Design, analysis and testing of a 3.5 kN Coaxial Pintle Demonstrator Engine

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Within an Astrium self-funded Research and Technology project called HOMER (HOver ManeuvER) a vehicle platform was built aiming at the demonstration of key capabilities required for future space exploration. To fulfil the project objectives, e.g. the ability to perform take-off, descent and soft landing or the demonstration of high reactivity lateral manoeuvres for hazard avoidance a powerful propulsion system was required. One major building block is the liquid rocket demonstrator engine tailored to these specific needs.

The key requirements for the engine development were derived from the demonstration objectives: a thrust level of 3.5 kN at sea level, the capability for thrust modulation, the use of a high energetic, hypergolic storable propellant combination MON/MMH, and a compact and lightweight design working at elevated propulsion system pressures in a range of 40 to 80 bar. Beginning from scratch an engine concept was defined comprising a coaxial pintle injector, a highly integrated flow control valve with dual face shut-off and a full metallic combustion chamber.

In general the development logic has foreseen a strongly integrated and concurrent engineering approach where design and analysis work was followed by manufacturing and subsequent verification to meet tight schedule and financial constraints. For the engine demonstrator the goal was to raise TRL from 3 to 6 during the project.

Following a conceptual phase for the engine the detailed design and manufacturing was initiated. Already during this period of the work in-house engineering capabilities were considered to capitalize on existing know-how and experience at an early stage. Analyses have been done by using state-of-the-art tools addressing the following topics: prediction of transient engine system behaviour, prediction of engine performances and combustion stability limits, description of the injector hydraulics, combustion modelling, thermal modelling and structural mechanics.

To verify hardware behaviour and to validate the applied analysis tools different tests were performed on single components and engine level throughout the development: tests to describe transient flow control valve behaviour with water/Helium, hydraulic injector cold tests with water, hot-firing tests with a battleship hardware and finally successful hot-firing of the demonstrator engine. This led to a release of the vehicle demo flight, which was performed successfully in October 2012.

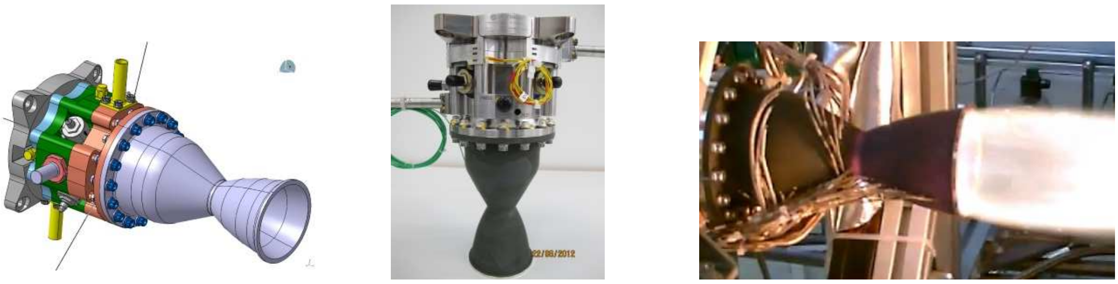

Figure 1: The HOMER 3.5kN coaxial pintle demonstrator engine.

The paper presents the test results obtained during the test campaigns with a comparison to the analyses and the design predictions that were performed for the pulsable 3.5 kN coaxial pintle demonstrator engine. The paper treats the design of the pintle, the combustion chamber and the nozzle, the hydraulic behaviour, the trimming of the hardware to meet the main propulsion system interface conditions, the combustion simulations and cooling film prediction, the thermal modelling and results, and finally the combustion performance of the engine.

Brief overview of contents

- **Combustion chamber and pintle injector design optimization**

The combustion chamber design was optimized to achieve a stable combustion within the operational envelope. During the hot firing test campaign, the low frequency stability limit of the engine was determined. In addition, gas ingestion tests were performed to evaluate the thruster response. The overall combustion roughness within the test envelope was within expectations.

- **Nozzle design optimization**

The contour of the nozzle extension for the engine was designed for optimal thrust at sea level conditions. Several optimization procedures were considered and the theoretical thrust and specific impulse were compared to test results.

- **Trimming**

A trimming of the thruster was performed to meet interface pressure requirements at the design point. To perform the trimming, a numerical thruster model was developed to predict the attained operating point (chamber pressure and mixture ratio) as a function of the imposed interface pressures. The model incorporates the established experimental combustion efficiency and the hydraulic pintle behaviour. The trimming was performed by means of orifices. Simulations and successive cold flow tests were performed to establish the hydraulic behaviour of the pintle and the manufactured set of orifices. The final required orifices were determined in hot firing tests.

- **Combustion simulations and film predictions**

Combustion simulations were made. These simulations also included a modelling of the oxidizer cooling film that is laid onto the combustion chamber wall as an inherent feature of the current pintle injector. The modelling of propellant disintegration, film deposition and evaporation and well as combustion determine not only the thermal loading but also the performance predictions of the engine.

- **Thermal modelling and results**

The pintle engine test hardware was instrumented with several circumferential and axial arrays of thermocouple sensors. One of the specific aims was to verify the presence, distribution and length of the cooling film. The measurements were compared to transient simulations results obtained from an ESATAN thermal model including film cooling.

- **Thruster performance**

The thruster performance has been characterized over the course of several hot firing test campaigns. A synthesis of these results is made, showing the dependence of the performance on mixture ratio and chamber pressure.

- **Comparison flight vs. test bench performance**

The demo flight operating point was evaluated using the thruster model based on the expected thruster performance and hydraulic behaviour. A comparison was made to the measured combustion chamber pressure and the mass flow rates obtained from the feed system orifices.