3D-PRINTED COAXIAL INJECTOR FOR A LOX/KEROSENE ROCKET ENGINE

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Abstract

The European-funded project SMILE aims for a design study of a dedicated Small Satellite Launch Vehicle (SSLV). SSLVs face a strong cost competition from existing big launch systems. In addition to the logistical and mission benefits of a SSLV, cheaper costs per launch are desirable to offer the best solution for the most customers. Liquid propulsion systems are considered to be a very promising solution, as they offer a potential benefit in terms of reusability. Thus, system refurbishment and hence cost-efficient operation becomes possible. It gains even more importance when sophisticated manufacturing techniques are applied. Reusable SSLVs are currently not available on the market. Therefore, the feature of reusability could be an additional economic benefit for small-sat launchers.

Within the SMILE launcher development, a liquid rocket engine was designed for LOX/kerosene propellants and 70 bar combustion chamber pressure. Thereby, the injector head component can be deemed as the most complex subcomponent. The design of a 3D printed injector adds new possibilities for fuel and coolant distribution as well as sensor integration. Therefore, the current work focusses on this specific component. The work is split into design, machining and integration (DLR) as well as printing design optimisation, printing and post-treatment (3D Systems). A first version (HP-DSI v1) of the injector was designed and printed. Internal flow simulations were conducted in order to assess pressure losses and fuel distributions in the feed lines. Subsequent cold flow tests showed a good agreement for each propellant. Finally, hot firing tests were performed indicating short combustion lengths and well performing film layers. Based on the outcomes, a new updated design version HP-DSI v2 will be prepared and tested before project closure.

1 INTRODUCTION

1.1 SMILE Project

In the upcoming years, there is a huge demand for small satellites to sun-synchronous, lower earth orbits. Up to now, nearly all small satellites are launched as secondary payload, i.e. they are entirely dependent of the constraints set by the primary payload, such as launch date and target orbit. Dedicated small-sat launchers could potentially fill the gap and satisfy market needs in terms of flexibility and availability. However, launch costs of less than 50,000 € per kg payload are required when competing with the above mentioned piggy-back ride shares. To this date, there are several launcher initiatives for small satellites but only a few of them are on the edge of being operational.

Hence, 14 partners from eight European countries are collaborating within the Horizon 2020 project “SMall Innovative Launcher for Europe” (SMILE), further described in [1]. It started in January 2016 and continues until the end of 2018. The project covers all aspects of marketing, developing and operating a cost-effective launcher with a well-balanced mix of companies, SMEs, and institutes.

The SMILE project aims at a conceptual design approach for an independent European launcher delivering small satellites up to 150 kg using a multidisciplinary design optimisation approach. Critical technologies like propulsion, structures and avionics will be particularly highlighted. In addition, ground segment provisions will be provided.

The launcher design aims for cost reduction, including design for series production, reusability and the use of components of the shelf as far as possible. To be able to meet the target price, the design will be based on existing advanced technologies as a starting point and drive the development of required new technologies forward as part of the project. The overall objectives of the SMILE project therefore are:

- To design a concept for an innovative, cost-effective European launcher for small satellites.
- To design a Europe-based launch capability for small launchers based on the evolution of the existent sounding rocket launch site at Andøya Space Centre.
- To increase the Technology Readiness Level (TRL) of critical technologies for low-cost European launchers.
- To develop prototypes of components, demonstrating these critical technologies.

1.2 Development Logic of the LPRE Injector for SMILE

DLR has a strong experience in the development and testing of liquid rocket engines. However, LOX/kerosene bipropellants were not considered for rocket propulsion in the recent years. Due to the demands of cost-efficiency, availability and easy handling, LOX/kerosene was chosen as a promising solution. Therefore, existing designs were adapted to this propellant combination.

In doing so, a ceramic-based and a water-cooled thrust chamber assembly are designed and will be tested. The proposed combustor component is made of ceramic liners actively cooled by film and transpiration. In addition, a ceramic nozzle section is foreseen.

The injector head is made via additive manufacturing techniques as described further down. A clustered design is considered which results in multiple turbo-pump-fed sub-scaled engines, depending on the mission scenario. DLR’s engine enables reliable low-cost components to fit into the envisaged target price while offering full reusability potential.

It is favoured to choose modular propulsion components for the entire launch vehicle. This means that the same unitary engines (or very similar derivatives) are used for the first and second stages. Following this approach, the first and second stages can be equipped e.g. with four and one unitary engines, respectively.

Additive manufacturing seems to be an efficient way to significantly reduce production costs for highly complex structures. For this reason, the complex injector component as part of the engine was selected to be manufactured following this approach.

A proper design for additive manufacturing starts with understanding all the required functionalities a part has to fulfil. For many designers, the description or visualisation of pure required functionalities versus design impressions originating from well-known, mature manufacturing techniques is a difficult distinction to make. In the design process for the injector, the technical design was done by DLR, while the *design-for-manufacturing* aspects were integrated and optimised by the application engineers from the Customer Innovation Center of 3D Systems. This co-engineering approach boosted the iterative approach in which step-by-step, the overall added-value of the injector within the complete propulsion system increased.

Drivers for additive manufacturing

The choice for 3D printing was based mainly on following functional drivers:

i) in general, the design of a printed injector adds new possibilities for fuel and coolant distribution, optimising for performance and cooling aspects;
ii) the design of 3D-pathed channels for the propellants via printing allows for an easy implementation of pressure and temperature sensor channels;
iii) the integral injector avoids a substantial number of intermediate production and assembly steps, not to mention the quality aspects related to complex assemblies when using conventional production techniques;
iv) thermal, mass and hydraulic performances can all be independently optimised and are no longer contingent on the selected fabrication methods [2];
v) hence, the injector component is a highly integrated and multifunctional part with very few machining steps.

A short lead time of approximately four weeks made it possible to test more parts compared to other production processes, leading to a larger testing database and reduced development time.

Although weight optimisation aspects were not integrated in HP-DSI v1, a first modest mass optimisation for the future HP-DSI v2 already reduced the mass of the part by more than 10%. The scope of the project phase aimed only at tests on ground, making mass an obsolete criterion.

1.3 Manufacturing Technology

The manufacturing technique used by 3D Systems Leuven (LayerWise NV) to produce the injector is Laser Beam Melting (LBM). Following sections give a short description about the technology, hardware, software and material used.

1.3.1 Technology: Laser Beam Melting (LBM)

Laser Beam Melting – also called Direct Metal Printing (DMP) by 3D Systems – is an Additive Manufacturing (AM) technique in which successive layers of metal powder are selectively molten by the interaction of a laser beam and thus forming a layer-by-layer product from a 3D model CAD-file. Figure 1 shows a schematic of this LBM process.

Great progress has been realised in the development and optimisation of the LBM technology, which has resulted in the production of consistent high quality and fully dense parts. Consequently, the AM market has extended from prototyping to serial production as well as customized part production of a wide variety of metals for high end applications, such as aerospace, automotive and healthcare [3].

The LBM technology offers a wide range of advantages:

i) a short time-to-market,
ii) a high material utilization rate,
iii) a high degree of geometrical freedom,
iv) a reduction of process steps, leading to shorter lead times,
v) an extended life time / enhanced performance of a part (eg. by internal cooling channels) and
vi) a near-net-shape production.

These advantages make the LBM technology competitive with conventional manufacturing techniques [4].

The ProX™ DMP 320 metal printer is designed for high precision, high throughput Laser Beam Melting (LBM) and is optimised for critical applications requiring complex parts.

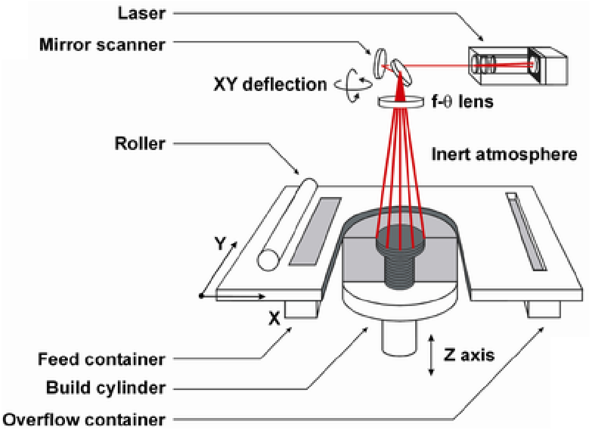

Figure 1: Schematic of the Laser Beam Melting (LBM) process

1.3.2 Machine: ProX™ DMP 320

Thanks to the unique vacuum chamber concept of the ProX DMP 320, argon gas consumption is heavily reduced while at the same time the printer has shown to be best in class atmosphere purity characterised by low oxygen levels (~25 ppm). This results in several key benefits, including a better conservation of powder quality, fewer oxide interstitials during printing, and improved mechanical properties specifically for O2-sensitive alloys.

To obtain high surface quality - mainly for the internal cavities as those cannot be post-processed easily - a layer thickness of 30 µm was chosen for the production of the injector.

Figure 2: ProX™ DMP 320 (building envelope 275x275x420mm; 1 laser of 500W)

The metal additive manufacturing software 3DXpert™ – used for the file preparation – is a powerful tool to prepare and optimise part data quickly, enabling rapid design for metal additive manufacturing to shorten production time and increase part precision.

2 DESIGN AND DEVELOPEMENT

For the design of LOX/kerosene rocket engines, state-of-the-art and robust technologies were envisaged. Therefore, coaxial injection techniques were found to be promising candidates for a proper injection system. For the current approach, both propellants are in supercritical/liquid state, hence a double swirl injector was chosen. Figure 3 shows a functional sketch of a corresponding double swirl injector element with internal component mixing.

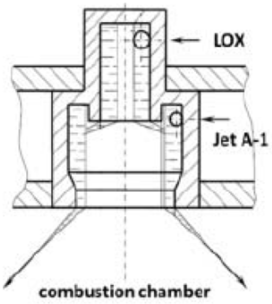

Figure 3: Sketch of a liquid-liquid double swirl injector element with internal mixing zone

2.1.1 Functional Requirements

Besides oxidiser-fuel mixing functionality, two different cooling solutions were implemented in the injector. Both solutions consist of fine channels with minimum feature sizes of 0.2 mm and maximum length/diameter ratios of 45.

More detailed, a classical film laying element is integrated into the injector element which enables to directly adjust the film mass flow rate at the injector.

Furthermore, a coolant distribution system for transpiration was installed; as the combustion chamber walls are made of permeable ceramics they can be transpired by the chosen coolant (preferably kerosene fuel) and thereby be convectively cooled. An additional coolant film forms on the inner hot side and protects the wall structure from high temperatures. In case of a coolant malfunction, the ceramic material is still able to withstand the occurring heat fluxes in a passive way for a certain time. The combination of all functional requirements is depicted in Figure 4.

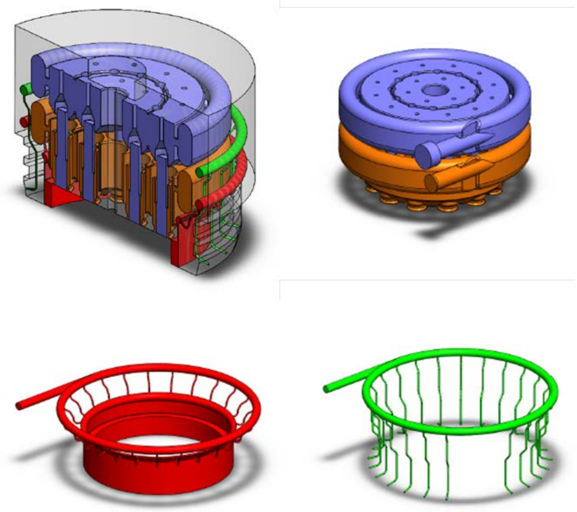

Figure 4: Flow volumes of the HP-DSI v1.8; orange = kerosene, blue = LOX, red = film layer, green = transpiration cooling

Compared to classical regenerative cooling, both mentioned cooling techniques comprise very low pressure losses which is favourable for the propellant (and coolant) feed system as the overall pressure loss is substantially smaller. This allows for instance for less turbo-pump performance or on the other side for elevated combustion chamber pressures and hence engine performance.

The remaining functional requirements were to implement a mechanical interface to the surrounding structures and data acquisition like: combustion chamber, ignitor, pressure sensors and thermocouples. The latter imposed the need for more accurate CNC post-machining operations on a lathe to foresee some sealing surfaces and smooth interface surfaces.

2.1.2 Operating Conditions

In order to allow for subsequent testing, a sub-scaled version of the designated propulsion system was designed [5]. Because of cost reasons and available infrastructure, the maximum mass flow was limited to 2.45 kg/s. All design parameters are listed in Table 1.

Due to mission requirements, a combustion chamber pressure of 70 bar was chosen; this resulted in 18 single coaxial elements for the injector head.

Table 1: HP-DSI parameter

Combustion chamber pressure $\mathbf{p_{cc}}$	70	bar
Overall Mixture ratio	2.4	-
Nominal Thrust	7.5	kN
Total mass flow $\dot{m}_{tot}$	2.45	kg/s
Mass flow LOX $\dot{m}_{LOX}$	1.75	kg/s
Mass flow kerosene $\dot{m}_{Kerosene}$	0.73	kg/s
Mass flow main fuel $\dot{m}_{mf}$	0.55	kg/s
Mass flow film cooling $\dot{m}_{fc}$	0.09	kg/s
Mass flow transpiration cooling $\dot{m}_{tc}$	0.09	kg/s
CC diameter	0.075	m
Number of elements	18	pcs

2.1.3 Material: Ni718

Ni718 LaserForm® (A) is a precipitation hardening nickel chromium based superalloy with a high niobium content. Together with the many other alloying elements, a wide variety of complex phases is formed in the microstructure. This variety of complex phases contributes to the challenge of controlling the microstructure in order to obtain desirable strengthening phases such as: γ' face-centred cubic (Ni_3Nb) phase, metastable γ" body-centred tetragonal (Ni_3Al) phase and the needle-like δ orthorhombic (Ni_3Nb) phase [6] [7]. A sequence of heat treatment steps is needed to obtain a proper distribution of these complex phases, to result in excellent mechanical and corrosion resistant properties.

The high cooling rates of the LBM process allows directional, dendritic-cellular grains to grow, thus a microstructure with columnar grains in a supersaturated state is obtained. Yet, the poor diffusibility of the heavy elements like niobium and molybdenum may lead to micro-segregation [6]. Consequently, brittle intermetallic Laves $(Ni,Fe,Cr)_2(Nb,Mo,Ti)$ phase can precipitate in the interdendritic region due to the interdendritic segregation of Nb [8]. The high cooling rates from the LBM process might partially inhibit segregation of Nb and reduce the formation of the brittle Laves phase. Yet, it is likely that the Laves phase is still present in the LBM microstructure. The presence of Laves phase may form a preferred site for crack initiation and can affect the strength and ductility as well as fatigue and creep properties at both room temperature and elevated temperature [9]. Further research is required to confirm this hypothesis. In addition, NbC is less prone to precipitate in the matrix upon fast cooling. However, Zhang et al. [10] claims that fine globular NbC might still be present in small fractions in LBM microstructure.

Table 2 shows the mechanical properties of the ProX DMP 320 Ni718 for the conditions As-built, Homogenization Solution Annealing Ageing (HSAA) and Direct Ageing, respectively. The as-built condition obtains a high elongation but with impaired strength. Upon heat treatment, the material is hardened through precipitation of the strengthening phases γ' (Ni3Nb) and γ'' (Ni3Al). Yet, it is important to note that similar strength properties are obtained after HSAA as well as Direct Ageing. This observation finds its reasoning in the inherent characteristics of the Direct Metal Printing Process. During LBM of Ni718, a similar supersaturated condition of the Ni γ-matrix is obtained as it is the case after a solution annealing heat treatment followed by argon quenching. Therefore, Ni718 manufactured by LBM can undergo directly an age hardening heat treatment without prior solution annealing with subsequent argon quenching. The Direct Ageing heat treatment allows a significant time reduction of heat treatment without impairing strength properties. For this reason, the two-step Direct Ageing heat treatment is applied at 720°C and 620°C, respectively. The heat treatment allows the material to relief residual stresses and hardens the material through precipitation hardening.

Table 2: Mechanical properties of ProX™ DMP 320 Ni718 Laserform® (A)

Condition	UTS (MPa)	Yield Strength (MPa)	Total Elongation (%)
As-built	970 ± 20	680 ± 20	28 ± 1
HSAA[1]	1340 ± 20	1200 ± 20	14 ± 2
Direct Ageing[2]	1380 ± 20	1220 ± 50	11 ± 2

Mechanical properties derived from tensile testing of vertical flat tensile specimens.

[1] HSAA: homogenization (1065°C) + solution annealing (980°C) + ageing 1 (720°C) + ageing 2 (620°C)

[2] Direct Ageing: ageing 1 (720°C) + ageing 2 (620°C)

2.1.4 Design & Prototyping phase

Knowing the main functional requirements with their dimensions and volumetric design space, the most important decision - at the earliest stage possible - is to determine the orientation in which a part is printed. The layer-by-layer process inherently means that not all geometries can be printed in any orientation, see Figure 5.

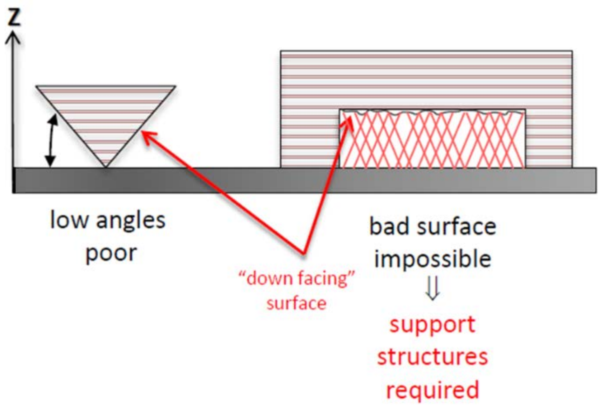

Figure 5: Extract of design rules for LBM by 3D Systems

Furthermore, the orientation of surfaces also influences the roughness. A well-known property is the *stair-casing effect,* also strongly depending on the layer thickness used to manufacture a part, as displayed in Figure 6.

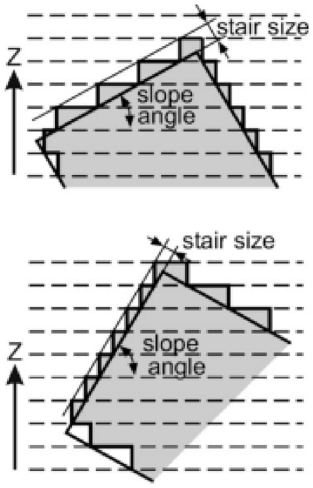

Figure 6: Different sizes of stairs related to the orientation of a surface

Typically, the smallest and/or most complex elements determine the orientation. In the case of the injector, it is the 0.2 mm cooling film gap (the axis of the cylinder) imposing a vertical orientation. This reduced the amount of potential orientations to two. The removal of powder out of all internal cavities – together with a firm connection to the baseplate – finalized the orientation with all exit holes pointing upwards.
A next challenge was to avoid the need for any support structure in cavities where a controlled method to remove support structures afterwards would be impossible to implement. Mainly for the cavities where oxidizer and fuel are mixed, a dome-shaped redesign drastically reshaped the internal lay-out, requiring a new CFD validation.
The large inlet channels are printed with their axis parallel to the horizontal plane. A rule of thumb is that horizontal channels can be printed without the need for support if the radius remains below 4 mm. Although the channels were designed with a circular cross-section exceeding this maximum size, the functionality only handles about a certain mass flow. The result was to reshape circular channels to an oval cross-section, guaranteeing the performance of the injector.
With a volume of around 500 cm³ of material that requires melting, the thermal stresses during the production are substantial. Although anticipated by designing a flat bottom side and placing it directly onto the building platform to have a rigid connection, plastic deformation due to thermal stresses was the root cause for two different leakages on one of the first prototypes, as depicted in Figure 7.

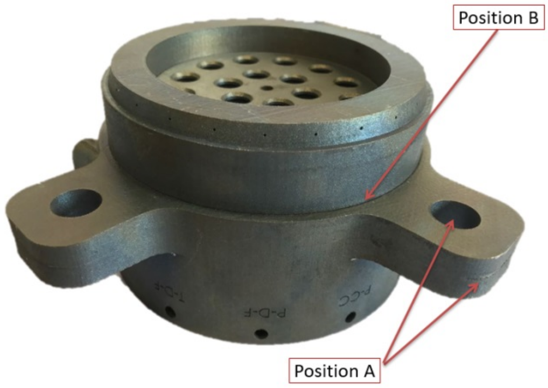

Figure 7: Locations of leakages on HP-DSI v1.6

Position A
High thermal stresses caused a support structure underneath the four mechanical interfaces to brake abruptly, leading to a shift at that layer in the part. During pressure testing it became clear that liquid from the nearest internal cavity – however more than 10 mm further away – escaped the injector through this porous layer.
In next iterations, the support structures to avoid plastic deformation were reinforced.

Position B
As one of the last steps in a proper design cycle for LBM, stress concentrators are avoided by shaping a part as organically as possible. This means that sharp edges – for many conventional production techniques a preferred transition between surfaces – should be adjusted by implementing fillets. The radius in position B was too sharp, leading to a stress concentration during

the printing process, where a crack originated. After machining this zone to implement sealing grooves, it became clear that the defect was not a superficial crack, as shown in Figure 8.

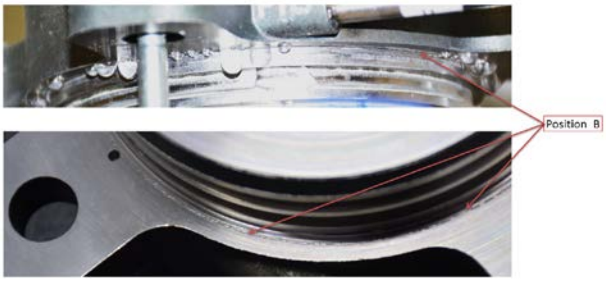

Figure 8: Leakage in a circular pattern due to crack on HP-DSI v1.6

The defect in position B however could be repaired using laser welding.

2.2 Manufacturing process steps

Although the focus is mainly on the printing technology, a ready-to-use metal-printed part typically runs through a dozen important process steps, as shown in Figure 9.
Some specific aspects of the process for the injector are discussed separately.

Figure 9: Manufacturing flowchart for the injector

2.2.1 Powder removal

For the injector, special attention was given to the challenging task of removing all remaining powder out of the internal cavities and channels. A weight of almost 30 kg, baseplate included, is difficult to handle manually. It is however essential to remove all powder in this phase since - once the part had its heat treatment - any remaining powder does not flow anymore. The part has to be stress relieved while still attached to the baseplate as thermal stresses are induced in the baseplate as well.
Furthermore, the default operation of only using compressed air is insufficient to guarantee all powder is removed.
Therefore the part got a combined treatment in which pressurized air (Figure 10) and vibratory systems in different angles of orientation were used to evacuate powder. Functional testing of the channels at this stage is difficult since interfaces are not suited yet to fit leak-tight connections. Tomography is a possible alternative, but because of the large wall-thicknesses in combination with fine channels, also this process cannot guarantee 100% cleanliness.

Figure 10: Illustration of the powder removal process

2.2.2 Micro shot peening

Most of the functional elements in the injector do not get any special surface finishing. Besides CNC machining, shotpeening is the only process affecting the condition of the surface.
The shotpeening process performed by 3D Systems Leuven happens with ceramic material rather than metal beads, meaning the process induces a negligible amount of compressive stresses at the surface to improve on fatigue performance. The main benefit of shotpeening is that the process removes any potential semi-

sintered particles, smoothening the surfaces and improving cleanliness aspects.

Controlling this process at internal cavities is very challenging again so determining, verifying and fixing the process parameters are important to optimise for repeatability.

Previous experiments [11] confirmed no additional post-treatment like turning, abrasive flow machining or chemical polishing to reduce the surface roughness further are required for liquid rocket injectors.

2.3 Injector Characterisation

The first design cycle in the SMILE project resulted in the production of HP-DSI v1.8 which was successfully fire tested. Figure 11 shows the machined component prior testing.

Figure 11: Liquid propellant injector HP-DSI v1.8

Injector HP-DSI v1.8 has a weight of 3.6 kg and bounding box dimensions 166 x 166 x 68 mm. The manufacturing time on a ProX DMP 320 system in Ni718 material with a layer thickness of 30 µm is 60 hours for one part in a single job.

2.3.1 Film Layer

The fully integrated film layer is injected at the faceplate of the HP-DSI. A homogenous film demands for a proper coolant distribution. Hence, the feedline connects tangential to the manifold and splits up into 25 channels connected to the injection slit. To validate the performance of the film cooling feedline, several design iteration loops were performed. Figure 12 displays the pressure losses (left) as well as the coolant streamlines (right). The nominal mass flow of 90 g/s Jet A-1 results in a pressure loss of $\Delta p_{fc} = 1.4\,bar$. First cold flow checks demonstrated a homogenous film as displayed in Figure 12 (bottom).

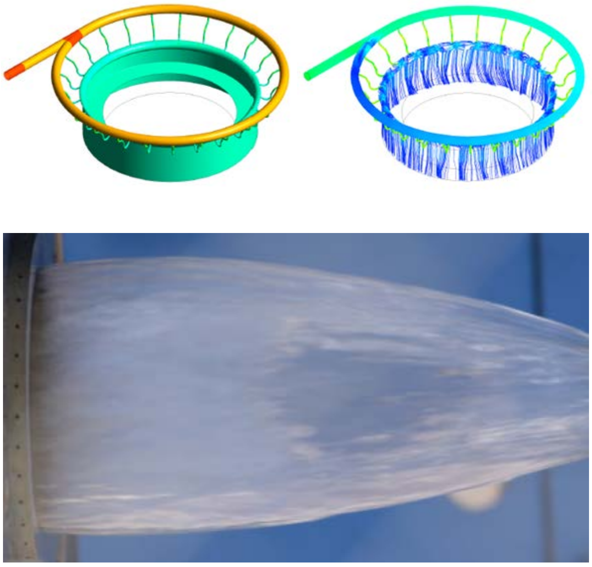

Figure 12: Pressure gradient numerical analysis of the film layer of the HP-DSI v1.8 (top) and flow test image with 90 g/s Jet A-1 (bottom)

2.3.2 Main Propellant Flow

The main propellant flow is more complex to analyse. The two propellants LOX and Jet A-1 are different in all physical properties and most important in injection temperature. The numerical analysis was necessary for a design regarding the requirement for a proper pressure loss of $\Delta p_{inj} = 0{,}2 * p_{cc}$.

Numerical analyses of the propellant distribution are mandatory as classical design philosophies have to be skipped and adapted to the new AM processes. The principle design of a single injector element was carried out in first place; it is the major design driver for the spray angle and induced pressure losses. Furthermore, the geometry of the two coaxial tubes had to be tailored to efficient propellant mixing.

Considering only a single element is also beneficial regarding computing resources as the CFD mesh is much smaller compared to the entire injector component.

After the iterative design on single elements, the HP-DSI was analysed further as whole. These investigations focussed on the propellant distribution and the pressure losses in the domes. Figure 13 displays the pressure distribution results of the HP-DSI v1.8 of the final iteration. The calculated pressure losses in the LOX ($\Delta p_{inj,LOX} = 32\,bar$) as well as in the fuel ($\Delta p_{inj,Jet} = 9\,bar$) manifold were confirmed later at the cold flow tests.

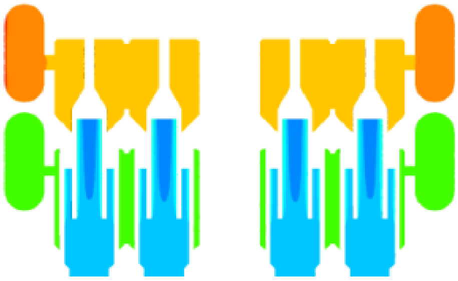

Figure 13: Pressure gradient numerical analysis for the main flow of HP-DSI v1.8

Future optimisation efforts aim to adapt the pressure losses towards the envisaged levels of $\Delta p_{inj} = 0{,}2 * p_{cc} = 14\ bar$, which was not achieved yet. It is also important to equal the values for a smoother start up sequence.

Cold flow tests at PLD Space added valuable information for the development of the injector, not just for the internal flow but also for the spray behaviour. The displayed spray photographs in Figure 14 show both the LOX and Jet A-1 spray.

The LOX spray test was performed with LOX and gaseous nitrogen in parallel for safety reasons. The measured internal values of the injector feed system were in good agreement with the simulations. All conducted cold flow spray tests indicated homogeneous injection. Subsequently, first hot firing tests were aimed for.

Figure 14: Cold flow test image with nominal mass flow of LOX/GN2 (bottom) and Jet A-1 (top)

2.3.3 Hot firing

After several cold flows and ignitor tests, the HP-DSI was hot fire tested. The fine tuning of the ignition system provoked some delays, but first attempts of starting up the sub-scaled engine resulted in the first successful start in October 2017. The hot run was executed for 5 seconds duration with steady state conditions after 2 seconds. The generated data indicate a short combustion length and a well performing film layer. Two hot runs were performed and will be used for the future development of the HP-DSI v2.

Figure 15: Liquid propellant injector HP-DSI v1.8 hot firings, with a water-cooled combustion chamber (PLD Space high pressure test bench, 2017)

3 CONCLUSION

Within the SMILE project, LOX/kerosene liquid propulsion systems were considered which enable system refurbishment and hence cost-efficient operation. DLR designed the first injector version HP-DSI v1 for 70 bar operation. This component was considered to be 3D-printed. Before full-scale printing, one partial proof-of-concept was printed. LBM production - although mature enough to produce satellite flight parts on a weekly basis at 3D Systems Leuven - still requires an iterative design approach and prototyping phase. The disruptive design mind-set, the geometrical deviations inherently coupled to LBM, the radically different surface properties, the complex chain of manufacturing processes, and the lack of adequate simulation tools to simulate the entire production process to expose its potential risks and technical issues.

The cost of a series production of injector parts required to assemble a small European launcher was studied. Taken into account that the estimated annual production rate achieves a dedicated number of launches per year, it can be concluded that the production costs of the 3D printed injector component is cheaper compared to state-of-the-art injector heads manufactured via conventional manufacturing methods.

Numerical simulations on internal flows were conducted to estimate the fuel distributions and associated pressure losses in the feed lines for each propellant. Cold flow tests for each propellant showed a good agreement between numerical and experimentally measured data.

Final hot firing tests confirmed a good performance for both mixing and cooling techniques. This paved the way for the further development of a new updated injector version, HP DSI v2.

4 ACKNOWLEDGEMENTS

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