime is maintained. Across the shock and after the shock the static temperature will rise. The final temperature is dictated by the amount of cold gas introduced in the mixing chamber and the evaporated amount of quenching liquid. Due to liquid injection, pressure increases together with the outflow. Since the outflow becomes larger than the inlet flow, the collection chamber pressure progressively decrease, and hence the shock wave moves downward in the divergent. On top of the quenching chamber a hollow-cone spray with an angle of 120° ensures the mist capturing the particles and impinging the walls. A deflected spray is selected since it guarantees better stability for varying pressure over a limited interval in the chamber and it represents a better compromise between droplet size (about 100 microns), impinging velocity, and operating pressure. A schematic representation of the injector functioning can be found in Figure 4. Proper mass flow rate is discharged by the injector depending on the pressure differential between the collection chamber and the quenching liquid tank, pressurized by compressed air.

3.3 Quenching Treatment

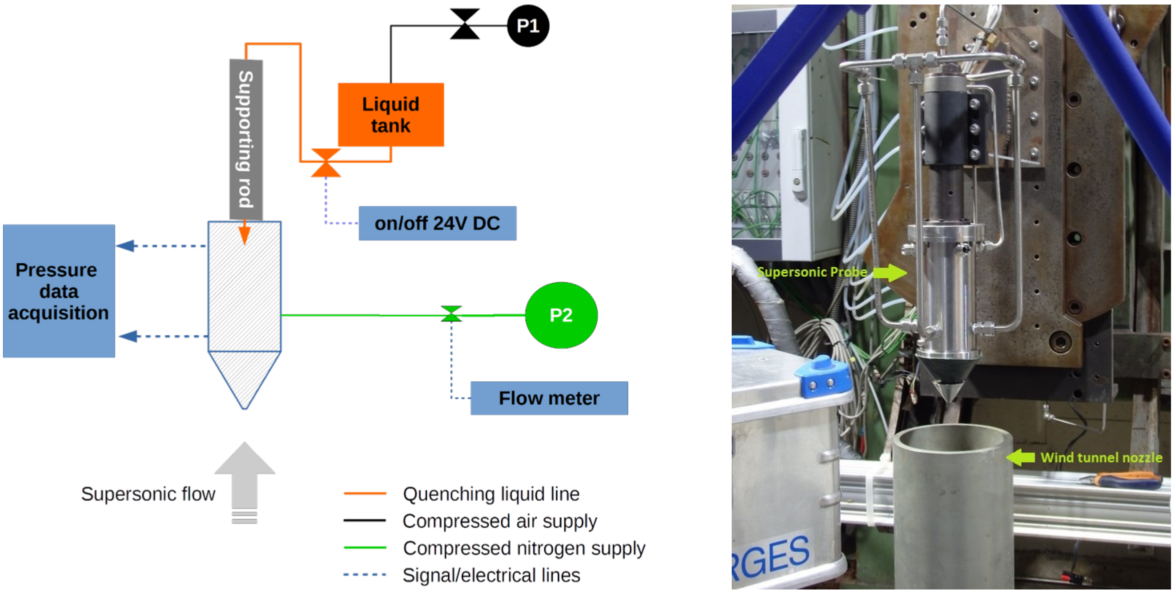
Both the quenching medium and the treatment of CCPs after their capture must preserve the particles. In particular, the conditions of time, temperature and storage in a liquid medium have to be carefully selected to avoid chemical and physical alteration of the CCPs. The liquid in which the powder is stored is the same that is going to quench the particles in the collecting system.

The exhaust gases of AP-based composite propellant rockets are acid since they contain HCl. Aluminum is amphoteric, thus the solution should be as neutral as possible to avoid undesired reactions. However, neutralization reactions produce water and salts: the former might influence the active aluminum content, the latter could mix with the CCPs. Considering the design of the probe the quenching liquid should have a viscosity favoring atomization to be used as

a spray. Moreover, partially evaporization and dissociation of the quenching liquid because of the hot exhaust gases could lead to undesired reaction with the combustion products. Hence, evaporation without dissociating is required.
The agglomerates experience intensive cracking due to the high thermal strain. Some metal is then exposed by these cracks to air and oxidizes, during both particle freezing and storage. If the sample is stored for a few days no appreciable increase in the oxide content can be observed, but if the storage time is as long as a few months the additional oxidation becomes relevant and it can even destroy the particle.
Tetrachloroethylene was chosen as the quenching medium since the consolidated experience gained by the SPLab team in terms of treatment of the CCPs after their capture by means of a quenching liquid. Quenching treatment procedure is confidential.

4. Preliminary Validation Tests

Cold flow tests in relevant environment were performed to assess the fluid dynamic development concept and the collection method and to complete an important qualification step of the measurement technique.
The interface between the SPLab probe with its tank and the DLR vertical test section facility (VMK) is shown in Figure 5. The tank is connected with a flexible hose to a compressed air vessel allowing a pressure inside the tank up to 15 bar. The tank connects to the probe by means of a pipe line featuring an electrovalve that controls the liquid provided to the injector. A relay switch circuit controlled by Arduino (i.e., an open-source electronics platform, which senses the environment by receiving inputs from many sensors, and affects its surroundings by controlling lights and actuators), dictates the electrovalve opening and the closure, assuring the correct functioning of the injector for 1 second. A nitrogen tank supplies the secondary flow, entering the probe by three holes in the stagnation chamber.



(a) (b)

Figure 5: POLIMI-DLR Interface: (a) overall scheme; (b) details of the implementation.

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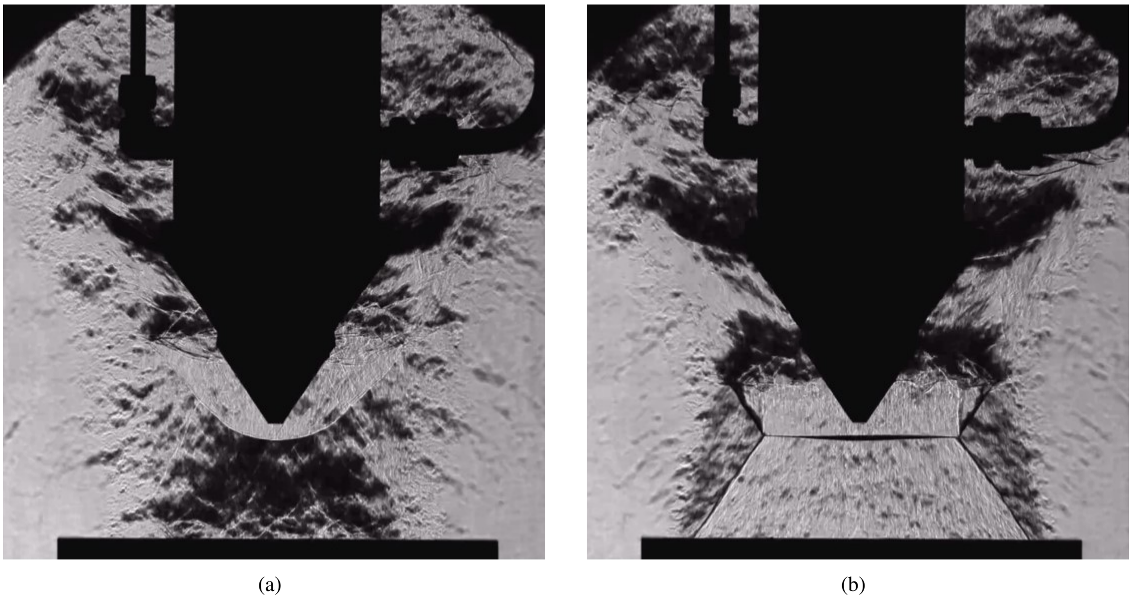
(a) (b)

Figure 6: Schlieren images of the VMK tests. Moments of the starting transient: (a) initial bow shock; (b) bow shock disappearance. Test at 15 bar.

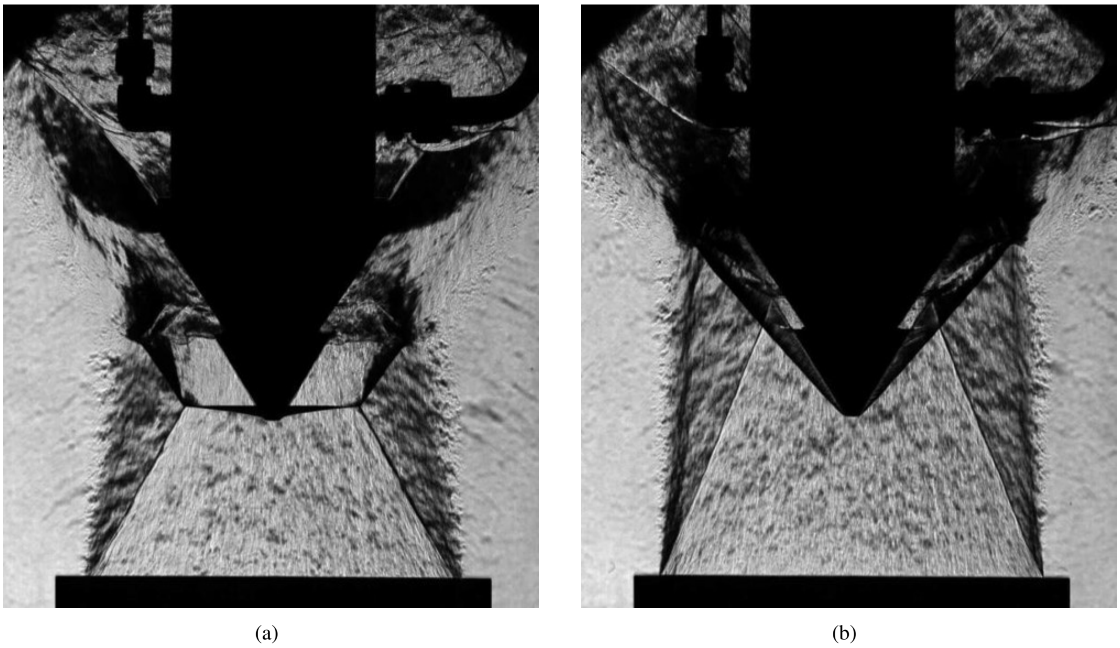
(a) (b)

Figure 7: Schlieren images of the VMK tests at (a) 15 bar; (b) 25 bar.

The required nitrogen mass flow rate is controlled by a Bronkhorst flowmeter (Bronkhorst IN-Flow F-116BI-IIU-90-V). Pipings and transducers (i.e., measuring the pressure inside the stagnation chamber and in the collection chamber) are housed to be protected by the supersonic flow. The probe is connected to a supporting arm which is capable of motion in three directions by translation. The exact centering of the probe with respect to the nozzle and an adequate distance from the exit section can be set. In fact, during the test, it is mandatory to have the Mach disk behind the inlet of the tip to guarantee the correct functioning of the probe.

The vertical wind tunnel located at DLR operates with a contour nozzle granting a Mach number equal to 3 at the exit section and expanding a flow at ambient temperature and at different total pressure.

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4.1 Qualitative Functionality Test Results

The fluid dynamic behavior during the transient start-up is observable in Figure 6. A region featured by an intense density gradient appears in front of the probe inlet (Fig. 6(a)) and readily disappears (Fig. 6(b)). Steady state conditions are shown in Figure 7. At the inlet tip the bow shock is not present uggesting supersonic flow with the inlet duct. The inclination angle of the tip externally guarantees an attached shock wave. A straight flow, key point of a contour nozzle, and the Mach disk at different location with respect to the probe inlet section corresponding to different total pressure can also be appreciated.

4.2 Qualitative Collection Method Test Results

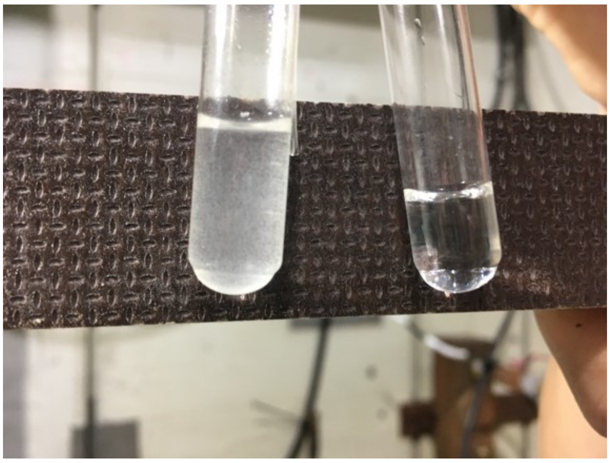

Figure 8: Qualitative results for the collection test: on the left tube with water and seeded particles; on the right tube with water.

The collection technique is tested featuring supersonic cold flow seeded with micrometric magnesia particles. Inside the collection chamber quenching liquid spray collects the condensed combustion products from the decelerated and cooled flow. Considering the operating conditions of the VMK, an ad-hoc tip was manufactured to match the nominal condition in terms of ingested mass flow rate and mass flow ratio. As a result a smaller in diameter tip was created. Qualitative results in terms of successful collection test is highlighted in Figure 8.

5. Conclusion

An innovative intrusive technique for the collection of the CCPs in the proximity of the rocket nozzle was developed. The small device is put in the proximity of the nozzle to capture condensed particles before they react with the atmosphere and undergoing modifications due to velocity gradients or shock wave. The system design is very compact to limit incoming heat flux and influences on the external flow field.

The probe nose has a conical shape. This leads to the formation of attached oblique shock waves, allowing the rocket plume to enter the inlet duct while it is still supersonic. The flow is diluted with a cold supersonic inert gas. The resulting flow mixture is close to critical conditions and relatively cold. The gas enters a divergent nozzle where it crosses a normal shock wave, set by means of a back pressure. The flow keeps decelerating before entering the collection chamber, where a quenching liquid spray collects the condensed combustion products from the cold subsonic flow. The chamber is provided with an exhaust nozzle in such a way that the combination of inlet gas and outflow guarantees the back-pressure necessary to generate the shock wave in the divergent. Tests performed at DLR could validate the working principle of the collection technique in cold-flow tests at a representative Mach number.. Supersonic cold flow tests and Schlieren visualization enabled to infer the transient and the steady state conditions. In particular, the bow shock in front of the inlet during the start up phase and the attached shock wave during the nominal functioning were appreciated. The collection method validity was also verified. A seeded supersonic flow was operated and particles were eventually collected.

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