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STRUCTURAL DEVELOPMENT AND MANUFACUTRING OF THE DEMOP1 DEMONSTRATOR

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Abstract

Aerospike engines are considered as more efficient alternatives to bell nozzle configurations. However, their development has been ignored in the past decades due to their complex cooling and manufacturing requirements. With the recent advancements in materials for propulsion applications and additive manufacturing technologies, aerospike engines are becoming a viable option for launch vehicles. The DemoP1 demonstrator of Pangea Aerospace has been developed with the aim of demonstrating these technologies and provide a basis for a booster-class engine. This paper introduces the design, analysis, and manufacturing steps carried out on DemoP1.

Keywords: Aerospike, Rocket engine, Combustion chamber, Liquid oxygen, Liquid methane

1. Introduction

Pangea Aerospace is planning to develop a booster-class aerospike engine for its future MESO launch vehicle. In order to evaluate the new technologies, concepts, and layouts that such an engine would incorporate, a subscale demonstrator called DemoP1 has been developed. Its main characteristics are shown in Table 1.

Table 1 - DemoP1 high-level specifications

Propellants	LOX/LCH4
Cycle	Pressure-fed
Thrust (sea level)	20 kN
Specific impulse (seal level)	268 s
Mixture ratio	2.8
Expansion ratio	5
Dimensions	240 x 240 x 290 mm

Research activities have been ongoing since mid-2019 and the preliminary fluidic and structural development were introduced in [1]. Since then, the design has been finalized (Figure 1) and several versions of DemoP1 have been manufactured from CuCrZr and GRCop-42 copper alloys. Hot-fire testing of the demonstrators are due in 2021 Q4.

This paper first introduces the layout of the engine, the driving parameters of the design, description of the main subsystems, and challenges encountered. Then the analyses carried out on the engine are discussed. Finally, the manufacturing steps and the manufactured parts are presented.

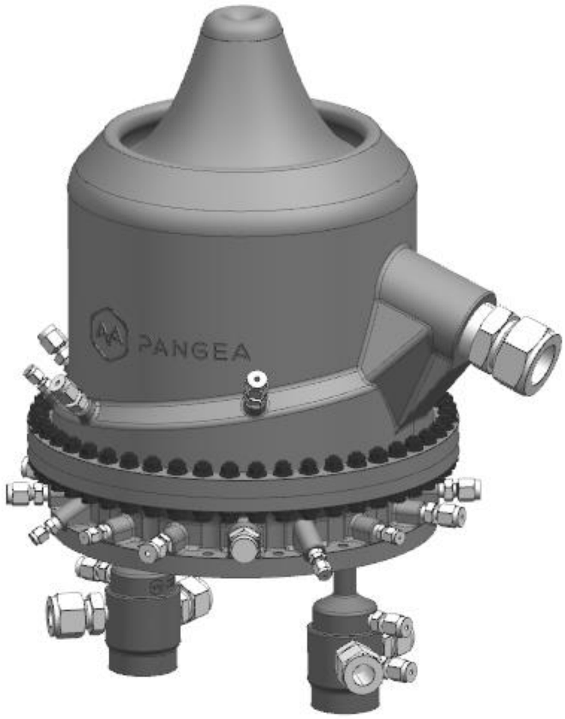

Figure 1 - The DemoP1 engine

2. Design

2.1 Layout and preliminary design

In terms of the layout of the engine, the following factors were driving the design:

- The combustion chamber of an aerospike engine is enclosed by the surfaces of the internal “Plug”, the External Housing, and the Injector Plate. The sectioning, sealing, and joining of these components had to be predefined before carrying out the detail design of the subsystems.
- Functional requirements and dimensions dictated by fluidic design.
- Igniter access to the combustion chamber.
- Due to the cooling requirements, complex internal features and cost effectiveness, the engine was additively manufactured. This method imposed constraints set by Design for Additive Manufacturing (DFAM) principles on the engine such as limited overhang angle, wall thickness, assurance of powder removal, and limitations in build volume.

2.2 Sectioning

To ease the joining and sealing of the engine, the Plug and Injector Plate forms a single part, referred to as Plug in this paper, if not specified otherwise.

The External Housing is connected to the Plug via a bolted flange, which also accommodates a sealing. As the largest diameter of the Plug is located closer to the Injector Head closer than the smallest diameter of the External Housing, their assembly is possible axially (Figure 2). The disassembleability of the two parts makes it possible to carry out inspection and possible refurbishing to meet reusability requirements.

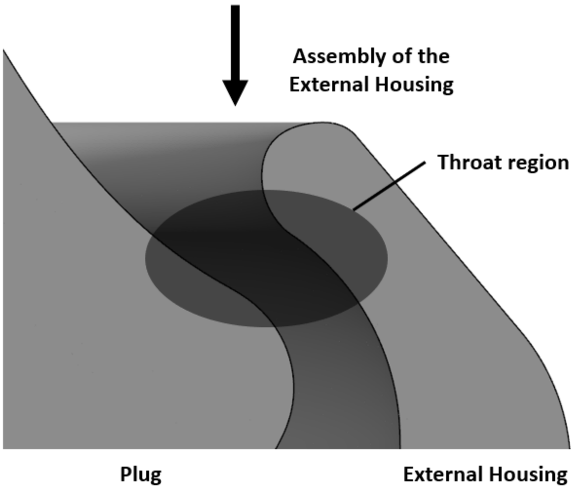

Figure 2 - Assembly of the engine parts

2.3 Cooling system

DemoP1 has a dual regenerative cooling system. The LCH4 fuel is cooling the External housing of the engine, while the LOX oxidizer is cooling the Plug.

The LCH4 enters the engine through an inlet manifold, which has tapered cross-section to aid the distribution of the fuel along the circumference of the External Housing. The coolant channels cover the surface of the External Housing that faces the combustion chamber, then run into the injector head manifold, which is connected to the combustion chamber via injectors (Figure 3).

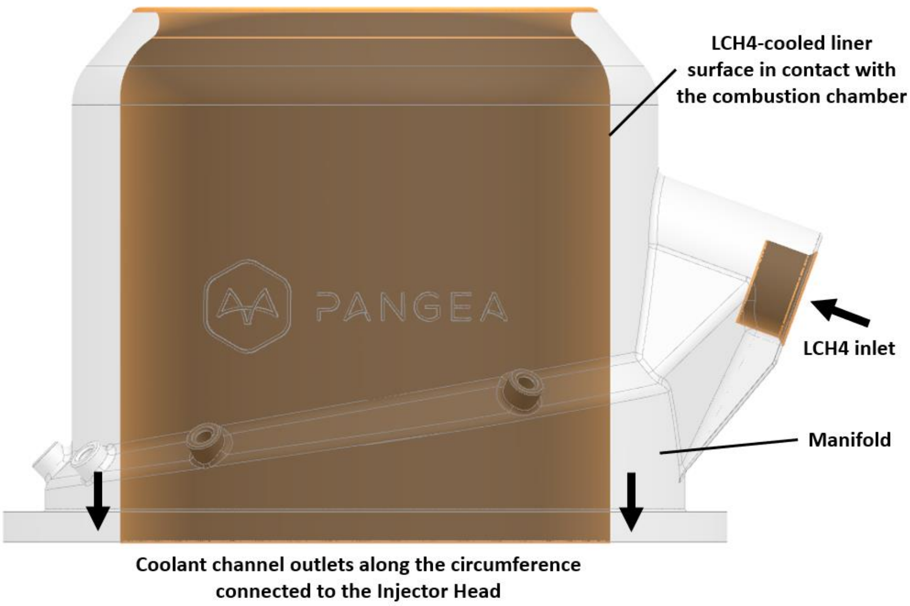

Figure 3 - Cooling of the External Housing

The LOX enters the engine through a tubular structure running up to the top end of the Plug, where it is distributed into coolant channels. The spiral coolant channels cover the surface of the Plug that faces the combustion chamber, and similarly to the case of the LCH4 they run into the injector head manifold (Figure 4).

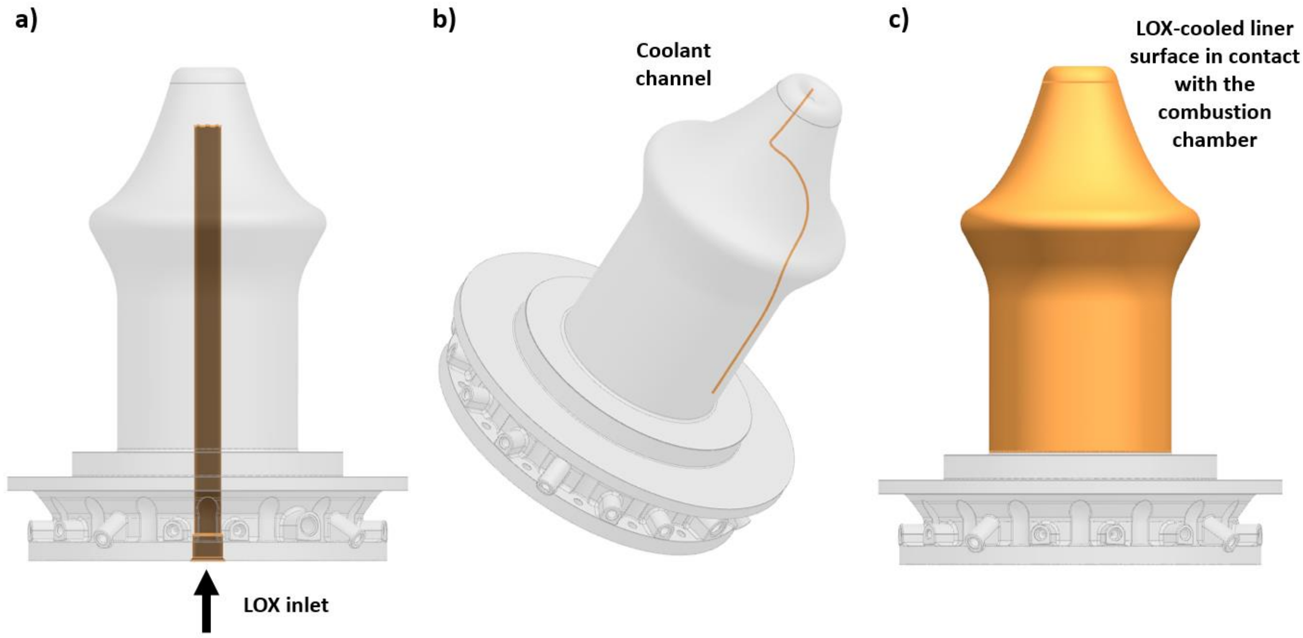

Figure 4 - Cooling of the Plug: a) inlet tubular structure b) spiral coolant channel c) liner surface

Additionally, there is a film cooling system integrated into the engine responsible for cooling the liner wall inside the combustion chamber.

2.4 Plug and External Housing

The main dimensions of the External Housing were defined by the combustion chamber contours and the maximum diameter that can be printed on an EOS M290 machine. The main challenge was to develop the system of the cooling channels and manifold that can distribute the coolants across the surface of the liner and make powder removal possible at the same time. The wall thicknesses were defined based on structural considerations.

The main dimensions of the Plug were also defined by the combustion chamber contours but the maximum printable height provided by the printer was also critical for this part. It accommodates one bolting flange for connection with the External Housing, and another one for connection with the engine mount during the operation of the engine. The propellants are collected in their respective Injector Head manifolds and injected into the combustion chamber. Apart from the Injector Head, the tubular structure shown in Figure 4a) and some other internal structural reinforcements, the rest of the inside of the Plug is hollow. Because of this, and the complexity of the manifolds and coolant channels, dedicated powder removal channels were integrated into the engine. Finally, the Plug is providing access to numerous thermocouples, pressure sensors, and accelerometers along its circumference and mounting face.

Wall thicknesses, reinforcements and layout of both parts were optimized to aid additive manufacturing and reduce deformations and warpage during printing. Excessive shrinking and warpage of the parts could have led to inaccurate throat gap after assembly and subsequent reduction in performance.

2.5 Igniter

The ignition system of DemoP1 is composed of two augmented spark igniters (one is shown in Figure 5) utilizing gaseous oxygen and hydrogen. Instead of an active cooling system, they are cooled by a bypass circuit which is fed into to the combustion chamber of the engine at its exit. They are additively manufactured using the Haynes 282 nickel alloy which has excellent corrosion resistance and strength even at high temperatures.

Figure 5 - The Igniter of DemoP1

2.6 Sealing

The main objective is to seal the combustion chamber from the outside environment at the boundary of the Plug and External Housing. However, there is also a LCH4 coolant channel passing from the External Housing to the Plug. To prevent leakage from the coolant channel to the combustion chamber, an additional sealing is needed (Figure 6).

Due to the low hardness and strength of the GRCop-42 and CuCrZr alloys, metal seals could not be used without damaging the copper surfaces. Instead, RACO® spring-energized polymer seals have been selected.

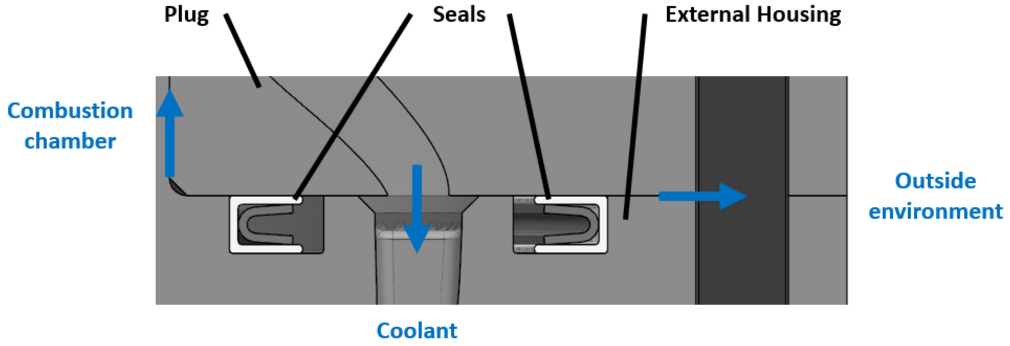

Figure 6 - Seals between Plug and External Housing

Additional sealing is used for the Igniters to prevent hot gas escaping along the Igniter bolt flange - engine interface. Similarly, RACO® seals were used for this purpose.

Finally, the exit of the combustion chamber can be sealed with elastomer o-rings for leak testing, but this cover and sealant is not used during firing (Figure 7).

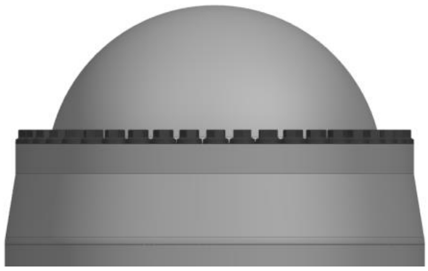

Figure 7 - Cover for leak test

3. Analysis

3.1 Preliminary analyses

Several full and periodic slice FEA models of the engine were developed early in the development stage to provide inputs for the detail design.

High-frequency instability in the combustion chamber is caused by the interaction of the gas pressure oscillations and thermal processes during their combustion. A numerical analysis was used to investigate the acoustic oscillation modes of the engine. It revealed that the External Housing is susceptible to transversal oscillations which can interfere with the flow at the throat; and that the LOX inlet tube in the Plug is also critical for longitudinal oscillations.

Built upon this, a high-cycle fatigue model was developed that highlighted various areas across the engine susceptible to fatigue failure. These have been addressed by reinforcing struts, adjusted wall-thicknesses, and refined features.

3.2 Bolted joints

The Plug and External Housing are joined by bolted joints. The role of this connection is to withstand the pressure of the combustion chamber and provide enough preload for the seals during the pre-cooling, firing and post-cooling of the engine.

First, a thermo-mechanical finite element analysis (FEA) was carried out to obtain bolt loads based on combustion chamber pressure, thermal expansion, and seal loading. Computational fluid dynamics (CFD) simulations were used as input to accurately predict the temperature field. Then, the bolts were designed according to the ECSS Threaded fasteners handbook [2]. The greatest challenge was to comply with the low yield strength of the copper alloy flanges, which limited the maximum applicable bolt preload. Overtightening the joints could have crushed the surface of the flange and lead to the loss of preload. The copper flanges also have larger coefficient of thermal expansion (CTE) than the steel bolts, which means their thickness is reduced more than the length of the bolts during engine precooling, leading to further reduction in preload.

3.3 Sealing

To ensure the sufficient sealing of the engine, the gaps appearing during operation in the vicinity of the seals must be kept below the allowable values set by the manufacturer. The thermo-mechanical simulation introduced in Section 3.1 was used for this purpose. Due to the extreme hot and cold temperatures the parts are subjected to, it was necessary to use temperature-dependent elastic modulus, CTE and thermal conductivity values to accurately capture the deformation of the flanges.

The deformation of the flanges can be seen in Figure 8 with an exaggerated scale for better representation. The pressure of the combustion chamber is trying to peel the Plug and the External Housing bolt flanges in the direction of the arrows. The critical seal is the inner one, as it is located farther from the bolt circle and the gap is thus larger. However, it is assumed that possible leakage from the coolant channel to the combustion chamber should not cause detrimental failure, only loss of efficiency due to pressure loss and altered mixture ratio. Nevertheless, gaps around both seals were calculated to be within the allowable range.

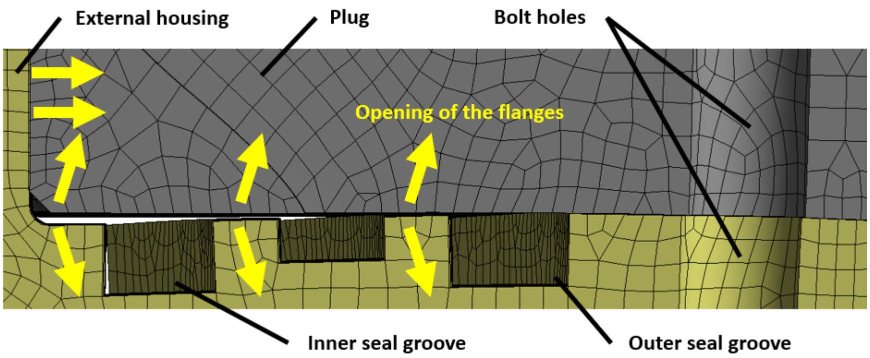

Figure 8 - Seal gap analysis

3.4 Coolant channels

The liners separating the combustion chamber from the coolant channels in the Plug and External Housing are subjected to the most severe loading conditions in the engine. During pre-cooling, firing, shutdown, and post-cooling they experience alternating cryogenic and hot temperatures and pressurization cycles. Subsequently, the material is subjected to tension-compression loading, which can lead to the eventual rupture of the wall [3].

First, material characterization was needed to obtain the temperature-dependent properties in the elasto-plastic region of the material. Then these were fed into ANSYS and used in a thermo-mechanical simulation using temperature and pressure data from CFD simulations. The resultant plastic strain values were compared with material allowables to ensure that the liners will not fail. Tangential plastic strains in the liner during the hot-firing can be seen in Figure 9.

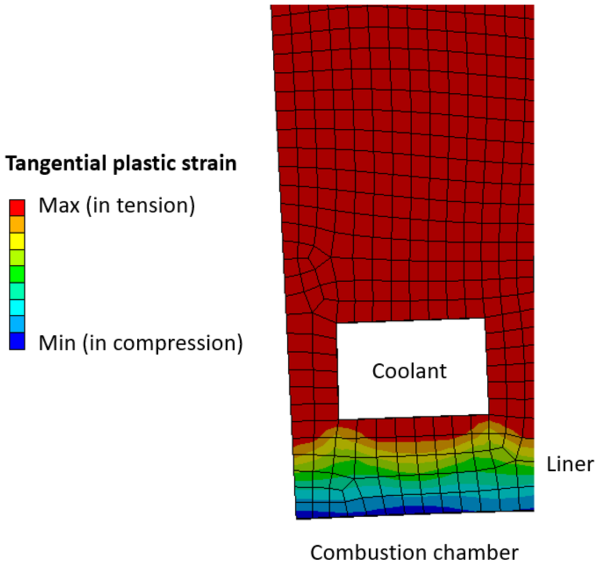

Figure 9 - Tangential plastic strain distribution during hot-firing of the engine

4. Manufacturing

4.1 Plug and External Housing

Direct Metal Laser Sintering (DMLS) was used to manufacture the Plug and the External Housing. Each had a GRCop-42 and a CuCrZr version, printed with EOS M290 and M400 printers, respectively.

As a first step, coupons were manufactured to perform material characterizations and metallurgical examinations. These results not only provided inputs for structural analysis but also for tuning the printing parameters to achieve the intended quality and performance without defects and porosity.

Besides adhering to DFAM principles during the design of the parts, several subscale components were also manufactured in order to qualify the printing processes to achieve the desired accuracy on the final parts. These included injector hole and cooling channel cross-sections, surface roughness of walls with different print angles, shrinkage, and deformation of components etc.

As a final step before printing, the components were modified to include necessary support structures, excess material for machining and other features to aid powder removal and post processing.

The printing was followed by the various combination of powder removal, Computational Tomography (CT) scanning, 3D scanning, heat treatment, welding, and machining steps. The CT scan results were also used to adjust material removal during machining due to discrepancies between nominal Computer Aided Design (CAD) data and “as-printed” components. The final step was the polishing of the combustion chamber liner surfaces. The manufactured Plug can be seen in Figure 10.

Figure 10 - Manufactured Plug

4.2 Igniter

The Igniter was manufactured of Haynes 282 alloy with an EOS M290 machine. Whereas the steps involved were similar to the ones described in Section 4.1 for the Plug and External Housing, the number and complexity of the post processing steps could be reduced as the part was relatively simpler. However, Electrical Discharge Machining (EDM) was used to produce holes for the propellant inlets with required tolerances. A manufactured igniter during hot-fire testing can be seen in Figure 11.

Figure 11 - Igniter hot-fire test

5. Conclusions

The purpose of the development of DemoP1 was to demonstrate the technologies and viability of the systems that are required for a booster-class aerospike engine.

The engine layout was primarily driven by fluidic requirements, additive manufacturing limitations, sealing requirements and assembleability. The final design incorporated two parts and an ignition system, and the cooling of the combustion chamber was achieved with a dual circuit regenerative cooling system using LOX and LCH4.

Analyses were performed to ensure that the most critical subsystems such as the coolant channels, bolted joints and seals can withstand the operating conditions of the engine.

Two versions of the engine have been successfully manufactured from GRCop-42 and CuCrZr alloys.

The development and manufacturing stage of the DemoP1 demonstrator engine has been finished and it is on schedule for hot-fire testing in 2021 Q4.

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7. Copyright statement

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