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Architecture Trade-Off for the VEGA-E upper stage LOX/CH4 engine

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Abstract

In frame of the of the VEGA Evolution Preparation Program, focus is given on the development of a new cryogenic LOx/CH4 engine fed with turbopumps.
This paper focuses on the trade-off studies for the engine architecture definition, considering both open and closed expander thermodynamic cycles. Various subsystems configurations have been also taken into account, analyzing their best combination in term of performance .
Different cooling strategies configurations and technologies are considered for the combustion chamber, while for the turbopumps both low and high pressure ratio turbines are investigated.

1. Introduction

On November 2012 the VEga Consolidation and Evolution Programme (VECEP) has entered in force, with the scope to enlarge the Vega market position for the short-medium term with the so-called Vega C configuration (maiden flight Mid 2019), see Fig.1, by covering typical LEO SAR payloads (up to 2200 kg) and increasing flexibility for multiple payloads at competitive launch costs.
Moreover, during ESA Council at Ministerial level, held in Dec 2016, go-ahead for the preparation of the long term evolution of the launcher (beyond 2025) has been given with the approval of the VEGA Evolution Program (VEGA E).
Main objectives of the VEGA E program are:

- reduction of the launch system recurring costs wrt VEGA C, keeping the same target payloads, through the implementation of very low cost LOX-Methane upper stage solutions and a new engine based on expander cycle using innovative technologies;
  increase of VEGA operating flexibility and market competitiveness with a family of launch vehicles based on building blocks, including a two and three stages configurations (see Fig. 2), with the LOX-Methane stage as common element;
- elimination of toxic propellants from the launch vehicle configuration, mitigating the risk of future reach legislation banning the use of hydrazine derivatives for space applications;
- optimize VUS development at affordable cost (reuse of VEGA C developments, synergies with A6 , max use of existing test facilities, incremental complexity approach).

Specifically, the present paper provides the status of the VUS (VEGA Upper Stage) engine architecture trade-off , aimed at identifying the optimal configuration considering performance, technical complexity, recurring and non-recurring cost targets.

Each engine configuration has been analyzed in terms of performance and budgets, nominal and extreme modes, feeding system preliminary requirements, configuration of the TCA, transient operations concept (start-up/shut down) and recurring/non-recurring cost impacts.

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Figure 1: VEga Consolidation and Evolution Program.

Figure 2: VEGA E family concept.

2. Engine cycles

The reference upper stage engine for the VEGA-E launcher is an expander cycle, characterized by the extraction of the power for the feeding system through the combustion chamber cooling system. Two main variants of the cycle have been studied in the trade-off:

- closed expander, where all the fuel flow expanding in the turbines is sent to the thrust chamber;

- partially open expander, where part of the fuel used to drive the turbines is discharged off-board through an auxiliary nozzle.

Moreover, for each configuration, two variants of the thrust chamber have been assessed:

- use of a combustion chamber made by a traditional manufacturing technique, based on a bi-material approach;
- use of an innovative chamber made by Additive Layer Manufacturing technique using a Single Material Single Part approach.

In the following is provided the functional description of the close and open cycle architecture with the engine schematic.

Close Cycle Description

The propellants are fed to the turbopumps The two turbopumps are driven by two turbines in series fed by CH_4 after heating up in the regenerative cooling system of the combustion chamber.

The engine power and mixture ratio is controlled by a regulator valve (RV) installed in a by-pass line, and a throttle valve (TV) installed in the LOX line at pump outlet.

The ignition is performed by a torch igniter fed with gaseous oxygen and methane from an independent feeding circuit. The propellant feeding at the TCA is controlled by the valves FCV and OCV respectively for the fuel and the oxidizer. The valve OCV also controls the oxidizer chilling-down and bleeding at shut-down. The flow schematic for the engine configuration is presented in Figure 2.

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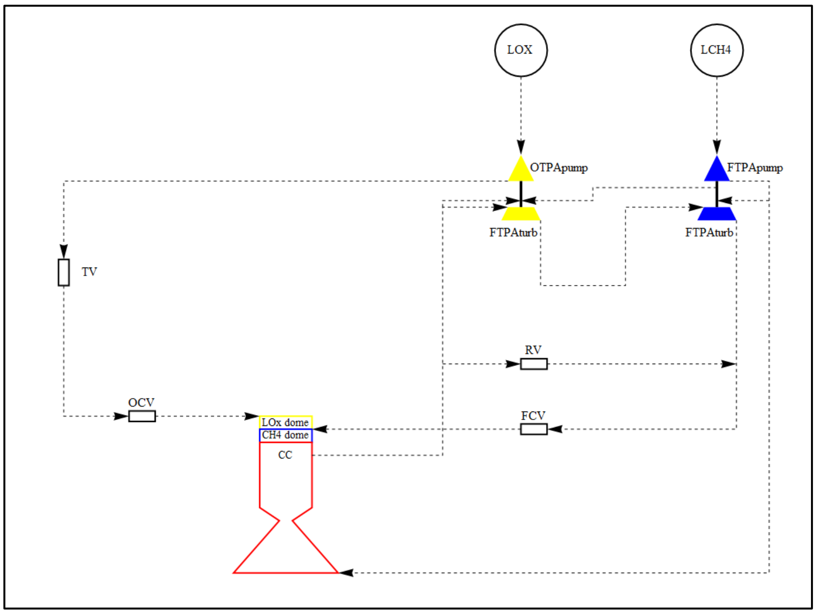

Figure 2: Closed Cycle Engine simplified schematic.

Partially Open Cycle Description

The functional description is the same provided for the closed-cycle configuration. The only relevant difference is relevant to the turbopumps operation: the fuel turbopump is driven by one turbine fed by CH4 after heating up in the regenerative cooling system of the combustion chamber. The oxidizer turbopump is driven by turbine fed by part of the gaseous methane coming from the fuel turbine, which is discharged off-board in an auxiliary nozzle. In this way, the flow in the oxidizer turbine operates in supersonic conditions.

The flow schematic for the engine configuration is presented in the Figure 3.

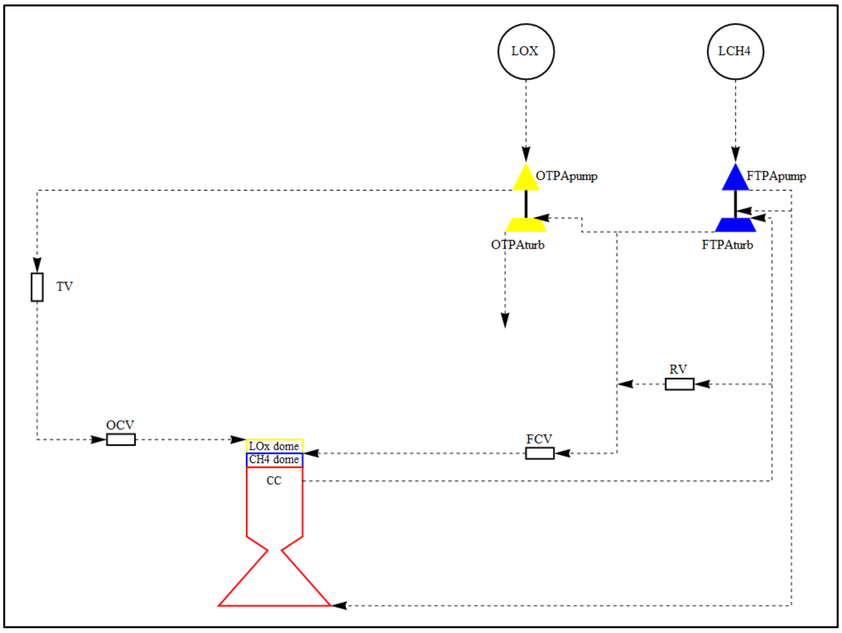

Figure 3: Open Cycle Engine simplified schematic.

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3. Engine performance trade-off

The engine trade-off study considers one level of trust, 98.1 [kN] for different configuration characterized by close cycle or open cycle, and by two possible trust chamber assembly configuration, the bi-material combustion chamber with Copper Alloy Liner or the SMSP combustion chamber with Inconel, RD 2. The trade-off results in 4configurations shown in the following table.

Configuration	Thrust [kN]	Pcc [bar]	ExpR [-]
VUS_T98P50	98.1	50	108.4
VUS_T98P60	98.1	60	131.0
VUS_T98P70	98.1	70	153.6
VUS_T98P79	98.1	78.8	173.5

Table 1: Engine configuration under investigation.

For each configuration the following design steps are performed:

- Definition of the engine nominal mode;
- Combustion chamber geometry definition;
- Cooling system preliminary design;
- Pump concept design;
- Turbine concept study;
- Engine system equilibrium point identification.

This procedure allows to estimate the engine performance based on a consolidated sub-systems concept design procedure. In particular, starting from the engine target performance and the engine maximum allowable length, it is possible to define the total mass flow and throat diameter, then the combustion chamber and nozzle geometries. An example of the TCA geometries for the first four configuration is shown in Figure 4.

The first step of the procedure, the fluid dynamic network corresponding to the engine schematics, presented in Figure 2 and Figure 3, are solved to identify the preliminary engine equilibrium point and to define the boundary conditions for the sub-systems design. At this stage several hypothesis are done on the sub-systems performance and efficiency.

The second step is the preliminary design of the chamber cooling system using a fixed configuration for each study that corresponds to a coolant inlet section right after the throat section with a direction towards the injector head, then the coolant is injected again after the first inlet section with a direction towards the nozzle exit, see for example Figure 4. The cooling system geometry is used, in the performance code, for the estimation of the pressure losses, temperature rise and liner temperatures. An example of the typical code output is shown in Figure 5.

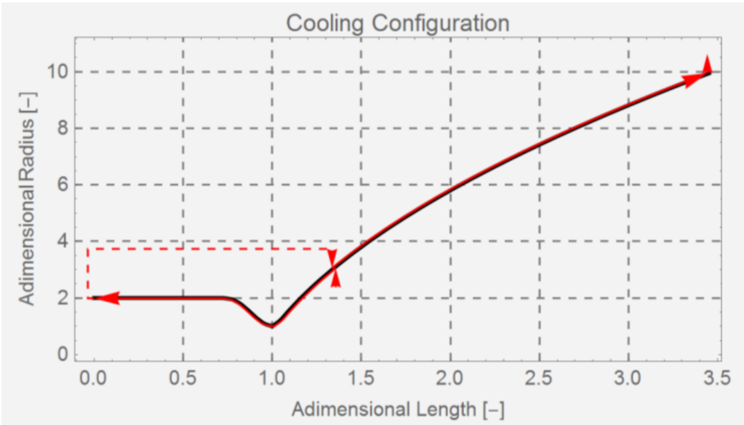

Figure 4: TCA cooling concept architecture.

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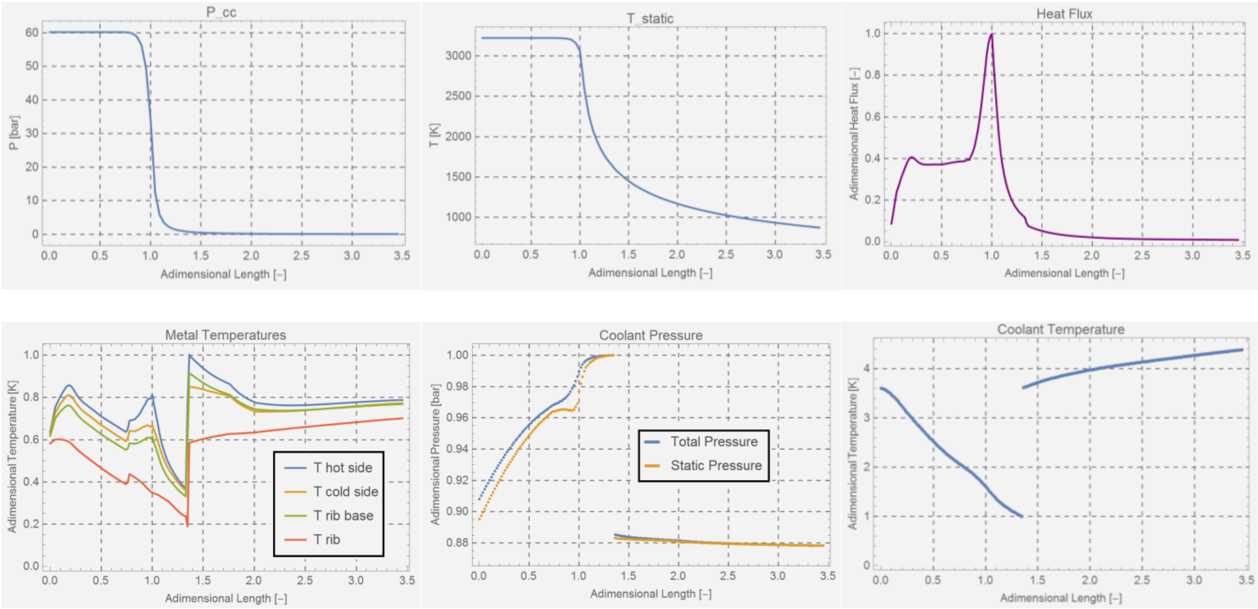

Figure 5: An example of the typical code output.

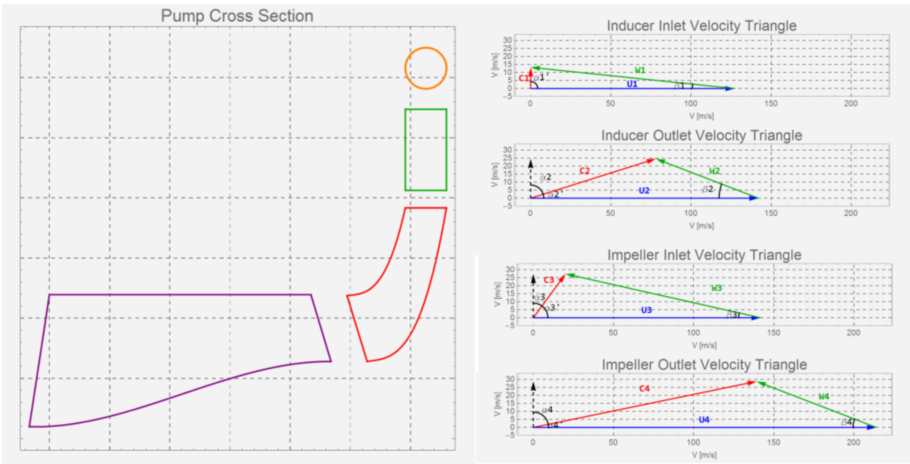

Figure 6: An example of pump preliminary geometry and performance.

The third step is the concept design of the pumps, starting from the mass flow and the pressure rise needed. It is defined the pump architecture and overall geometries in order to estimate the rotational speed, efficiency, losses and torque. Through the pump design maps it is possible to estimate the pump global efficiency that is used in the engine code to reach the convergence on the equilibrium point. An example of pump preliminary geometry and performance in term of velocity triangles is shown in Figure 6.

The fourth step is relevant to the concept design of the turbines, based on design maps, general rules on velocity triangles and rotor reaction degree. Starting from the values of mass flow, inlet temperature, pressure ratio, rotational speed and pump power, it is possible to estimate the turbine global efficiency, that is used in the engine code.

The fifth step is an iterative procedure needed to find the equilibrium point of the engine, in particular the engine fluid network is updated, with the new values of pressure losses, temperature rise and efficiencies coming from the sub-system models. Several preliminary design loops are needed to reach a stable solution and it is useful to identify unrealistic engine configuration that correspond to a lack of power to reach the combustion chamber pressure level identify by the nominal mode. Unless it is a not automatic and time consuming procedure, it guarantees the representativeness of the engine

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configuration under investigation, because the preliminary and concept design of the sub-systems take into account the major critical aspects that could impact negatively on the engine feasibility.

The sub-system concept design allows also to estimate the main parameters that characterize each component such as the liner temperatures of the combustion chamber, the turbopumps rotational speed, the pump pressure load, pump pressure rise splitting, pump efficiency, preliminary pump blade angles, the turbine degree of reaction, turbine blade load, turbine efficiency and preliminary stator and rotor blades angles.

4. Technological activities

The engine trade-off study consider two possible technologies to be used for the TCA manufacturing after their characterization in dedicated firing test campaign of suitable chamber prototypes. Preliminary activities to increase their TRL maturity have been conducted by AVIO with internal R&D funding.

Specifically, a brazing technology has been validated with the manufacturing of the AVIO Proto-D combustion chamber cooled with water and fed with LOx and CH4. In this case, the combustion chamber is composed by two main parts characterized by two different materials, in particular the liner made by copper alloy and the close-out made by nickel alloy, that need to be joined together in order to form the chamber cooling system and to guarantee the structural integrity to the chamber. In the first phase of the validation activity the strategy was to use the brazing alloy that would guarantee the highest strength of the junction, then brazing alloy characterized by high melting temperature. Actually the scope was reached, obtaining an ultimate stress higher than the copper alloy ultimate value. A tensile test campaign was performed to estimate the materials mechanical properties for different brazing cycle and different heat treatment, the evidence was a decay of the mechanical properties of the liner material of about 40% less, in line with literature data. A second brazing process was developed in the second phase of the activity, in order to select a brazing alloy characterized by a lower melting temperature in order to reduce the impact on the liner mechanical properties. The experimental activity allowed to set-up a new brazing process with a lower melting temperature of about 15% less. The tensile tests highlighted a lower ultimate strength of the brazing junction 10% less than the previous process, but a consistent lower decay of the mechanical properties of the liner material, that is 20% respect to 40% of the previous one. After the successful accomplishment of the aforementioned activities, it was started the manufacturing of the Proto-D combustion chamber that was finally accepted through a dedicate hot firing test campaign, with five successful firing tests.

The second approach for the TCA manufacturing is the exploitation of the Additive Layer Manufacturing (ALM) technology. AVIO performed a dedicated development program devoted to the investigation of the technology validation, based on the use of several samples realized. The validation plan followed these steps:

- manufacturing of 1:1 scale samples of the chamber, for the estimation of manufacturing tolerances;
- manufacturing of several samples for the estimation of thermomechanical properties of the material, considering all the manufacturing phases (ALM fusion, hipping, annealing and ageing);
- manufacturing of 3 cylindrical modules of the SMSP combustion chamber, RD 2, with different ALM machines, for the definition and refinement of the manufacturing process;
- NDI controls on the manufactured modules: tomography, ultrasounds, penetrant liquid;
- Manufacturing of the SMSP nozzle module.

The aforementioned activities were performed successfully, and a dedicated firing test campaign was performed using one of the manufactured cylindrical modules, with five successful firing tests. The firing test campaign for the performance estimation of the nozzle module is foresees with 2017.

The third manufacturing technology under investigation is the electrodeposition process which scope is to build the cooling channels for the coolant passage in the easiest way without degradation of mechanical properties of the liner material, using the galvanic deposition of copper and nickel layers on the combustion chamber liner. The technological process foresee the following steps:

- machining the liner by forge base material obtaining the final geometry with all the ribs;
- filling the ribs with a electro conductive material characterized by low melting temperature;
- forming the cooling duct by closing the ribs at the tip through a copper deposition on the rib and on the filling material, obtaining an uniform copper layer;
- reinforce the structure with an external shell, obtained through a nickel layer deposition on the copper one
- total removal of the low melting temperature material to open the cooling channels.

The results is a zero leak structures with an external shell characterized by high strength and hardness. Some feasibility tests have been executed successfully following the steps described before, demonstrating that the electrodeposition technology is mature for the application to a combustion chamber. Obviously it is needed to set-up the process and to improve some technical aspects, like the characterization of the layer mechanical properties, the

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methodology to obtain thicker layer, the geometry optimization for the tip effect reduction, the study of the interfaces for the coolant inlet and outlet. Moreover it is very important to define a reliable plant for the filling material removal that is simple for very simple samples, but need more attention for complex geometry and the use of a steam plant.

The next step of the development program on the electroforming technology is to test the process on a representative geometry of the combustion chamber with the scope to verify the process on a scale 1:1 cylindrical and nozzle samples. It will be tested with a leak test, an instrumented proof test and finally a hot firing test of the two parts assy.

5. Conclusion

The final choice of the engine configuration is dictated by various considerations including performance impact in terms of payload capabilities; recurring and non-recurring cost impact for each option; technical risks linked to the different technologies under investigation, heritage on engine critical components. Besides preliminary analytical evaluations, the trade-off will be supported by breadboard test activities, especially on the TCA technology, to be completed by the end of 2017, which will drive the design of the first engine Development Model (DM1) to be hot firing tested by end 2019.

6. Nomenclature

ALM Additive Layer Manufacturing
CFD Computational Fluid Dynamic
FEM Finite Element Method
KeRC Keldysh Research Center
NDI Non Destructive Inspection
SMSP Single Material Single Part
TCA Thrust Chamber Assy
VECEP VEga Consolidation and Evolution Program

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