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PERSEUS Project

5kN LOX/Ethanol rocket engine fire tests

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Abstract
The PERSEUS project provides the opportunity for motivated students to pool their knowledge to the development of space launchers vehicles. Their applicative work refers to a subscale of a Nano Satellite Launcher which corresponds to an experimental rocket. They can work either through the classical pedagogic frame proposed by their university, either in a space association or as researchers in a laboratory. The CNES, with the help of its PERSEUS partners, is coordinating all these activities in order to achieve a complete life cycle of prototypes: objectives, studies, development realization, reviews, ground or flight test and exploitation.

1. Introduction

PERSEUS is a french acronyme for "Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique". The PERSEUS project was launched 10 years ago [1] & [2] by the French Space Agency. It was organized on three main objectives.
The first one is innovation and testing promising technologies applicable for space launch system.
The second is to rely on students to practice the first objective and, at the same time, to keep their motivation for space through their graduation.
The third objective is to provide a frame to students which enable them to build a set of ground and flight demonstrators in order to confirm or disprove the technology potential.

A first phase up to 2009 enabled to select the most attractive demonstrators which would gather students and 8 partners. Then in order to progress on these ground or flight demonstrators completion, a first agreement was signed for five years. Due to the success of this organization [3], in 2015, a new agreement (also five years duration) was signed with 12 partners (AJSEP, Bertin Technologies, GAREF, ASL, IPSA, ISAE-Supaero, MI-GSO, ONERA, Planètes Sciences, ROXEL, UEVE). The number of students who get involved every year is about 250. They are mainly involved through pedagogic activities and can extend their participation through space associations within their university. An integrated team (EPIP) located at Evry University (UEVE) coordinates all the activities.

2. Propulsion in the PERSEUS context

In the first years of the PERSEUS project, several hybrid rocket engines were design and test. In 2008, the first hybrid experimental rocket (FH01) was launched. Since then, 3 other flights were realized with hybrid engines. But due to major directives, it was decided to stop hybrid propulsion at the PERSEUS project level and to switch to commercial solid engines and bi-liquid propulsion. The project dedicated to the biliquid propulsion study was named MINERVA. The main objectives of this project are:

- Short and medium term: develop, realize and test biliquid engines
- Medium term : realize a test flight with a biliquid engine
- Long term : always envisage a NLV (Nano Launch Vehicule) integration*

It was decided, for the first engine, to use Liquid OXygen (LOX) and Ethanol as propellants.
As any other projects in PERSEUS, MINERVA integrates a lot of student's studies and realizations. As shown in Figure 1, during the last seven years, almost 200 students worked on propulsion inside PERSEUS. Every year, PERSEUS with its partners proposes at least 3 internships on this subject.

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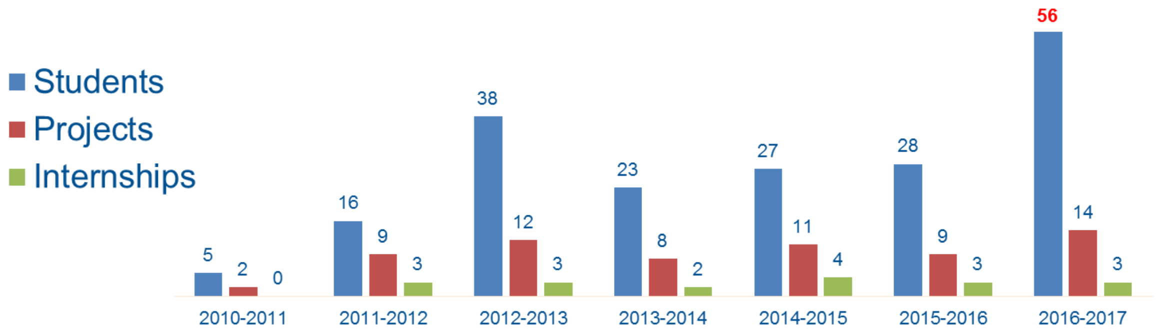

Figure 1 : Students participation in MINERVA project

3. Biliquid rocket engine

The first bi-liquid engine built is a classical biliquid engine using liquid Oxygen and Ethanol, able to propel a dedicated experimental rocket up to 6 km. This MINERVA project is coordinated directly by the PERSEUS integrated team. The purpose of the first engine was to demonstrate the ability of the PERSEUS project to perform fire tests. So, impinging triplet injectors (F-O-F) were designed in order to atomize the fuel and oxidant mixture in a chamber insulated with ablative protection (based on graphite). The mass flow of the 7 triplet injectors was defined in order to have a 5 kN vacuum thrust. The chamber pressure is fixed at 20 bars and the combustion time to 20 s (and up to 25s for an optimal rocket trajectory). The estimate combustion efficiency is around 95% for a vacuum specific impulse (ISV) of 295 s.

The first engine developed by PERSEUS is named **MLE5K-S1a** for **M**INERVA **L**ox-**E**thanol **5k**N of thrust. S1a means that it is the first ground design of the engine. This engine is part of a development family built as follow:

- MLE5K-**S1** : 7 impinging injectors
  - MLE5K-**S1a** : ablative chamber
  - MLE5K-**S1b** : version S1a with cooling system (calorimetric chamber)
- MLE5K-**S2** : Pintle system injector
- MLE5K-**S3** : engine with regenerative system

- MLE5K-**F1** : first flight demonstrator based on the best ground configuration

As shown is Figure 2, the design of this engine is dedicated to ground tests with a minimum safety factor of 6. It allows us to simply change some sub-systems as injection plate, thermal protection or throat. The achievement was made entirely by a small company (STIM) which has contributed by its expertise to the finalization of a design compatible with the conventional manufacturing processes.

Figure 2 : MLE5K-S1a final design

Some other designs were already studied as the MLE5K-S1b as indicated in Figure 3.

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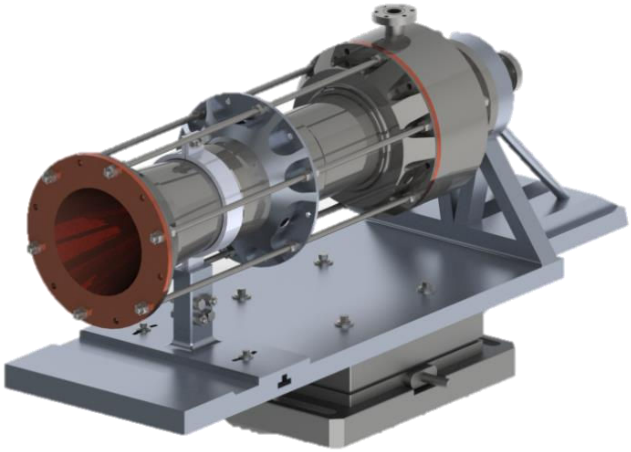

Figure 3 : MLE5K-S1b: Calorimetric chamber design

4. Cold Flow tests

Several water tests were performed at the Martel facilities in Poitier. Theses rather simple tests enable to check the correct mass flow coefficient, the mixing spray shape or any leakage in the injection dome and injector plates. First, a single triplet injector was tested (as shown on the bottom right picture below). After the tests analysis, the complete injector plate was adjusted to fit with our objectives (a pressure drop of 10 bars) and was tested with the same parameters and test bench configuration.

Figure 4 : Water tests in MARTEL test bench (CEAT - France)

On Figure 5, the results of the full injection plate tests. The 2 horizontal straight lines (in red and blue at Cd= 0.65 and Cd=0.7) indicate the mass flow coefficient used for the primary design of the MLE5K-S1a engine. The tests results are 2% (for the LOX side) to 6% (for the Ethanol side) higher than expected (indicated in red or blue points on the figure). All the experimental data's for a pressure drop under 2 bars are unusable (too small mass flow for the debit meter)

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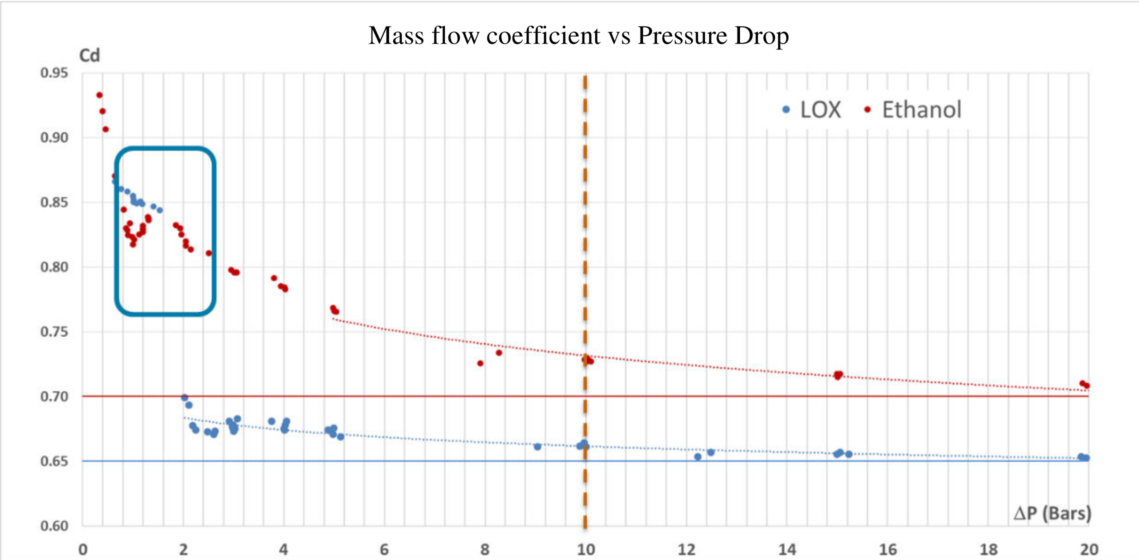

Figure 5 : Cold flow tests results

These cold flow tests were also realized with liquid nitrogen (LOX side) and Ethanol in the ROXEL test bench (Figure 6). These tests allowed us to adjust the test bench configuration before the fire tests campaign.

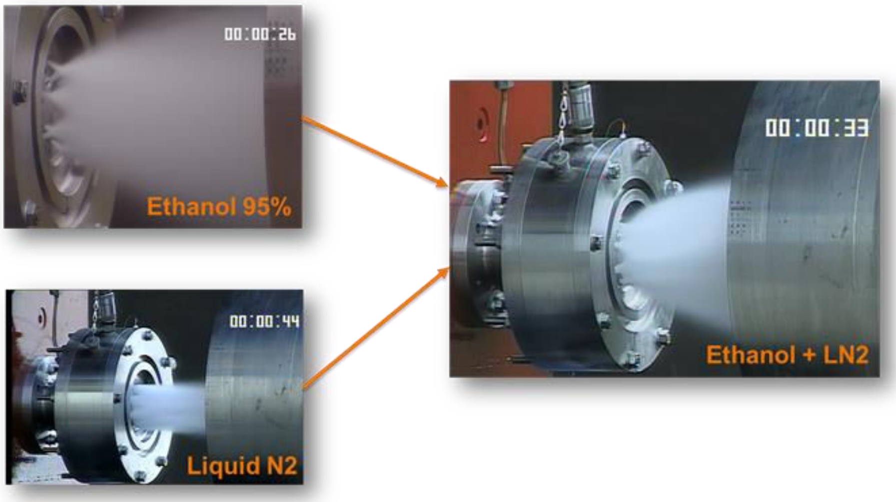

Figure 6 : Cold flow tests (LN2 and Ethanol)

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5. Fire tests

To realize fire tests with the MLE5K-S1a engine using liquid oxygen and ethanol, a specific ground segment is required to monitor the entire propulsive system. It essentially consists in two propellant feeding systems (also called SKID) which were built and operated by the ROXEL team. One Skid is dedicated to Lox feeding and the other one to the Fuel. One can note that the Fuel Skid was designed in order to be multi-fuel compatible: ethanol, kerosene, liquid methane, etc… Both were developed with the support of the CNES R&T department.

Here are some characteristics for these 2 SKID :

	LOX SKID	FUEL SKID
Propellant capacity (L)	50	150
Max Tank Pressure (bars)	50	80
Max Mass Flow (kg/s)	1.2	Ethanol : 1 LCH4 : 0.55 Kerosene : 0.65

Figure 7 : SKIDs main characteristics

Since October 2015, 40 tests were achieved. 31 tests were dedicated to the preparation phase (bench parameters, safety procedures,…) all without any combustion. 3 were used to achieve free field combustion tests (without thrust chamber) allowing us to adjust the ignition sequence.

The 2 figures below show the test setup in the ROXEL test stand. The ignition system is based on a retractable arm with a boiler igniter positioned near the nozzle exit. 45 measures lines are fitted to this entire test setup with a frequency acquisition of 5 kHz.

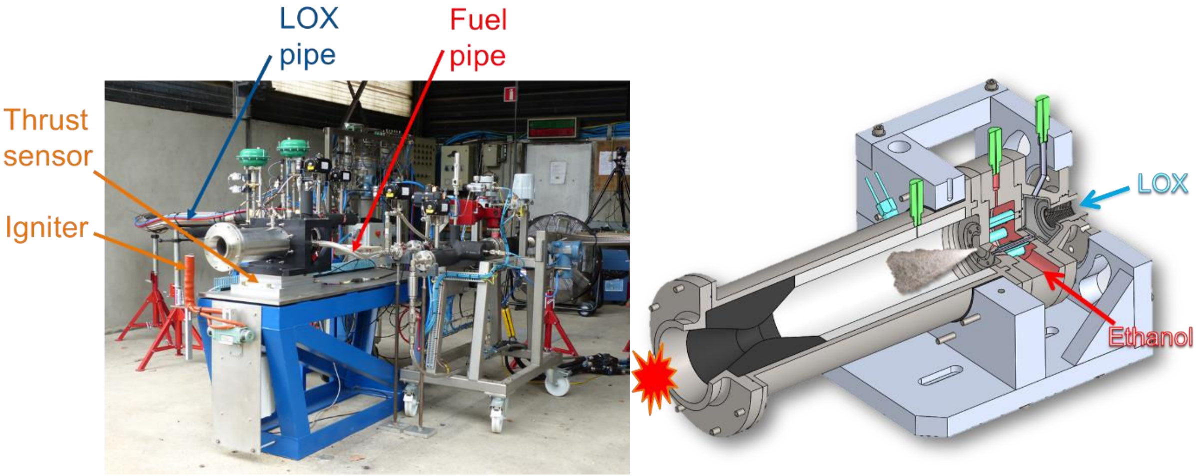

Figure 8 : Fire tests configuration

Since June 2016, 6 fire tests were achieved with the thrust chamber. The first 3 tests were realized with 4 seconds of combustion. It was dedicated to prove the repeatability of the ignition sequence and to determine the degradation rate of different systems (thermal protection, injection plate, carbon throat). Then, 2 fire tests were achieved with 20 and 22 seconds of combustion time. The results of the last test are summarized in the figure bellow (these figures are averages on the entire test).

LOX Dome Pressure	29 bars
Ethanol Dome Pressure	26 bars
Chamber pressure	19 bars
LOX mass flow	1.2 kg/s
Ethanol mass flow	0.8 kg/s
Mixing ratio	1.5
LOX injection velocity	27 m/s
Ethanol injection velocity	33 m/s
Combustion efficiency	≈ 90 %
Thrust	3.9 kN
ISP	198 s

Figure 9 : 22 seconds fire test figures

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Figure 10 : Firing test picture

During this last test, the LOX tank pressure oscillated between 30 and 40 bars (due to an issue in the pressurization control system) leading to a mixing ratio and thrust variation as one can see in Figure 11. The thrust objective of this test was to reach 4.3 kN of ground thrust. The gap between these 2 results can be explained by several reasons:

- A lower combustion efficiency (90 % instead of 95% estimated)
- A degraded injection plate (the same injection plate was used for 6 firing tests)
- A higher combustion temperature (due to an oxygen excess)
- A non-adapted nozzle design (the last part of this nozzle was in metal, so it deteriorated quickly)

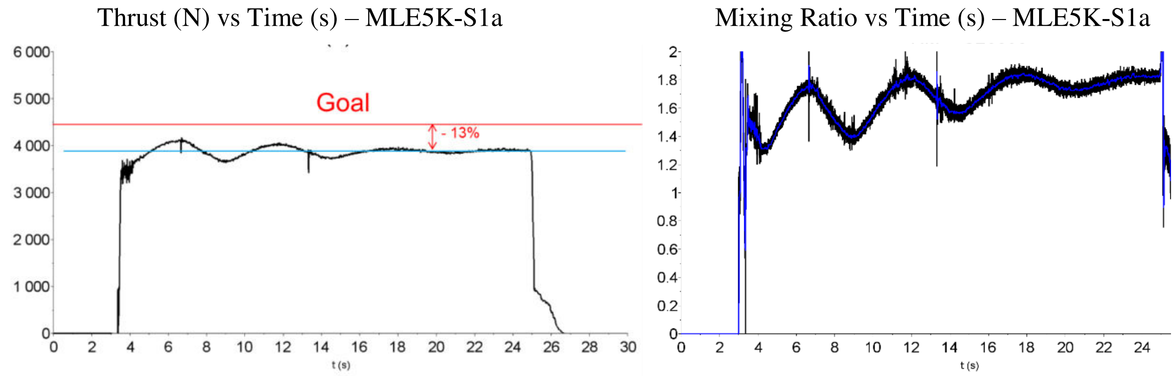

Figure 11 : MLE5K-S1a Thrust and mixing ratio - 22 seconds combustion

Thanks to the 5 kHz acquisition frequency, we are able to realize a frequency analysis on the chamber pressure (

Figure 12). As one can see, the 1050Hz to 1500 Hz window is visible on the entire test time. The 1700Hz frequency (represented by the green line) is the first mechanical frequency mode of the thrust sensor. One harmonic is also visible on this analysis (625 Hz – 1250 Hz). According to the chamber diameter and length, the theoretical combustion frequency is determined (up right corner of the figure below). These frequencies partially fit with the 1050Hz – 1500 Hz window especially for a high mixing ratio.

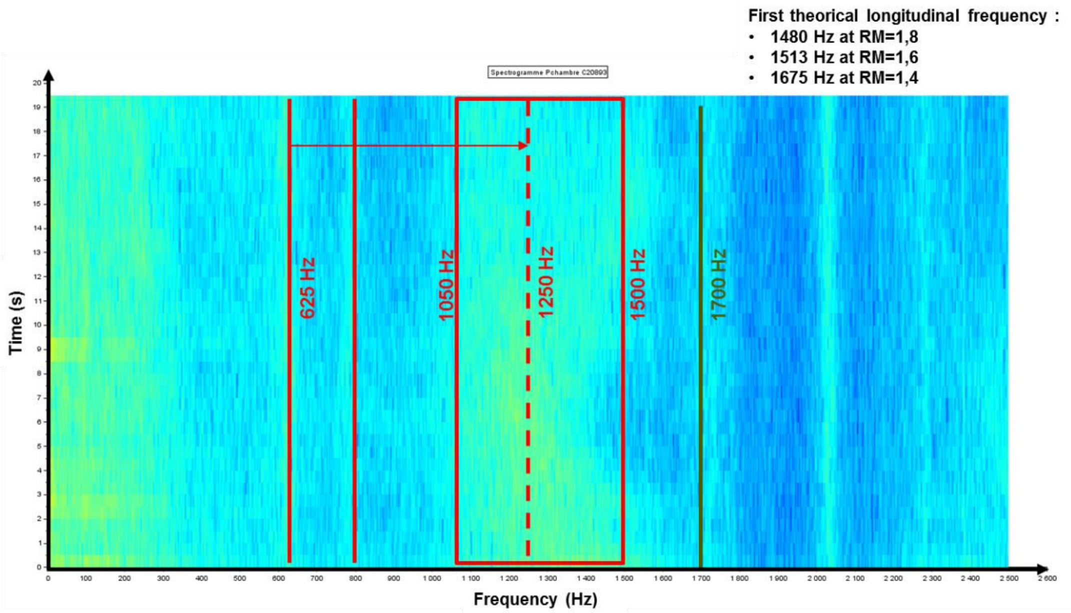

Figure 12 : Frequency analysis

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6. Biliquid rocket: first design

Thanks to the first LOX/Ethanol tests describe in the previous part, we started the development of the first PERSEUS biliquid rocket with for main objective to demonstrate the feasibility of using liquid propulsion on a French student rocket.

This rocket named ASTREOS 1 is the next evolution of the SERA family. It is a single stage rocket propelled by the MLE5K-V1 engine developed in the MINERA macro-project (engine derived from the MLE5K-S1a or other best definitions). The general architecture of this rocket is presented in the Figure 14. This design was performed by an ECL (Ecole Centrale de Lyon – French engineer school) student who realized a 6 months internship with the PERSEUS embedded team.

Here are some characteristics of this rocket:

Height	7 m
Diameter	160 – 250 mm
GLOW	≈ 105 kg
Propellant mass	35 kg
Burn time	20 s
Lift off thrust	4,7 kN
Apogee	≈ 7 km
Mach	≈ 1,2

Figure 13 : ASTREOS 1 Characteristics

This rocket uses a blow down pressurization system with nitrogen for the pressurization gas. All the avionics and recovery system will be derivated from a 10 years development in the previous PERSEUS rockets. The 2 propellants lines (LOX and Ethanol) are controlled by 2 single-acting valves using pneumatic actuators. The 2 structural tanks will be in welded aluminum or in composite with carbon fiber around an aluminum liner. The skirt (250 mm to 160 mm) will be realized in 3D printed titanium as it will be on the SERA 4 rocket (planned for April 2018). A spot is also dedicated to a 0.5kg payload under the nosecone.

Another objective of this rocket development is to develop all the GSE (Ground Support Equipment) including the launcher rail, propellant storage and filling system, disconnection system and safety equipments. All these parts are currently being studied by a 6 months internship student and will be realized during the 2017/2018 French school year.

During the preliminary study of this rocket, we realized a parametric analysis on the combustion time and the pressurization system. The results are indicated in Figure 15. As one can see, the optimal combustion time for the Blow Down system on this kind of rocket is around 30 seconds and increasing with the dry mass optimization. This analysis gives the objectives for the flight engine and rocket development.

Figure 14 : ASTREOS 1 general architecture

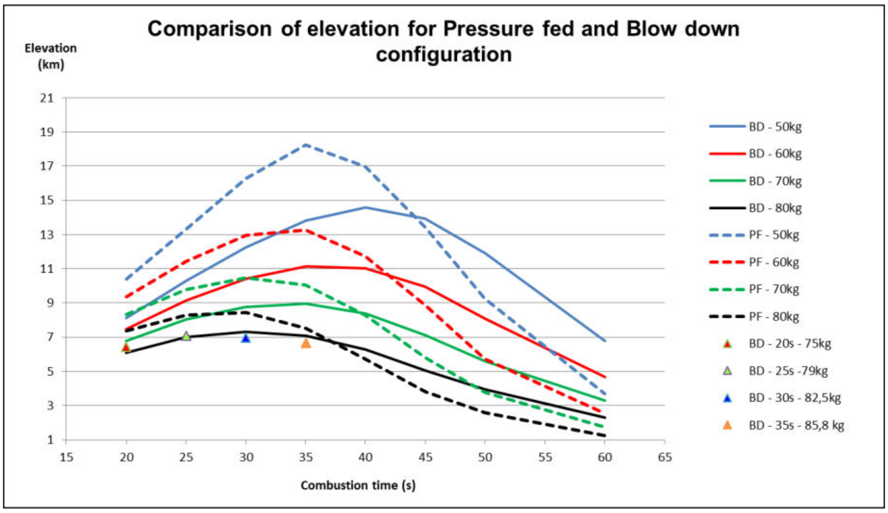

Figure 15 : ASTREOS parametric analysis

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7. Next evolutions and studies

A lot of other developments related to biliquid propulsion are still ongoing inside the PERSEUS project. A major development is the pintle injection system. Since 2012, the project is working on such an injector. The purpose of the first works performed by students was only to increase the mixing efficiency inside the combustion chamber. Recently the project also decided to add the thrust modulation capability. The most well-known way to achieve it, is also to use a system based on the pintle injector. So the injection system has been widely analyzed within the project. A synthesis of the student's works has enabled the design of a first engine design presented in the Figure 16. There is still some analysis to perform on this system mainly on the sealing system because of the different moving parts. Nevertheless the first cold flow tests will be realized during the 2017/2018 school year.

Figure 16 : Ground design of the thrust modulation pintle

Another short term major upgrade planned for the biliquid propulsion work within the PERSEUS project is to change of fuel, switching from the ethanol to the liquid methane. The main reason is that methane is a more suited fuel for reusable engine. As a consequence of this directive some studies and modifications of the previous results obtained for ethanol will need to be performed in order to be compliant with methane. The modifications concern the injection plate and mainly the fuel SKID which will be used at cryogenic temperature this time. Hopefully the Lox SKID and the global operation will not be too much impacted. The first engine firing tests in LOX/LCH4 are planned during 2018.

8. Conclusion

Thanks to the PERSEUS partner's, the firing engine tests are feasible on safe test setup. Due to the risks associated to these activities only professionals can operate this kind of engine. For the students who are in charge of the design and fabrication, they have the satisfaction to see their engine being fired. After the tests, they are also associated to the datas post processing in order to improve the next design. This improvement cycle was already performed within the PERSEUS project on experimental rocket propelled by amatory commercial solid engine which enable to switch from small subsonic rocket ARES up to supersonic rocket SERA [3]. This time it is applied on biliquid engine: improvements of the new engine design based on experimental tests feedbacks, with the purpose to switch both from impact injector to pintle injector to enable thrust modulation and from ethanol to cryogenic methane.

They are still some works to do before being able to launch the ASTREOS rocket propelled with a Liquid Oxygene/Methane engine. To reach this new step, the PERSEUS Project in association with its partner's, can rely on its specificity: the student motivations which is renewed each year!

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9. References

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10. Acronyms

3P : Plateau Projet PERSEUS
EPIP : Equipe Projet Intégrée PERSEUS (PERSEUS integrated team)
MINERVA : Moteur INnovant Experimental pour les Recherches sur les Véhicules Aérospatiaux
PERSEUS : Projet Etudiant de Recherche Spatiale Européen Universitaire et Scientifique
SERA : Supersonic European Rocket ARES
STIM : Société de Tolerie Industrielle et Mécanique
ULYSSE : Ultimate Liquid hYbrid Solid launch System Evaluation
SKID : Propellant Feeding system
MLE : Minerva LOX Ethanol
GLOW : Global Lift Off Weight