DOI: 10.13009/EUCASS2019-315

Development of the liquid oxygen and methane M10 rocket engine for the Vega-E upper stage

D. Kajon(1), D.Liuzzi (1), C. Boffa (1), M. Rudnykh(1), D. Drigo(1), L. Arione(1), N. Ierardo(2), A. Sirbi(2)

(1) Avio S.p.A., Via Ariana, km 5.2, 00034 Colleferro, Italy
(2) ESA-ESRIN: Largo Galileo Galilei 1, 00044 Frascati, Italy

Abstract

In the frame of the VEGA-E preparation programme to improve the competitiveness of VEGA launch service, AVIO is developing a new 10 Tons liquid cryogenic rocket engine called M10. The present work outlines the development status of the M10 rocket engine. The reference configuration for this engine is a full expander cycle using liquid oxygen and methane as propellants; the use of innovative technologies for the upper stage engine will enable the increase of competitiveness of VEGA-E through the reduction of the launch service costs and increase of flexibility. After having performed the Step 1 of the Preliminary Design Review (PDR) at engine level, the development of main engine subsystems (e.g. turbopumps, valves, cardan, igniter, ...) is ongoing and contributes to the design of the first Development Model (DM1) which will be manufactured by end 2019 and subject to hot firing tests. Regarding the core new development of the Thrust Chamber Assembly (TCA), a trade-off between the conventional bi-metallic nickel-copper manufacturing approach and an innovative design based on Additive Layer Manufacturing (ALM) is conducted, based on sub-scale hot firing tests of both configurations. At beginning of second semester of 2019, ALM TCA full scale autonomous testing will take place and the choice will be reflected also for DM1 engine configuration. The engine tests will consolidate the development of the engine looking for the best compromise between performances, recurring costs, reliability and development risks.

1. Nomenclature

ALM	Additive Layer Manufacturing
CDR	Critical Design Review
CH4	Methane
DM	Development Model
DV	Discharge Valves
DSP	Dynamic Seal Package
FLPP	Future Launchers Preparatory Program
FMV	Fuel Main Valve
FTPA	Fuel Turbopump Assembly
Isp	Specific Impulse
LNG	Liquefied Natural Gas
LOX	Liquid Oxygen
LPM	Liquid Propulsion Module
M10	LOX-CH4 10 ton engine for VUS
MR	Mixture Ratio
OMV	Oxygen Main Valve
OTPA	Oxygen Turbopump Assembly
PDR	Preliminary Design Review
PRR	Preliminary Requirements Review
QM	Qualification Model
RV	Regulator Valve
SMSP	Single Material Single Part
SPTF	Space Propulsion Test Facility
TCA	Thrust Chamber Assembly
TRL	Technology Readiness Level
TV	Throttle Valve
TVC	Thrust Vector Control
VEGA	Vettore Europeo Generazione Avanzata
VEGA-E	Vega Evolution Programme
VUS	VEGA-E Upper Stage

DOI: 10.13009/EUCASS2019-315

1. Introduction

Main goal of the VEGA-Evolution Programme is to increase the competitiveness through the reduction of the launch service costs and the increase of flexibility. In this perspective the development of a new low cost and green upper stage engine plays a key-role for the achievement of above goals. The upper stage main propulsion consists in the M10 engine, a 10-tons LOX-Methane closed expander cycle engine. The development of M10 engine is strongly supported by the experience and the technology maturation gained in AVIO during the framework of the LM10-MIRA engine demonstrator programme [5], funded by the Italian Space Agency, and other national and European initiatives [1].

The present work outlines the development status of the M10 upper stage engine. After having performed the Step 1 of the Preliminary Design Review (PDR) at engine level, the development of main engine subsystems (e.g. turbopumps, valves, cardan, igniter, ...) is ongoing and contributes to the design of the first Development Model (DM1) which will be manufactured by end 2019 and subject to hot firing tests. Regarding the core new development of the Thrust Chamber Assembly (TCA), a trade-off between the conventional bi-metallic nickel-copper manufacturing approach and an innovative design based on Additive Layer Manufacturing (ALM) has been done and sub-scale hot firing tests of the ALM configuration have been successfully performed. At beginning of second semester of 2019, ALM TCA full scale autonomous testing will take place; the choice will be reflected also for DM1 engine configuration. The engine tests will consolidate the development of the engine looking for the best compromise between performances, recurring costs, reliability and development risks.

1. The VEGA-E Launcher Cryogenic Upper Stage

Main objectives of the VEGA-E program are the reduction of the launch system recurring costs with respect to VEGA-C, keeping the same target payloads, through the implementation of low cost LOX-Methane upper stage solutions, increase of VEGA operating flexibility and market competitiveness with a family of launch vehicles based on building blocks, elimination of toxic propellants from the launch vehicle configuration, optimize development at affordable cost by re-use of VEGA-C developments, synergies with Ariane 6, maximal use of existing test facilities and an incremental complexity approach. The VEGA-E launcher family covers these objectives: it is constituted by different configurations – Light and Heavy launch systems - with the LOX-Methane Cryogenic VEGA Upper Stage (VUS) as common element.

Internal structure

Avionic Platform integrated with Payload adapter (main I/Fs ensured: standard 1194 and 937 mm)

Avionics

New optimized architecture allowing a strong cost saving enhancing capabilities

LPM

Common bulkhead solution with smart pressure control system to improve propellant management and mission flexibility

Roll Attitude Control System (RACS) green based on H2O2 propellant to minimize the environmental impacts

Inter-stage 2/3

3,7 m long and 2,4 m diameter CFRP anisogrid structure

M10 engine

The low cost and High Performance M10 engine, an expander cycle engine that introduces innovative technologies and simplified architecture

Figure 1 – LOX-Methane Cryogenic VEGA Upper Stage (VUS)

2. The M10 Engine development

M10 rocket engine is based on an expander closed-cycle and features a re-startable regenerative cooled single chamber. Combustion is initiated by a torch igniter, which is fed by gaseous hydrogen and oxygen stored at high pressure. The preliminary layout of the M10 engine is shown in Figure 4.

Two dedicated turbomachines, arranged in series, increase the propellants pressure to the needed level to feed the regenerative circuit and the combustion chamber. Both the oxygen and fuel turbopumps are driven by the methane, which is also used as coolant for the combustion chamber. Dedicated valves on methane and oxidizers lines allow to regulate engine power and manage engine transients. In particular, the regulator valve RV installed in a by-pass line allows to regulate the power of turbomachines, and in turns the mass flow rate of propellants at engine inlet interfaces. Oxidizer mass flow rate is directly controlled by means of the throttle valve TV, which is installed downstream the LOX pump. Finally, propellants are fed to the combustion chamber assembly by means of dedicated chamber valves OMV and FMV. In addition, the feeding system includes discharge valves DV for oxidizer and fuel, which allow to perform the chill-down, start-up and shut-down of the engine.

Figure 2 – M10 engine layout

The activities at engine level up to the Step 1 of the Preliminary Design Review (PDR) focus on the feasibility studies at system level, on the determination of robustness and margins of the engine baseline configuration and on the derivation of requirements for main engine subsystems. The development of main engine subsystems (e.g. TCA, turbopumps, valves, cardan, igniter, ...) has started to reach preliminary design loop and confirms the assumptions and requirements used at system level.

For the definition of the extreme working domain of the engine, a statistical method is used for combining the deviations of the main parameters of the engine and its subsystems, as for example tank propellant pressure and temperature, flow rates, trimming and throttling of the engine, modelling uncertainties, component performances, manufacturing tolerances and measurements uncertainties. It was then possible to define the engine functional domain, which is also including additional system margins with respect to what required to the engine subsystems, in order to mitigate the development risks which may occur during design activities of the engine components.

DOI: 10.13009/EUCASS2019-315

It was shown during the PDR review, that performance requirements in terms of Thrust, Mixture Ratio (MR) and Isp can be met and applied margin policy at engine level is sufficient to recover significant deviation of possible subassembly performance thanks to the regulation capability of the engine. Furthermore, design justification obtained by several loop of system analyses provided sufficient data to establish the preliminary functional requirements for main engine subsystems. No show stoppers have been evidenced for the configurations selected in the engine architecture trade-off.

3. The M10 Engine layout

Starting from engine architecture and simplified flow schematic (Figure 3), M10 engine layout has been developed as reflected in Figure 2.Figure 2 Relevant feature of M10 layout is the use of hard lines as main propellants feedlines, which also contribute to the structure of the engine together with mechanical supports and brackets. The position of primary engine components, such as LOX and CH4 turbopumps and main valves, has been defined and requirements for mechanical interfaces have been derived accordingly. Hence, the routing of propellants lines has been defined as a compromise between allowable volume, maximum pressure drops and manufacturing constraints.

In addition to hard propellants lines, M10 engine layout includes small diameter lines for helium supply to pneumatically-actuated valves. On the basis of preliminary developments done within other ESA programs such as FLPP, the implementation of additional electric valves is also considered as a possible way to reduce the complexity of engine assembly.

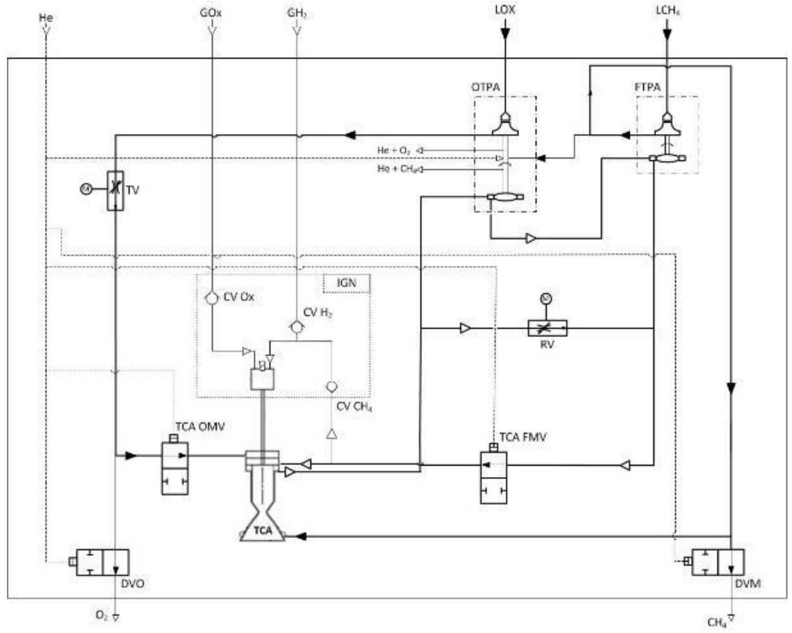

Figure 3 – Simplified Flow Schematic of M10 engine.

On the basis of M10 engine layout, the layout of first Development Model (DM1) has been defined. Only minor changes in lines routing have been implemented, in order to allow the possible use of existing design of subsystems and to profit of the heritage gained by AVIO and partners within similar programs. In fact, for optimisation of development costs and due to schedule constraints, the partial use of existing components with no modifications from Vulcain® and Vinci® rocket engines has been envisaged, as well as use of the methane turbopump successfully developed and tested by AVIO in the framework of MIRA program. A dedicated flight hardware turbopump will be designed for further development models of M10 engine.

The integration procedure of DM1 engine has been developed in compliance with engine layout and to be as representative as possible of the M10 flight engine integration steps. Inspections and checks at both components and engine level have been identified in the respect of hardware definition, European standards and engineering practice. Visual inspections, electrical checks of components and sensors, leak tests of flanged joints are included as integral part of the integration procedure. Tools and stands have been defined to support the AIT flow. DM1 integration activities will be performed at AVIO clean room premises in Colleferro, Italy.

DOI: 10.13009/EUCASS2019-315

4. Sub-Scale and Full Scale TCA test campaign

The TCA is the core element of the M10 engine that is developed by AVIO in frame of the VEGA-E program. The reference manufacturing technology that has been selected is the Additive Layer Manufacturing (ALM) by laser melting, that is selected after a trade-off and testing activity with respect to traditional technologies based on copper alloy liner. AVIO started its heritage on this technology through internal R&D program on cylindrical and DeLaval nozzle geometries that demonstrated the maturity for the application to the VEGA-E development program.
The developed activity on the sub-scale combustion chamber is declined with various steps, starting from the engineering design of the injector head and chamber cooling system, numerical simulations to verify design choices, laser parameters optimization phase, surface polishing technics set-up, welding validation, verification activity and manufacturing flow chart definition. The sub-scale combustion chamber is conceived with only one part and one material, taking advantage by the building volume of ALM machine currently available to the open market. The injector head is also manufactured with the same material and one part. Four technological models have been manufactured, three passed the acceptance and proof tests, the last was devoted to the firing test campaign. At the end of 2018 the sub-scale firing test campaign was successfully complete, performing 20 firing cycles and 370 seconds of firing time; the goal was to explore not only the life cycle but also the nominal performances within the operative range.

Figure 4 – Sub-scale TCA for development testing.

The success of this test campaign allowed to go through the full scale development activity. While for the injector head few things change from sub-scale to full scale concept, except dimensions and number of injectors, for the combustion chamber the entire architecture is adapted due to the limitations of the ALM technology and of the scale. The thrust chamber is conceived in two parts each with an integrated manifold, allowing to better control the channel cleanliness level and welded at the middle on the liner and on outer shell. Two technological models are already available both for injector head than for combustion chamber, the second were proof tested, while the manufacturing of the third TCA is ongoing and will be used for the full scale firing test campaign, planned in the second half of 2019.

DOI: 10.13009/EUCASS2019-315

Figure 5 – Full-scale TCA first two technological models

5. First M10 Engine Development Model (DM1) test campaign

In addition to individual tests at subsystem level, hot firing test campaign of DM1 engine is foreseen in the first semester of 2020. The test campaign will consist of a series of hot firing with the following objectives:

- Verification of engine performance at sea level conditions;
- Verification of the performance of engine subsystem assemblies at sea level conditions;
- Verification and adjustment of engine chill-down phase;
- Verification and adjustment of engine ignition sequence;
- Verification and adjustment of engine start-up and shut-down sequences;
- Verification and adjustment of the transition to the nominal mode;
- Verification of engine calibration;
- Verification of chamber cooling;
- Evaluation of thermal loads;
- Evaluation of effects of pressure and temperature variations at pump inlets;
- Verification of engine stability;
- Verification of engine overall life, in terms of start-ups and total firing time;
- Verification of engine sub-systems performance at critical operating points;
- Validation of models and tools used for the prediction of engine performance.

The results of DM1 test campaign shall allow to significantly reduce uncertainties of design, manufacturing and modelling, with large profit for following M10 development models. Moreover, implicitly the development model integration and acceptance will provide confirmation of the approach intended for flight engine and valuable feedback into the design of next development models. A total of 4 development model engines and 2 qualification engines is envisaged for the upcoming phases.

Figure 6 – LRE test stand at Space Propulsion Test Facility (SPTF) in Sardinia, Italy.

The baseline option for AVIO for the DM1 test campaign is to be performed at the Space Propulsion Test Facility (SPTF), currently under development in Sardinia (Italy). The test facility development is the result of an Italian initiative, which combines the efforts of the Italian space industry, Italian Space Agency (ASI), research centers and universities, as well as Italian regional and national authorities. The test facility will support the development of solid propellants rocket motors up to 2MN thrust, LOX/CH4 engines up to 2000 kN thrust and the production of Carbon-Carbon materials. A simplified representation of the Liquid Rocket Engine (LRE) test stand in SPTF is given in Figure 6. The LRE test stand will strongly contribute to the development of M10 engine, through tests on related development and qualification models. M10 development engine tests will be performed at sea level conditions. Hot firing runs will be performed at several points of the engine verification box, corresponding to different values of chamber pressure and propellants mixture ratio. Although at each testing point chamber pressure and propellants mixture ratio will be representative of the values of the flight engine, the thrust generated during DM1 tests will not correspond to the thrust of the flight engine due to the not full expansion as in vacuum conditions. Adaptations of the LRE test stand are planned to perform vacuum tests of the 10-ton engine on SPTF.

DOI: 10.13009/EUCASS2019-315

6. Conclusions

This paper described the development status of the M10 engine, the 10-tons engine for application on the VEGA-E launcher as main engine for the LOX-Methane VEGA Cryogenic Upper Stage.

The M10 engine successfully passed the PDR Step 1 milestone at beginning of 2019. In this frame the engine layout has been defined and the consolidated requirements for the engine equipment have been specified, with focus both on performance and cost objectives. The development of all main engine subsystems has consequently started. The use of innovative technologies such as Additive Layer Manufacturing (ALM) is applied to reduce in general the lead time and the engine recurring costs.

Regarding the core new development of the Thrust Chamber Assembly (TCA), a trade-off between the conventional bi-metallic nickel-copper manufacturing approach and an innovative design based on ALM is ongoing; sub-scale hot firing tests of ALM configuration have been successfully performed to validate this choice. At beginning of second semester of 2019, TCA full scale autonomous testing is taking place.

The same design of ALM TCA is also the baseline of the first Development Model (DM1) engine at full scale, where tests will be used to allow better understanding of the engine behavior and performances. The engine will be tested in a configuration including the turbopumps and main valves and tests are performed at sea level operation, with necessary modifications introduced to reach the operational points of the engine. The hot firing test campaign of the DM1 is planned to be performed at the Space Propulsion Test Facility (SPTF), currently under development by AVIO in Sardinia (Italy). The test campaign contributes to the development phase of the M10 engine for the VEGA-E preparatory programme, with ground qualification foreseen for 2024 and consequent maiden flight of VEGA-E launcher by 2025.

Acknowledgements

The activities described in the present paper are enclosed within the efforts undertaken within the VEGA-E Preparatory Programme, where AVIO acts as prime contractor of the launcher and M10 engine development for the European Space Agency. The authors thank and acknowledge all the colleagues involved and the other industrial partners, as well as ASI and ESA for constructive discussions and technical support.

References

[1] *Preparatory Activities and Development of the LOX-CH4 M10 Engine for the VEGA-E Upper Stage*, Kajon, D. ; Liuzzi, D.; Rudnykh, M. et alii, Space Propulsion Conference 2018

[2] *Architecture Trade-Off for the VEGA-E upper stage LOX/CH4 engine*, Liuzzi, D., Rudnykh, M.; Drigo, D.; Ierardo, N. , 7th EUropean Conference for Aeronautics and Space Sciences (EUCASS) 2017

[3] *Firing Test and Program Progress of the SMSP regenerative combustion chamber*, Liuzzi, D., Sciarra, M., Bianchi, G.; Rudnykh, M.; Drigo, D., 7th EUropean Conference for Aeronautics and Space Sciences (EUCASS) 2017

[4] *Design and Development of Single Material Single Part regenerative combustion chamber*, Liuzzi, D.; Rudnykh, M., 6th EUropean Conference for Aeronautics and Space Sciences (EUCASS) 2015

[5] *Development of LM10-MIRA LOX/LNG expander cycle demonstrator engine*, Rudnykh, M.; Carapellese, S.; Liuzzi, D.; Arione, L.; Caggiano, G.; Bellomi, P.; D'Aversa, E.; Pellegrini, R.; Lobov, S. D.; Gurtovoy, A. A.; Rachuk, V. S., Acta Astronautica, Volume 126, p. 364-374.