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Minerva, igniting the future: a PERSEUS story

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Abstract

In a context of disruptive innovation, CNES, through the PERSEUS (Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique) program of the Direction of Space Transportation, aims to make students aware of the different dimensions of space.
In the long term, the PERSEUS project aims to launch of a 5km apogee bi-fluid rocket with reuse on the basis of LOX/CH4 propulsion through the DREAM ON challenge.
Demonstrating critical technologies and capacities with a launch target in May 2024, the current ongoing core project, ASTREOS 1, shall serve as a stepping stone for a reusable DREAM ON sounding rocket. ASTREOS 1 will be the first bi-liquid demonstrator of PERSEUS program, equipped with the LOX-ethanol MINERVA engine.

1. Introduction

Today, space has become a geostrategic issue marked by a strong acceleration of investments and new uses. The space sector as a whole is undergoing a rapid evolution that is being fuelled by two correlated causes that are essentially feeding this dynamic. On the one hand, the digital revolution and, on the other hand, the role of space in this revolution, with more and more satellites providing and transporting a growing flow of data. This evolution is accompanied by an acceleration in the pace of innovation, an expansion of entrepreneurial ecosystems from upstream to downstream and the emergence of new players.

In this context of disruptive innovation, CNES, as the driving force behind France's space ambitions, through the PERSEUS (Projet Étudiant de Recherche Spatiale Européen Universitaire et Scientifique) program of the Direction of Space Transportation, aims to make students aware of the economic, strategic and political dimensions of space, which are more important than ever with the evolution of traditional space to NewSpace, and to encourage entrepreneurship of young people in this field. Through the realization of ground and flight demonstrators of space transportation systems, the objective is to sensitize students to the professions of the sector and to stimulate the innovation and the technological development by the young people within a school or associative framework.
In fact, the ambitious demonstrator projects implemented in the program are in line with the CNES strategy for space transportation. In the long term, the PERSEUS project aims to launch of a 5km apogee bi-fluid rocket with reuse on the basis of LOX/CH4 propulsion through the DREAM ON challenge.

Demonstrating critical technologies and capacities and with a launch target in May 2024, the current ongoing core project, ASTREOS 1, shall serve as a stepping stone for a reusable DREAM ON sounding rocket. ASTREOS 1 will be the first bi-liquid demonstrator of PERSEUS program.

To develop a bi-liquid sounding rocket, one of the paths to success is the mastery of the Propulsion Package, with in particular the testing of the bi-liquid LOX/Ethanol (in a first step) engine, so called Minerva. In this respect, the update and redefinition of the PERSEUS propulsion bench on the Vernon plateau at PERSEUS' partner ArianeGroup will be essential in order to carry out and operate the numerous cryogenic engine and stage tests. From the use of ablative materials to the implementation of a regenerative cooling circuit, different engine evolutions are foreseen to tackle the challenge of the bi-liquid propulsion. The development of these variants will obey to an incremental technological rationale which will enable students and Perseus project to improve their knowledge and master of this challenging field. These evolutions of the Minerva Rocket Engine will feed the versions of the ASTREOS sounding rocket family and also the DREAM ON rocket branch.

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This paper aims at giving an overview of the bi-liquid propulsion activities undertaken in PERSEUS- as well as deep insights for some of them- , of the results achieved so far and the next challenges in front of the PERSEUS program to fulfill this ambitious Agile Roadmap dedicated to the Propulsion package.

2. Propulsion roadmap

For more than 10 years the bi-liquid LOX-ethanol propulsion was studied in the Perseus frame. The name of the engine is MINERVA (Moteur INnovant Experimental pour les Recherches sur les Véhicules Aérospatiaux). In fact MINERVA is a family of engines which will integrate progressive improvements.
The common specification of this engine are the following:

- LOX-ethanol
- Chamber pressure = 20 bar
- Mixture ratio = 1,4
- Vacuum thrust = 5 kN
- Vacuum specific impulse = 295s
- Operating duration up to 25s

The basic configuration of the engine which have been tested in 2016-17 is described in [4] and illustrated by the Figure 1

Figure 1: Illustration of the configuration of the engine

The main characteristics of this configuration are:

- 7 impinging triplet injectors (F-O-F),
- Chamber insulated with ablative protection based on graphite,
- Bench mechanical design (not mass optimized).

The tests performed in 2016-17 demonstrated that the concept is viable, even if some limitations have been observed. Especially the heat transfer rate on the injector plate seems to be too high for long tests and the ignition appears to be poorly reproducible and prone to hard conditions for LOX lead ignition sequences.

From this basic configuration, some important improvements were required:

- Injector robustness and pressure drop decrease
- Mass decrease

In front of these axis several studies has been done and are in progress involving different student teams. These works will be described hereunder.

In parallel with the chamber studies, the other propulsive functions have been studied, especially the pressurization system and the feeding system on the stage, by experimental and computation approaches.

Depending on the technical and calendar risks of each study, the configurations of the successive ASTREOS rocket is continuously adapted. The present assignments of the improvements are the following:

ASTREOS 1 (2024)	ASTREOS 2 (#2025)	DREAM ON
Ablative parts design and manufacturing	Pintle injector	Two positions pintle injector
Lightened engine	Regenerative Chamber	Engine regulation
Tanks pressurization		Embedded igniter

Finally, the validation logic before flight of the propulsive system is also a work axis, through propulsion modelling, Engine tests and Stage tests.

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3. ASTREOS 1 propulsion: recent results

3.1. Ablative parts design and manufacturing (performed by EVERING University at Bordeaux)

The major work achieved is to master the manufacturing process of these two major parts of the engine.
The PTI (Internal thermal protection) is made with phenolic resin reinforced with carbon fiber winding. The throat is made with carbon-phenolic compound in a molding process (small parts of carbon/phenolic resin pressed and heated)
Two PTI have been produced and one throat.
These part are now waiting for engine test validation.

It is interesting to note that, due to fiber reinforcement, the PTI can sustain internal pressure. A pressure test up to 140bar was done. This capacity is not necessary for the ASTREOS 1 configuration. Indeed the metallic envelope will deal with the pressure stresses in the chamber. But this capacity could be useful for a possible further evolution of the engine in which this metallic part would be removed and replaced by an evolved composite PTI.

Figure 2: Pictures of the PTI

3.2. Lightened engine

This work have been done by a trainee from Université d'Evry.
As mentioned above the engine tested in 2016-17 was a bench configuration without mass optimization. For flight, it is mandatory to decrease strongly the mass of the engine.
Indeed the bench configuration illustrated on the figure 3 has a mass of 54kg which is very high for a 5kN thrust.

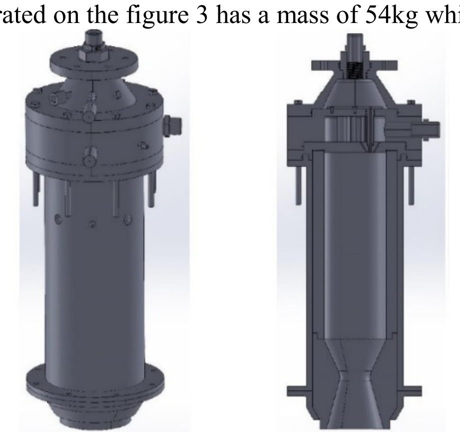

Figure 3: Views of the initial configuration of the engine

The different steps followed were:

- Status of the masses of the different parts
- Analysis of the drivers of the mass
- Redesign of the main parts and mechanical justification
- Drawings

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The main constraint for this work was to keep the internal shapes of the chamber and the injector in order to keep the knowledge gained during the previous engine tests.

The status of the masses showed that 44kg on 54kg were concentrated on 5 parts which have been optimized. A topological optimization of the ethanol dome is illustrated hereafter

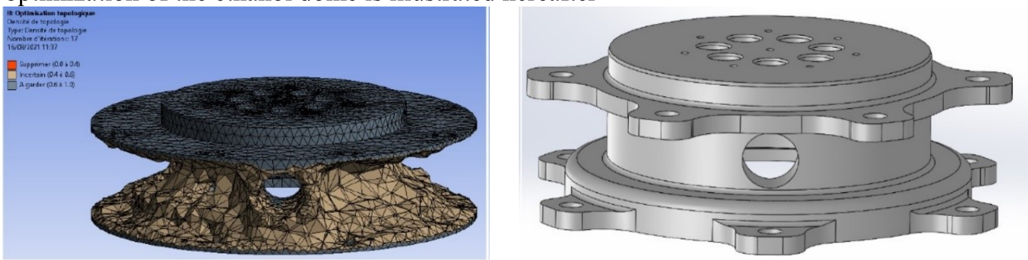

Figure 4: Topological optimization and final configuration of the ethanol dome

The final design after the mass optimization is the following:

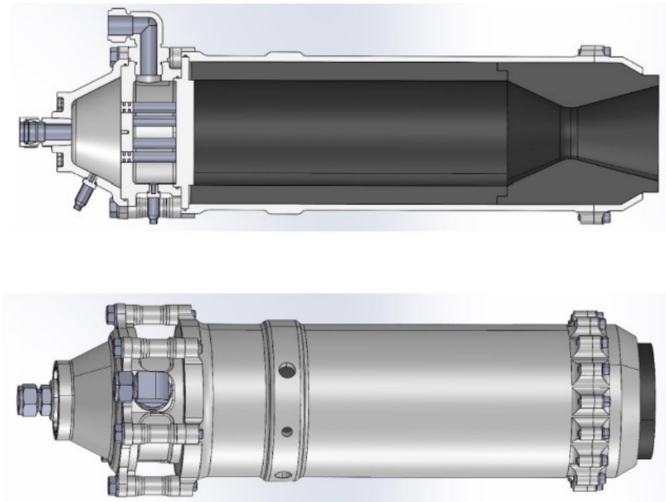

Figure 5: Views of the lightened engine

The final mass reached is 24,5kg, which is satisfactory.

The mechanical justification performed on this design shows that the stresses and the deformations remain acceptable, under 200MPa.

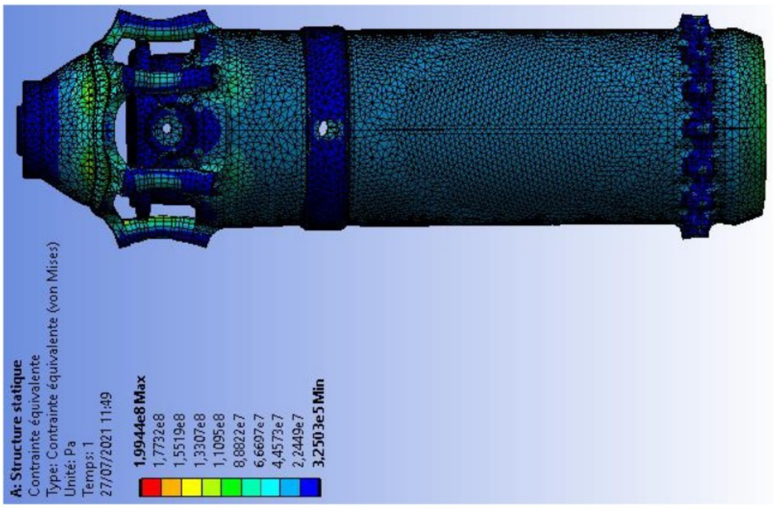

Figure 6: Stress computation of the lightened engine

3.3. Tanks pressurization (performed by INSA Rouen Students)

For a pressure fed cycle it is obviously very important to master the tanks pressurization.
The choice done to use nitrogen for this pressurization as the great advantage of the cost, but also the risk of condensation of the nitrogen in the LOX tank. Indeed at 30 bar the saturation temperature of the GN2 is higher than the LOX temperature.

These studies at INSA Rouen are backed to a bench able to test the GN2 high pressure tank, the pressurization regulator and the propellant tank during the pressurization before flight and during the emptying of the propellant tank.
A numerical simulator reproducing the configuration of the test bench has been developed too in order to dispose of test prediction as well as of a numerical platform in order to test the controller of the regulation valve used to maintain the pressurization level on the tank ullage (SWIL approach).

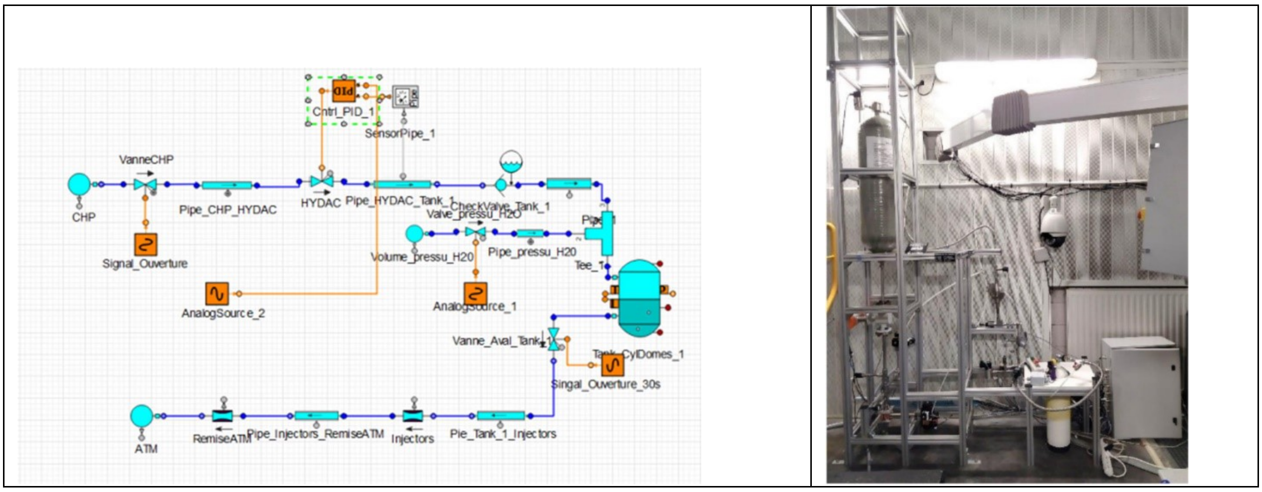

Figure 7: GN2 pressurization system Test bench and modelling

The test bench is equipped with a regulation valve (HYDAC valve) that is current commanded (4 – 20 mA). Via Labview 2 regulation strategies have been implemented using as input the measure of the pressure in the ullage part of the tank.
The first one is a regulation via a PID controller, the second one via a TOR (Tout ou Rien) controller. Figure 8 shows a comparison of the results when the valve is supplied with a pressure of 9 bar and set to regulate around 6 bar.
Results show that some oscillation persist in both solutions a quite high overshoot is presented at the beginning of the emptying of the tank.
In order to evaluate these results, a comparison with a “passive” regulation device (membrane or piston pressure reducer) is foreseen for the next year activity.

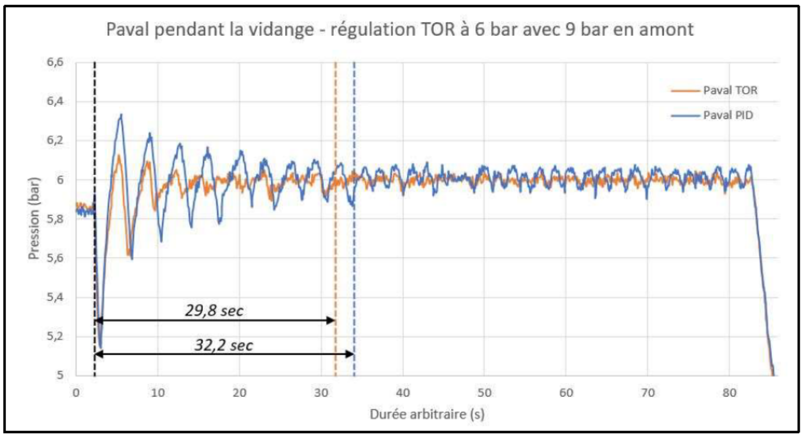

Figure 8: Comparison PID vs TOR regulation

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3.4. Engine thrust frame dimensioning (COSMOS association at Centrale Lyon)

The work consisted in the definition and justification of the engine thrust frame.
The retained solution consists in 4 rods fixed on the two extremities to interfaces flanges that can be connected to the LOX tank lower skirt on one side and to the injection head flange on the other side. The 4 rods are then stiffened with the additions of four couples of cross-arranged stiffeners.

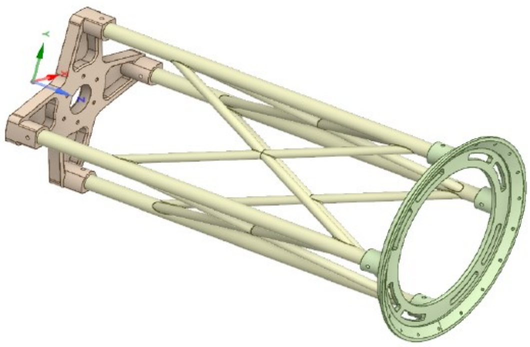

Figure 9: Engine thrust frame layout

The chosen material is Aluminum 7075 (Fortal) for its good elasticity limit and easy machining.

Static simulation shows an acceptable level of strain for the material (positives margins). The dynamic simulation allowed to estimate the first eigenfrequecy of the structure around 100 Hz. If this mode will be judged not sufficient wrt system specification, the frame can be further stiffened with of course a negative impact on the mass that is currently around 5 kg.

3.5 Propulsion modelling (COSMOS association at Centrale Lyon)

A simulator of the complete ASTREOS-I propulsion system has been developed over the last 2 years using the EcoSIM ESPSS software. Figure 10 shows the engine synoptic on EcoSIM environment

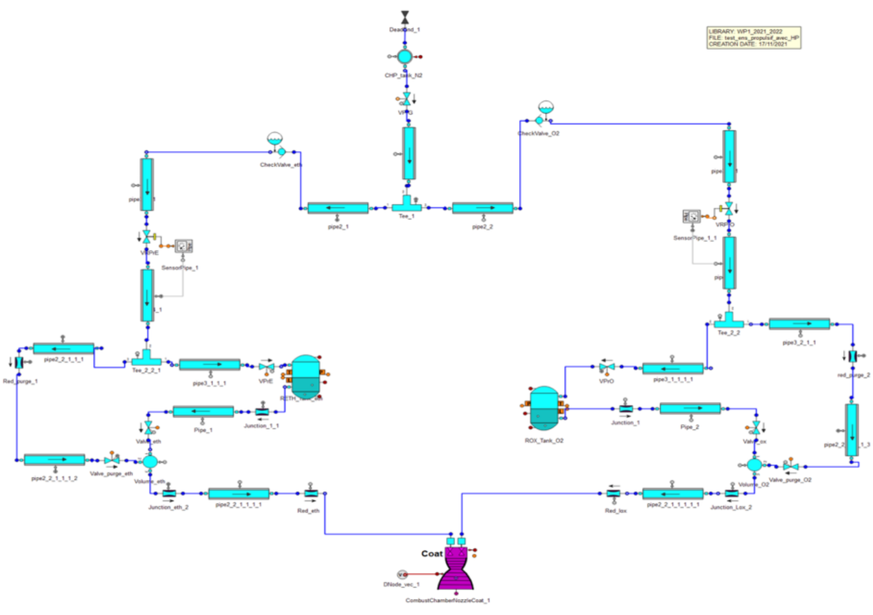

Figure 10: ASTREOS-I Propulsion system EcoSIM simulator

The model has been tuned on the current configuration of the propulsive system of ASTREOS-1:
- GN2 high pressure capacity : 27 l @240 bar
- LOX and Ethanol tank : 47 l @30 bar

- Total flow-rate :
- Chamber Pressure : 20 bar
- Mixture Ration : 1.4

It can simulate steady-state behavior of the engine as well as the tank priming and the chamber ignition sequence. The whole ASTREOS-I mission has been simulated allowing having a first estimation of the Nitrogen and propellant budget as well as the propulsive performances of the engine.
Figure 9 shows a zoom of the pressures evolutions in the chamber and in the domes at ignition as well as the mixture ratio of the propellants.
Figure 10 shows the evolutions of the tanks and HP capacity pressures over the whole mission.

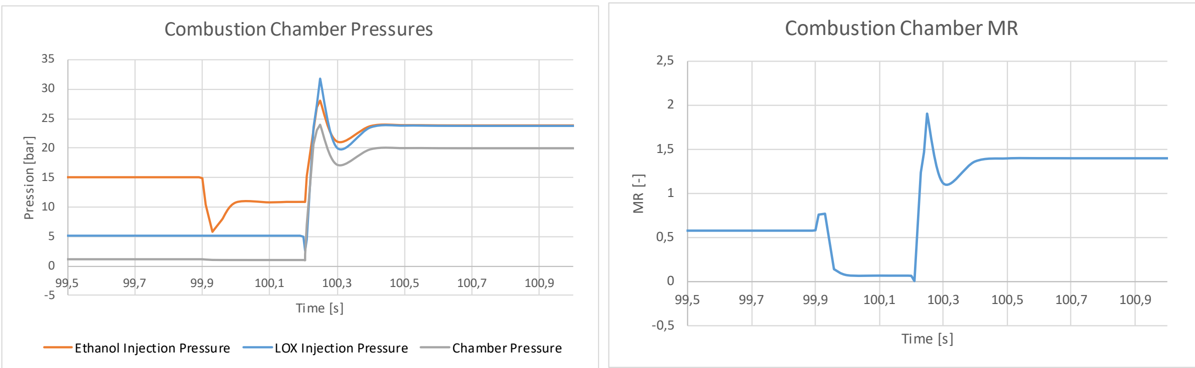

Figure 11: Chamber and dome pressure at ignition, MR at ignition

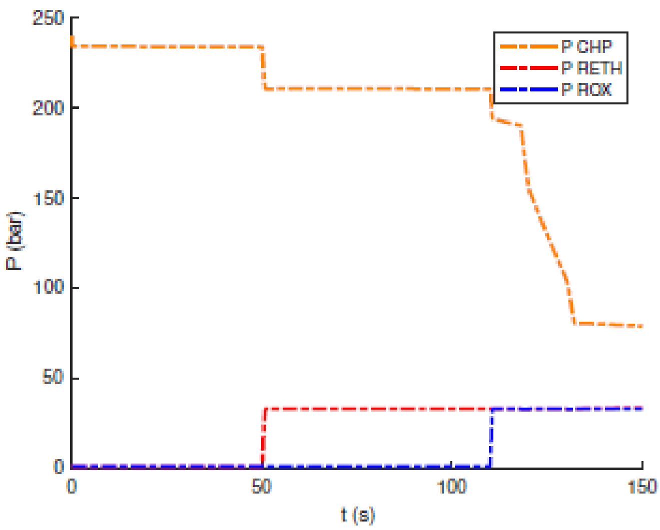

Figure 12: Tanks and HP Capacity pressures during the whole mission

Finally, the model has been used in order to perform a first sensibility analysis on engine performances. The varying parameters chosen for the analysis were: hydraulic sections of the ethanol and Lox calibrating orifices on feedlines, combustion efficiency and thrust coefficient efficiency. Performances were mapped in terms of thrust, ethanol and lox flow-rates and mixture ratio. Figure 11 shows a summary of the evolution of the 4 outputs varying (one by one) the 4 inputs.

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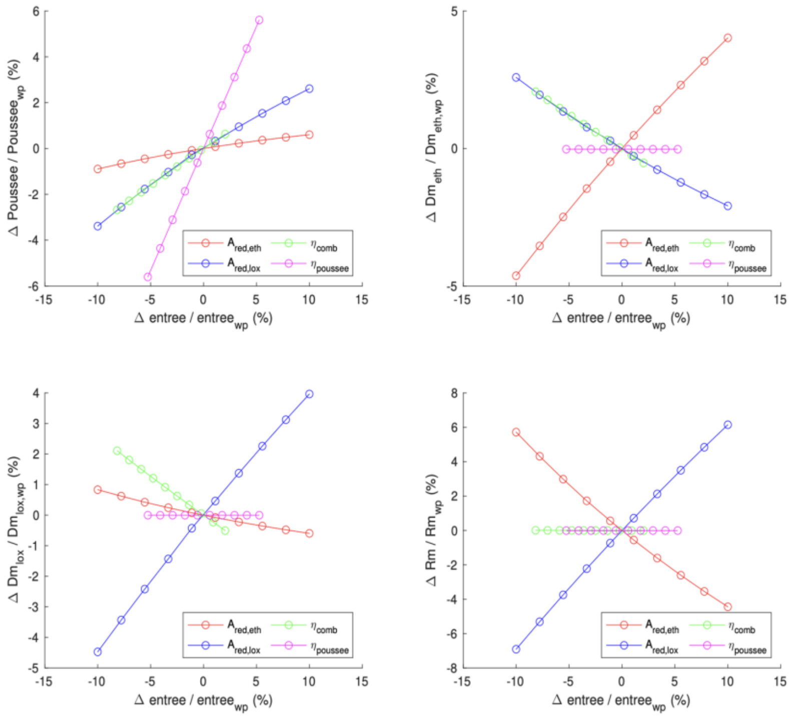

Figure 13: Results of the sensibility analysis of the MINERVA performances

This type analysis confirms the healthy status of the engine simulator and could be used in the future for the activities related to engine tuning. It served also as case study for the bigger and time-consuming activity of the engine domain determination via a Montecarlo analysis (that is foreseen in the next academic year).

3.6. Engine tests

These works were done by trainees in Ariane Group test site in Vernon
For different reasons the test bench on which the engine tests were performed in 2016-17 have been re-installed at Vernon in the Ariane Group test site. This test site is dedicated to rocket bi-liquid engine tests. Several engines were tested on this site for decades (Viking, HM7B, Vulcain, Vinci). So this test bench naturally found its place.

The principle of these tests is to be as close as possible to the launcher configuration:

- 2 propellant tanks pressurized with high pressure GN2 bootles
- Shortest lines between these tanks and the combustion chamber
- 2 on/off injection valves
- 2 on/off GN2 venting valves
- An external igniter (propane torch)

The other devices of the bench, needed for security reasons or for tank feeding and purging, have no impact on the test cycle.

Figure 14: Overall setting of the bench

This configuration requires to master the pressure of the 2 propellant tanks and the pressure drops between the tanks and the combustion chamber.
The pressure of the 2 propellant tanks is regulated by specific valves of the 2 skids.
The pressure drops between the tanks and the combustion chamber need to be characterized through 2 flow checks. In order to ease the setting of the operating point 2 setting valves (CVF1 and CVX1) are installed on each propellant lines. The flow checks allow also to characterize these setting valves.

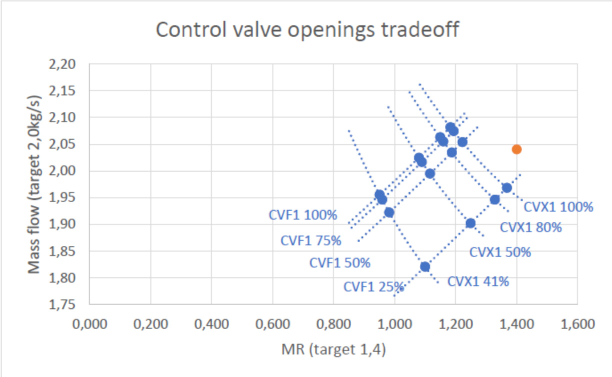

Figure 15: Setting abacus for 40bar tanks pressures

Another important experimental characterization is the times necessary to fill the propellant domes. These times allow determining the valves opening sequence to reach a soft ignition.

The flow checks have been performed during last months and the first firing test is planned mid-June.


Figure 16: Ethanol circuit flow check

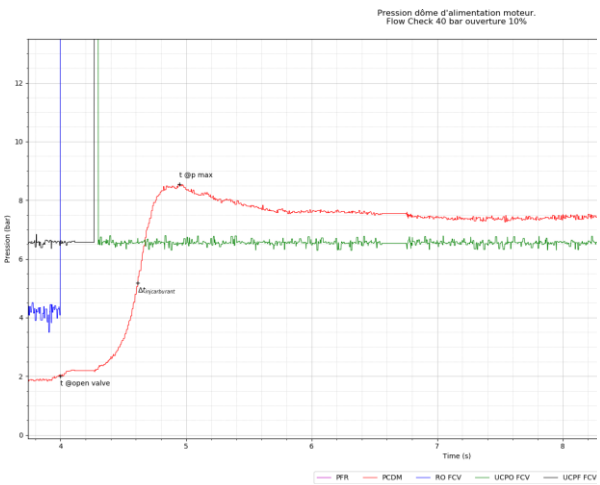

Figure 17: Transient characterization of the ethanol dome filling

After freezing the start sequence, it will be possible to perform the characterization tests of the new PTI and Throat presented in § 3.1.

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3.7 Stage tests

These works were done by trainees in Ariane Group test site in Vernon

Several stage functions will need an experimental validation. The simplest way would be to wait for a stage completely integrated and to test it. But this logic is not optimal because:

- The definition of some parts of the stage is not yet defined nor manufactured
- A late validation scenario is risky if a problem is identified
- A lot of functions can be functionally tested without the overall stage on simpler configurations and at a lower cost

For these reasons a progressive test plan has been studied and defined associated to different configurations assembled on a "battleship" stage.
The "battleship" stage is assembled on an external structure as illustrated hereunder:

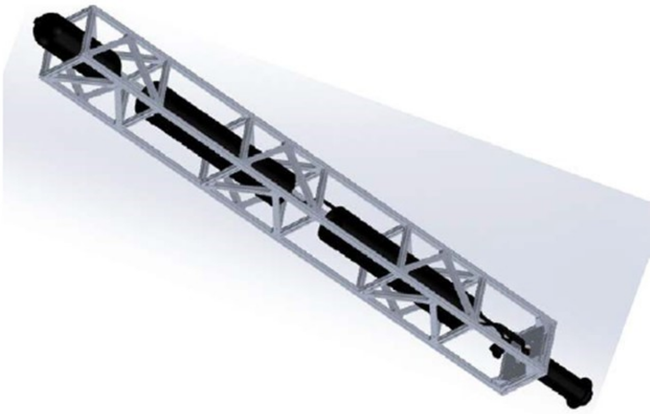

Figure 18: "Battleship" structure for stage tests

A study of the critical functions have been performed in order to identify the different configurations to be assembled and tested. The logic of implementation of these configurations is the following:

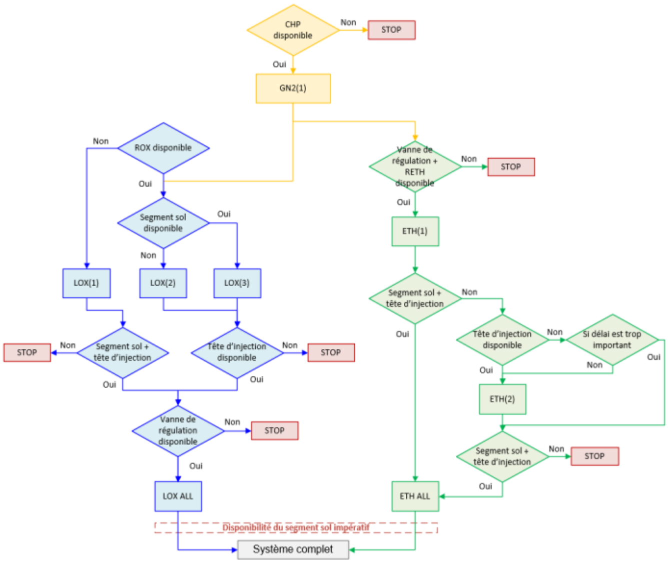

Figure 19: Stage tests configuration logic

As an example the first configuration only includes the GN2 high pressure capacity and the necessary devices to be able to inflate and purge this capacity. It is presently assembled on the external structure and the tests are planned mid-June.

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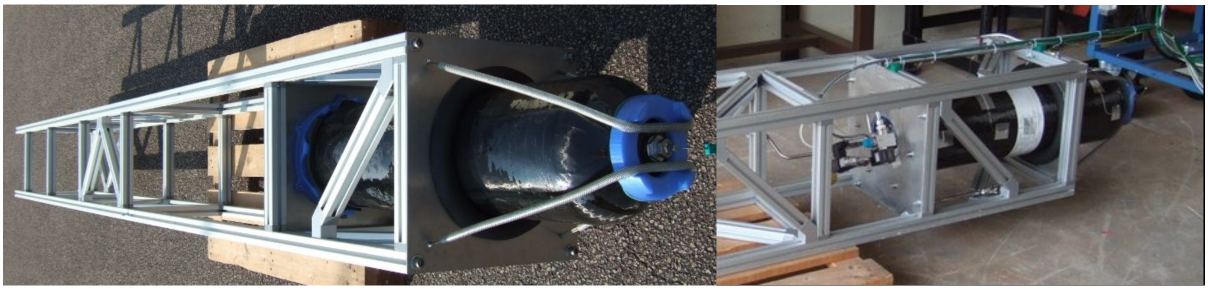

Figure 20: Configuration GN2(1) assembly

4. ASTREOS 2 propulsion : foreseen evolutions

4.1. Pintle injector (performed by ENSAM Lille)

In order to prepare an engine able to perform throttling, the pintle injector axis was chosen several years ago and different groups of students have progressively designed, justified and defined a pintle injector adapted to the chamber body of the Minerva engine.
As a first step, this pintle injector is a fixed one. The possibility of activation of the pintle has been studied by another team (see § 5.1.)
The global structure of this injector is illustrated hereafter:

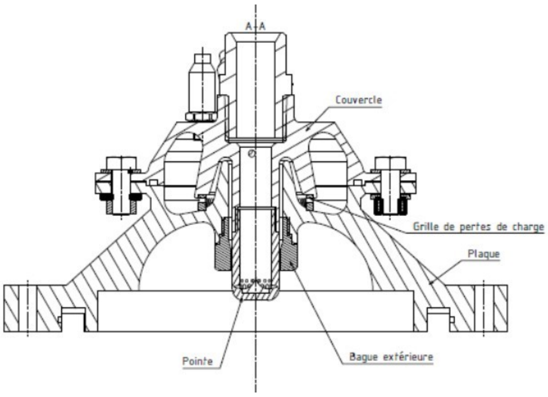

Figure 21: Overall view of the pintle injector

One can see that:

- The pintle itself is screwed in the cover. This authorize to use different material. Especially the pintle is planned to be in TZM. It allows also to test different geometries of pintle.
- For the same reason of exchangeability the outer ring is also screwed in the plate.
- A grid is placed between the plate and the cover to distribute regularly the ethanol all around the injector.

An aluminum mock-up of this design has been manufactured and water tests have been performed in order to check the injection pressure drops and the regularity of the injection of the propellant. The photos hereafter illustrate these tests:

Figure 22: Ethanol circuit flow and Ethanol + LOX circuits togather

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These results are sufficiently satisfactory in terms of symmetry and pressure drops to authorize fire tests as soon as possible.
In parallel, the detailed definition has been achieved and the manufacturing of the items for fire tests will be launched soon.

4.2. Regenerative Chamber

The regenerative chamber technology is generally applied in bi-liquid rocket engine.
At Minerva scale and for the pressure fed stage technology, the interest is probably lower. The manufacturing difficulties and the associated cost is also a factor against the application of the regenerative chamber technology in the Perseus program.

Nevertheless, as it is a major alternative, several students' teams had studied this option (Centrale-Supélec and Centrale Lyon in particular).
In order to limit the manufacturing cost and to explore a new technology, the specification of these studies were to use Inconel 718 additive layer manufacturing. This choice is not thermally optimal due to the limited thermal conductivity of the Inconel 718, but the temperature limit rather high could counterbalance it.

A first study by a Centrale-Supélec team was done for a LOX-CH4 chamber, using a 3D thermal computation in finite volumes, taking into account nucleate boiling in the regenerative circuit:

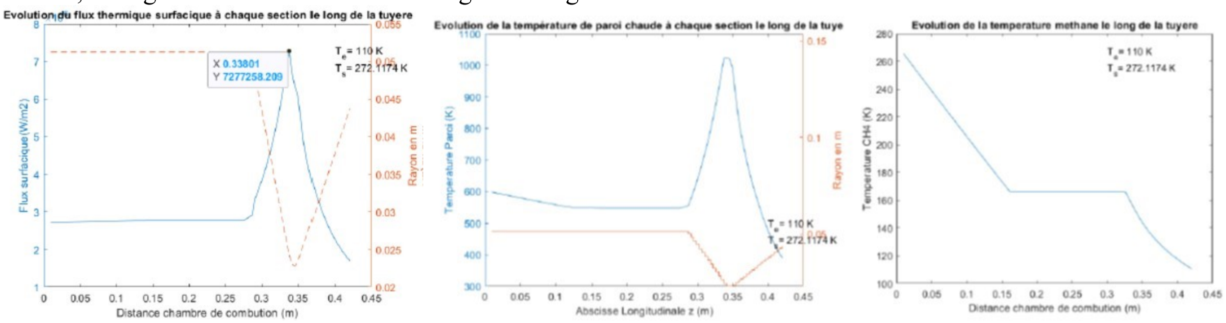

Figure 23: Results of thermal computation of a LOX-CH4 regenerative combustion chamber

These results are not satisfactory for several reasons:

- The hot wall temperature at throat level is rather high,
- The CH4 is diphasic in a large part of the regenerative circuit. This situation is rather dangerous due to the limitation of the cooling capacity and the possibility of thermohydraulic instabilities in this situation,
- The heat flux is higher than the critical heat flux in a large part of the regenerative circuit.

The conclusion of this study is that for this size of engine, this chamber pressure and a CH4 cooling, it is not possible to find a solution without thermal barrier or film cooling inside the chamber.

The following teams had continued this study with LOX-ethanol propellant and taking into account a film cooling.

Particularly a team from Centrale Lyon implemented in similar computations a film cooling in two axial positions in the chamber and obtained the following results:

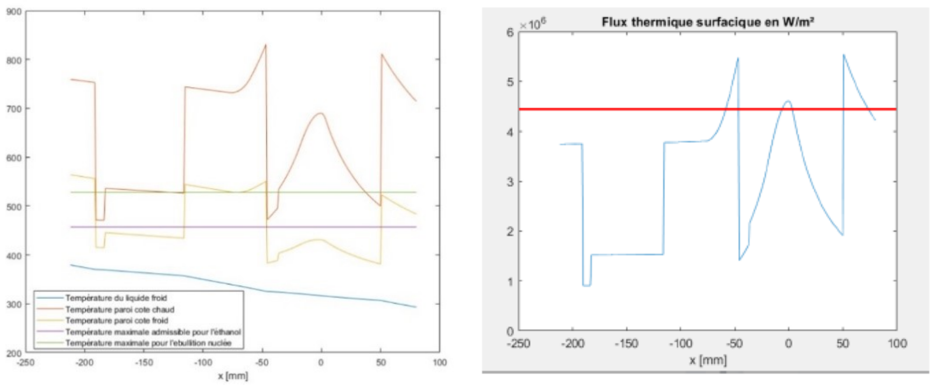

Figure 24: Results of thermal computation of a LOX-ethanol regenerative combustion chamber

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These results, obtained for 2 film injection (1% and 1,5% of the total ethanol flowrate) is very promising because the different design criteria are respected:

- Wall temperature always lower than 850 K
- Ethanol bulk temperature at CR exit lower than Ethanol saturation temperature at 30 bar
- Heat flux lower than Critical heat flux on almost all chamber profile (CHF was calculated according to [5]).

Nevertheless, the overall design of the regenerative circuit remains to consolidate. In particular, the inlet and outlet CR manifold and the injection configuration of the film in the chamber has to be optimized from an hydraulic point of view (minimization of the pressure loss). The following figures show some possible configurations but not all of them allow to take into account constraints coming from the ALM manufacturing.
The hydraulic characterization of the CR as well as the efficiency of the film injection will be part of the activities of the next year.

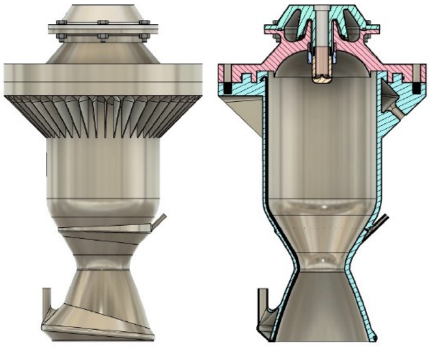

Figure 25: Regenerative Combustion Chamber

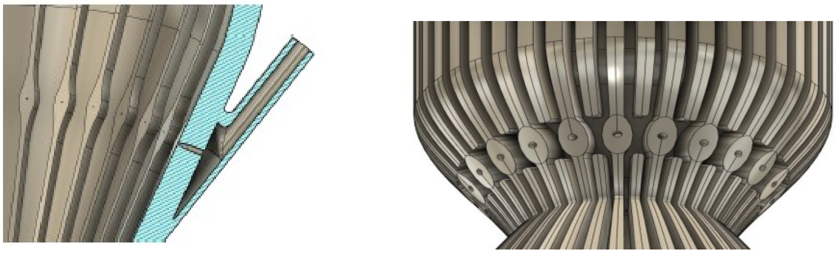

Figure 26: Possible configurations for the film cooling layout

5. DREAM ON propulsion: future improvements

5.1. Two positions pintle injector (ENSAM Aix-en-Provence)

The specification of this 2 positions pintle injector is

- to be able to reach 100% and 60% operating point,
- with a very simple actuation principle, using the GN2 available at launcher level,
- without changing too much the basic pintle designed by ENSAM Lille team.

The global arrangement is the following:

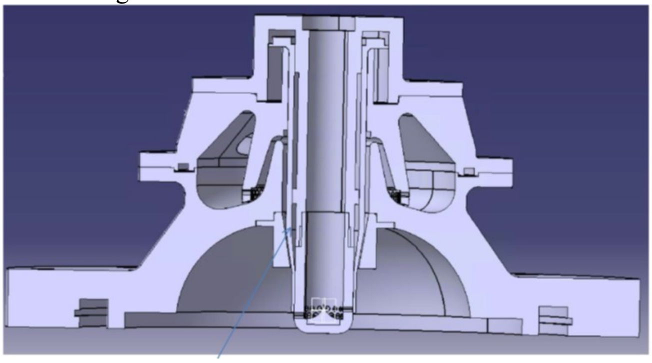

Figure 27: Overview of the actuated pintle injector

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The change of the operating point is obtained by the shift of a tube (the blue arrow on the fire above). This shift had 2 consequences: the obturation of 1 of the 2 raws of hole of the pintle and the reduction of the annular gap of the ethanol injection. The geometry of these 2 effects is adjusted to maintain the same mixture ratio for the 2 operating points.

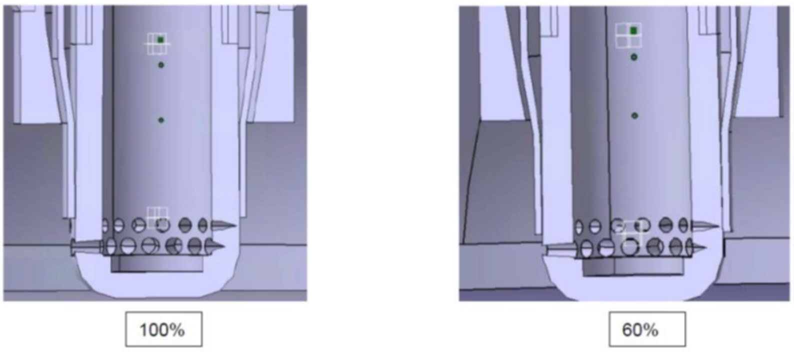

Figure 28: 2 positions of the adjustable pintle injector

The actuation is a single acting cylinder. A spring maintains the tube on the upper position (100%) without GN2 feeding and, when desired, the feeding of the chamber by the GN2 available at engine level pushes the cylinder on its lower position.

Some verifications have been performed by computation concerning some critical aspect of this design:

- Side chains in order to insure limited distortions of the annular gap of the ethanol injection
- Acceptability of the necessary gap between the pintle and the tube wrt obturation effect of the pintle holes
- Thermal dilation of the different parts vs semi-static seals

A mock-up in PLA additive manufacturing have been done and assembled.

Figure 29: Additive manufacturing mock-up of the pintle injector

Unfortunately, the tightness of this mock-up was not sufficient to test it in water.

5.3. Engine throatability (COSMOS Centrale de Lyon)

The possibility to reduce the thrust of a rocket engine on a lower level is a capability that become essential in the frame of a reusable launch system. The propulsion system of DREAM ON demonstrator needs to dispose of such capability. For this reason a group of students from the association, COSMOS of Centrale Lyon starts some reflexion around this topic.

The first configuration studied is a LOX-CH4 pressure fed engine cycle equipped with 2 flow-regulation valves (instead of 2 chamber isolation valves) that allow to control directly the flow-rate (and as a consequence the chamber pressure and mixture ratio) of the propellant entering in the chamber.

A pressure-fed rocket engine is a naturally stable system with a rather fast dynamic (with the hypothesis that the gas pressure regulator used to set the tank pressure can provide a sufficient high flow-rate to match the propellant flow-rate consumed by the engine). The only difficult could arise from the strong non-linearity of the system (especially if we consider very low functioning point).

The approach used on this study was to build a simplify simulator of the engine, identify it by determine numerically the Jacobien matrix of the ODE system around 2 (or more) functioning points and to synthetize a full state feedback corrector (FSF).

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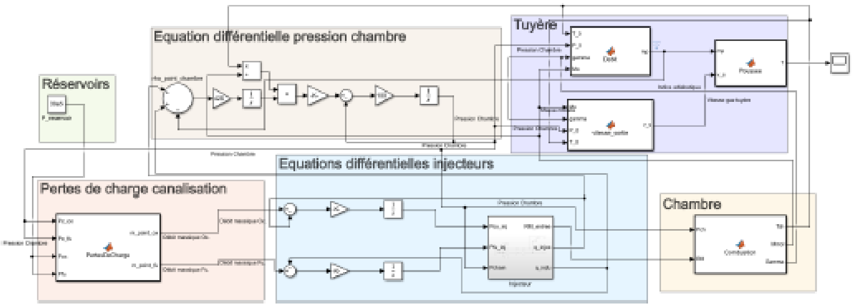

Figure 31: Non-linear Engine simulator (Controller not implemented)

Since not all the states of our systems are measured, the synthesis of an observatory is necessary.
Results of this studie are not yet available.

5.2. Embedded igniter (Polytech Orléans)

The final goal of this work is to make available an igniter which could be implemented in an evolution of the combustion chamber to allow a re-ignition of the engine after a ballistic phase.
It involves the design of the igniter itself, but also the embedded feeding system and the bench able to test the igniter and its feeding system. During the previous years, a first design of the igniter and the bench have been done. The manufacturing and the assembly of the bench are now in progress.

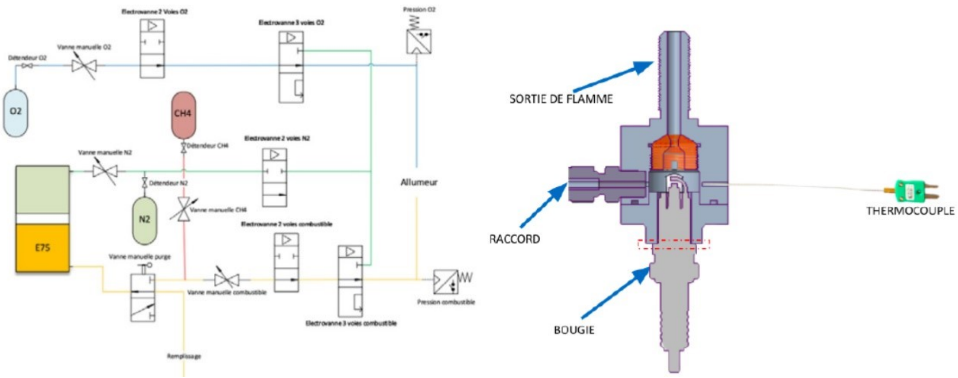

Figure 32: Functional scheme of the igniter bench and design of the igniter

6. Conclusion

All these various results gained by different students from several French universities demonstrate the great interest of the Perseus program. Even if some delays are seen due to the lack of experience of the students and technical difficulties encountered, the program is progressing towards the goal of a first ASTREOS launch with a bi-liquid propulsion. In parallel some important technologies are prepared for the following steps of this program.

7. References

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