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CNES/DLR cooperation for the preparation of future reusable launcher cryogenic engines

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Abstract

Cooperation has started between the German Aerospace Centre, DLR Lampoldshausen and the launcher directorate of the French National Centre for Space studies CNES. Aim of the collaboration is the preparation of technologies and tools for the future cryogenic engines, in particular using methane as propellant. In this first step, the main focuses are the combustion chamber thematic (ignition, combustion, chamber cooling), the system analysis of engine coupled with test bench, and the turbopumps.

1. Introduction

Up to now, main stage engines of European launchers have been using oxygen / hydrogen combustion. In the future, the imperatives for low cost and reusable rocket propulsion are challenging the established solutions. The combination of liquid oxygen and methane for launcher propulsion has been studied around the world in recent years as an interesting compromise between cost and performance.

The LOx / methane reusable prototype engine Prometheus (Precursor Reusable Oxygen METHane cost Effective propUlsion System) is considered as an essential first step towards the very low cost European system launchers. The new engine aims a very low cost engine, with 100 Tons vacuum thrust level, compatibility with lower and upper stage uses, LOx/CH4 propellant combination, designed around a Gas Generator cycle with a high thrust modulation, and including robust reusability features. The project was initiated by CNES and ArianeGroup and is now developed in ESA (European Space Agency) FLPP-NEO (Future Launchers Preparatory Program - NEO) program framework.

In order to accompany this crucial project for the future of European launchers, discussions between the partners CNES Launcher Directorate and DLR Institute of Space Propulsion started in 2017. First objective was an exchange on the technological roadmaps for oxygen / methane engines. Then, common working plans covering the different technical domains were defined and agreed and are now in progress on both side. In addition, the results obtained thanks to this cooperation, will also contribute to the validation of the technological platform Boreas developed by CNES on French side (with ArianeGroup SAS company) and Lumen developed by DLR/RA.

The first topics identified for the cooperation were the system analysis of engines coupled with test benches, the methane combustion problematics, with a focus on injection and heat transfers and turbopumps.

The system studies are first focused on the transient simulation of the demonstrator engines and their dedicated test benches (the new position P8.3 at DLR Lampoldshausen for Boreas and Lumen, and the modified P5 for Prometheus). The results are then coupled to permit the full simulation of start-up process and transient operations of the engine on the test position.
The study of the heat fluxes in the combustion chamber is tackled incrementally with simulations of a test case for the hot flow side using the results coming from Mascotte test campaign performed by ONERA, test and simulation of the cold flow side using the results coming from electrically heated tube (EHT) test campaign performed by DLR, before addressing the simulation of the full coupled problem.

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Regarding turbopumps, a first item of interest is related to the cavitation, in particular when using LNG as propellant. Test and CFD simulation are foreseen. Other activities related to 0D tools benchmarking and bearing testing and rotordynamics are under discussion.

The present paper describes in detail the different cooperation activities included in the framework of the cooperation agreements signed between CNES and DLR. Some first results of the common work are also presented.

2. System analysis

2.1 Work logic

The system engine and test bench modelling activities aims at improving the numerical simulation tools at system level in support of the current and future engine development programs, starting with Prometheus, BOREAS and LUMEN. All the modellings is performed in parallel by both partners using two different tools, CNES in-house simulation tool CARINS [1,2] on one side and EcosimPro/ESPSS on DLR side.

The work plan is divided into four main work axes. The first step for the cooperation is an exchange on component level to make sure that both tools have comparable features. The second work package concerns the modelling of existing test benches at DLR Lampoldshausen. Engine modelling constitutes the third work package with the modelling of three already defined engines: Boreas, Lumen and Prometheus and potentially a forth joint demonstrator. The last step consists in the coupling of test bench and engine modelling, starting with Boreas and Lumen both at P8.3 bench and Prometheus at P5 test bench.

2.2 Component modelling

The first activity focuses on the development of component numerical models with a lumped parameters approach. The idea is to dispose of a set of components that can be, later, assembled in order to create complete engine and test bench simulators. The models are based on physical conservation laws as well as empirical well-known relations and they should be able to take into account all physical phenomenon relevant to the components functioning phases. To be able to compare the results of different complex simulators it is important to know the modelling strategy considered for the elementary bricks and the physical phenomena taken into account.

This activity was the first to start with the modelling of single sub-components at the beginning and a progressive increase of complexity. The following test case is the integration of volumes, pipes, valve and orifice into the filling of a tank from a source. The next figure illustrates the synoptic associated to the test case under EcoSim on the left and with Carins on the right.

The media is Lox with an inlet pressure P1 of 15, 10 and 5 MPa and a temperature of 100K. Different pope geometries in lengths and diameters, different number of nodes for the pipe discretization and different opening laws for the valve have been tested and compared.

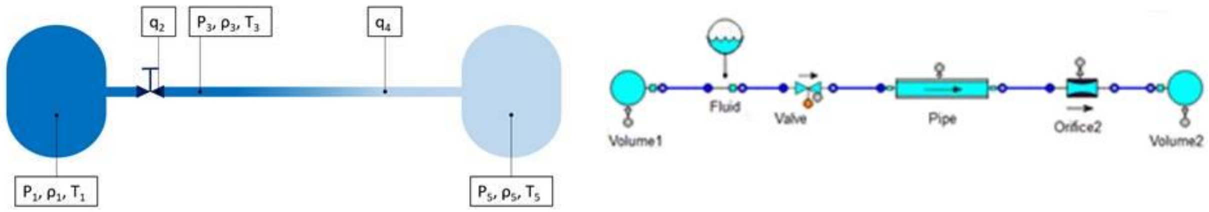

Figure 1: Tank filling test case modelled with EcomSim (left) and Carins (right)

The comparison of the results obtained so far has shown satisfactory behaviour of the physical parameters from both partners. The differences are mainly due to heat transfer models and will be investigates in future activities.

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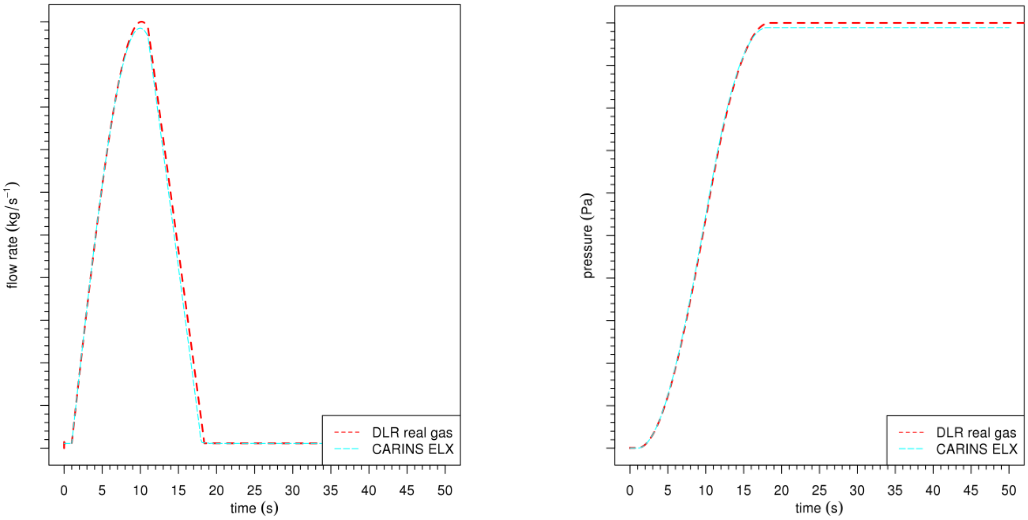

Figure 2: comparison of mass flow evolution at orifice and tank pressure evolution

2.3 Demonstrator engines

The main objective here is the creation of complete engine numerical models using the models developed previously as fundamental bricks for the system simulator. In the framework of the modelling activities will concentrates on four engines: BOREAS, LUMEN, Prometheus and a future CNES/DLR joint demonstrator. Models should be suitable for the simulation of the steady-state functioning of the engines but also for the transient functioning during the switching to different functioning points and during the ignition and extinction phase.

Since none of these engines have been tested on a test bench yet, their validation could not be done with experimental data-set, but a comparison between CNES and DLR simulation results will permit to identify potential lack of modelling or physical phenomena in the models or on the contrary to confirm some modelling choices and the results obtained.

2.4 Test bench modelling

This activity aims at creating models for the simulation of the test benches relevant for the on-going projects. The numerical models will help to foresee the functional behavior of the benches and to anticipate their capability to fulfill the demonstration objectives. Additionally, they can be used for estimating the maximum capacities of the system. Existing functional test data can be used for the validation of the numerical output of the models. The reduced-parameter models will take into account transient behavior of the flow and the physical phenomena with non-negligible account on the functioning of the test benches, e.g. two-phase flow, heat transfer and water hammer.

Three test benches are of interest for the present study: P8.1, a high pressure bench with a large amount of validation data, P8.3, a low pressure bench under development for the testing of both demonstrator Boreas and Lumen, and P5, the full-scale bench of main stage engines like Prometheus. The modelling of P8.1 bench has started. Fig. 3 is a simplified representation of test bench P8 configuration.

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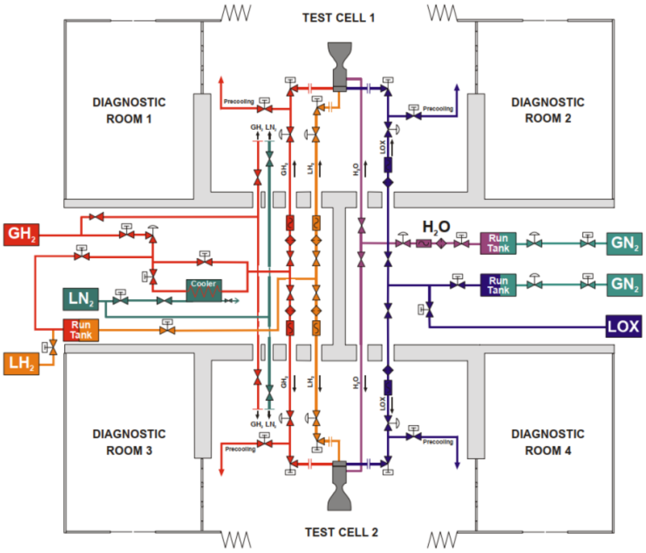

Figure 3: simplified synoptic of P8.1/2 test bench

Starting the activity with modelling of P8.1/2 offers the possibility to test the improved models developed in the first activity with a large number of available data sets. The subdivision of each work package is oriented on the relevant feed lines (FL), e.g. LOX FL, LH2/LNG FL. This allows the creation of separate models, which can be validated using different data sets, and in future the subsequent combination of these feed line models into full test bench models. These analyses permit to increase the confidence in the numerical models and to collect evidence on which physical phenomena may be negligible for their impact on the global functional of the systems.

2.5 Coupled simulations

In this last activity, the simulators of the engines and test benches will be lumped together into lumped simulations. The transient and steady-state behaviour will be assessed. The respective run-in data of Boreas (LOx/LH2 engine) and Lumen (LOx/LNG engine) at P8.3 bench offer validation test cases for the coupled system behaviour. Coupled simulations of Prometheus coupled to test bench P5 will be performed as a preparation of the up-coming test campaign.

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3. Combustion chamber

3.1 Work logic

The propellant combination LOX/methane poses additional challenges for combustion modelling compared to LOX/LH2. The current CFD combustion methods need to be adapted and improved for accurate simulations of thermos-physical phenomenon in combustion chambers. The two main characteristics that can be studied to validate the CFD combustion methods are the flame topology and heat flux prediction.

The goal of these activities is the development of a CFD tool for the study and prediction of the behaviour in LOX/methane combustion chamber. A step by step strategy is implemented to try and de-couple the different physical phenomena taking place in a rocket engine combustion chamber.

The work plan is divided into three main work steps, with a gradual increase of the problem complexity: the characterization and simulation of the LOX/methane combustion and the generated heat fluxes, the study of the “cold side” (heat flux on coolant side), and the coupling of combustion and cooling aspects.

3.2 Hot side heat flux – BhPhRM test case

The study of the heat flux on the hot side is based on an existing test case. The BhPhRM (high pressure and high Mixture Ratio combustion chamber) test specimen was operated at the MASCOTTE test bench at ONERA laboratory [3-6]. It is composed of an injection head, two calorimetric sectors for temperature measurement of the wall and an optical window that can be placed up- or down-stream of the calorimetric segment for flame diagnostics. The tests were performed under various configurations during a 2018 campaign performed with the full calorimetric configuration as illustrated in Fig. 4. No optical access was used during this campaign. This configuration supplies full information on wall temperature and thermal flux (inversed method) along the combustion chamber.

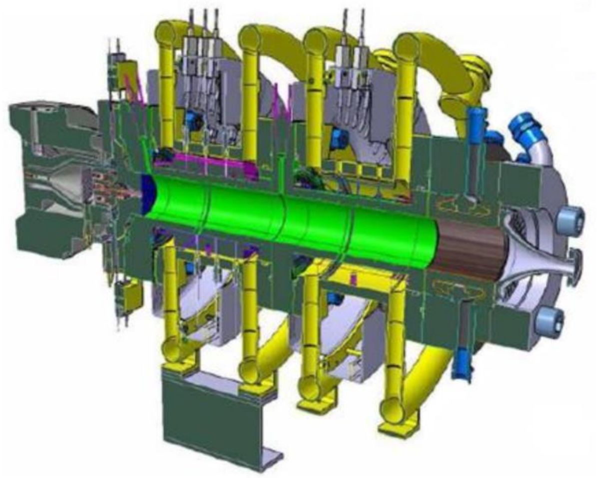

Figure 4: BhPhRM full calorimetric configuration

The injection head offers two configurations of the five oxygen injectors with a variation of external to central injectors distance (30 mm and 40 mm). This variation permits to study the influence of wall-flame distance. Both calorimetric sectors measure 200 mm in length and 56 mm in diameter. They are water cooled and well instrumented for accurate temperature information along the combustion chamber and the cooling circuit. The first segment presents 33 thermocouples both in hot and cold side wall and 18 in the coolant; the second segment presents 18 and 6 thermocouples.

Two types of injectors have been implemented with different inner diameter of the oxygen coaxial injector: LH injectors, with high momentum ratio (2.5 to 41) in LOx and GOx conditions and LB injectors with lower momentum ratio (0.4 to 7) in LOx conditions.

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For this activity two test cases were chosen from the test matrix. Test case A features super-critical conditions at combustion chamber pressure of 6.2 MPa and mixture ratio of 3.35 with LH injectors and two configurations with both injector geometries. Test case B features sub-critical conditions at combustion chamber pressure of 3.3 MPa and mixture ratio of 3.4 with LH injectors in the 30 mm configuration. An optional alternative is proposed featuring the same conditions with LB injectors.

3.3 Cold side heat flux – EHT campaign

The objective of this work package is the study of the cold side decoupled from the combustion phenomena. This activity will also allow improving the current correlations used to predict the behavior of the methane during its heating process mainly applied to diphasic flows.

The Electrical Heated Tube (EHT) is a setup specifically developed and manufactured to investigate heat transfer processes in cryogenic fluids at sub- trans- and supercritical conditions. EHT can be operated at up to 10 MPa or at Pr= P/Pcrit up to 2.2 (for methane critical temperature is 190.6 K and critical pressure 4.61 MPa). A common test campaign is in preparation to investigate methane cooling and to generate an experimental database for the validation of numerical simulations and the improvement of CFD methods. The next campaign will take place at facility P6.1 at DLR, which allows a wider range of operation conditions.

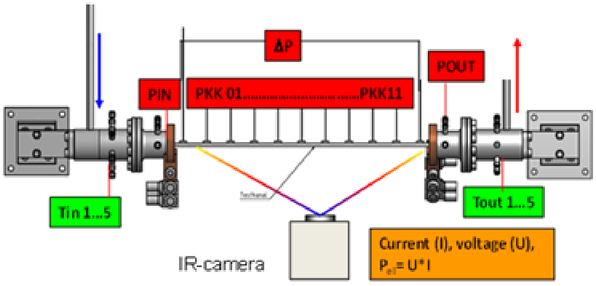

Figure 5: Test specimen EHT-II and measurement procedure

The EHT experiment consists of an Inconel tube heated with electrical power up to 15 kW. Temperature and pressure measurements are performed at inlet and outlet and along the channel. In addition, an infrared camera can be placed facing the test specimen for surface temperature measurement, as illustrated in Fig. 5.

3.4 Coupled simulation – HARCC test case

The main objective of this activity is to implement the improved methods developed earlier for the simulation of heat fluxes toward coupled simulations taking combustion phenomena and methane cooling into account. To this end, a test case has been chosen yielding validation data for the simulations. The HARCC test campaign was performed on a cylindrical combustion chamber segment at the European research and technology test facility P8. The goal of this experiment was the investigation of heat transfer and hydrodynamic losses in the regenerative cooling circuit under realistic conditions using cryogenic methane for coolant.

The tests were performed with the DLR-Subscale combustor model "D". The test segment was integrated at a distance of 2.5 diameters downstream the combustion chamber injector head (see Fig. 6) guaranteeing homogeneous flow and temperature field with a constant distribution of hot gas flow parameters in the segment.

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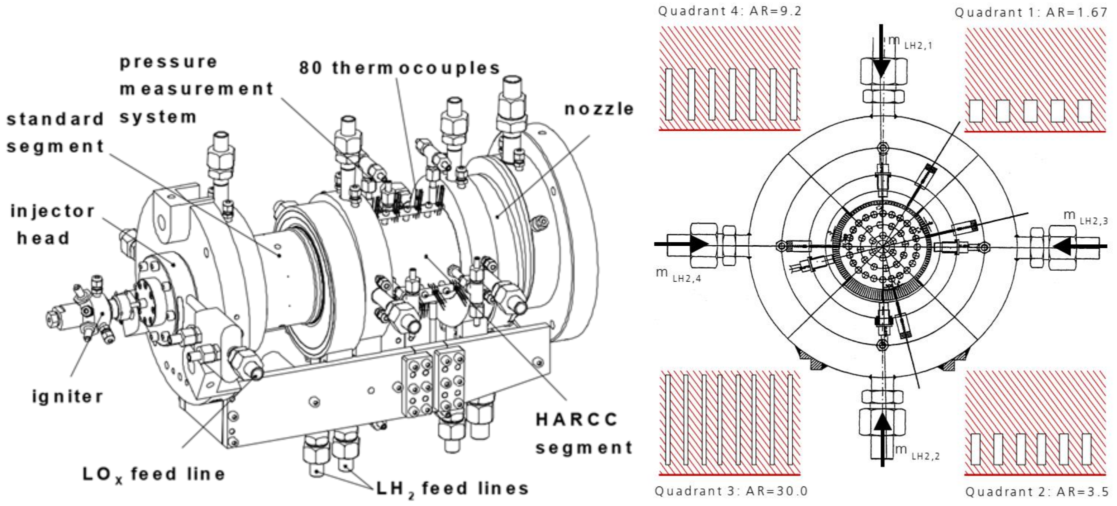

Figure 6: Combustion chamber D configuration (left) and HARCC-Segment cooling channel geometry (right)

The HARCC segment is a single cylindrical segment of 200 mm length divided into four sectors, each presenting a different channel area ratio (AR, height to width ratio). This configuration reduces the number of required tests, while ensuring similar test conditions for all sectors. On the hot gas side, all sectors have exactly the same flow and thermal boundary conditions, which would be very difficult to reach in successive tests. The geometry of the cooling channels is presented in Fig. xx, right.

The thermal field was measured using 80 thermocouples, 20 per quadrant. Those are integrated in the combustion chamber wall between two cooling channels at four axial positions and five distances to the combustion chamber wall. To ensure a defined measurement position, the thermocouples are thermally insulated and spring pressed with a constant and defined force (F = 3N) into their positions. Static pressure was measured inside the inlet and outlet manifold for every sector.

For this activity, two test cases have been defined. Test case 1 features a combustion chamber pressure of 3.98 MPa, a mixture ratio 3.35, for injector mass flow of LNG 0.941 kg/s and LOX 2.99 kg/s. Test case 2 features a combustion chamber pressure of 3.97 MPa, a mixture ratio of 2.35, for injector mass flow of LNG 1.297 kg/s and LOX 2.99 kg/s

4. Turbopumps

4.1 Work logic

The discussions on turbopump activities have started end of 2018. The work plan is not yet as detailed as on the other topics of the cooperation. So far three main axes have been identified for the common work: exchange on pump and turbine 0D pre-design tools and analysis, bearing testing and rotordynamics, and cavitation in cryogenic conditions.

4.2 Pre-design tools

The goal of the first activity is to compare and analyse the designs obtained with same inputs using different tools. The small engine demonstrators Boreas and Lumen will be used as reference for this activity. DLR will perform a design of BOREAS pump and turbine using hydrogen and oxygen inputs, whereas CNES will perform a design of LUMEN pump and turbine using methane and oxygen inputs. The obtained results will be compared and analysed in an assessment of the tools available. CNES is using a commercial code enhanced with proper functions whereas DLR is using an in-house code.

4.3 Cryo-Testing of new generation bearings for low cost production

This activity is intended to improve the TRL (technology readiness level) of new bearings technologies for cryogenic turbomachines, joining CNES expertise in bearing design and analysis with DLR knowledge of test rig design and mastering.

Figure 7: ball bearings elements

Validation of design tools through "test-as-you-fly" campaigns is intended to be key for technology and methods evolution, especially considering the multi-physics nature of bearings behavior. The outcome of these tests shall be the performance assessment of low-cost bearing architectures, capable to withstand the harsh thermo-mechanics and tribology of rocket engine turbomachines.

4.4 Cavitation in cryogenic conditions

Understanding cavitation and cavitation induced phenomena in turbopumps is of upmost importance for the safe operation of a liquid rocket engine. Since LNG is not as well investigated in this regard as LH2 or LOx are, there is a need for research with the real fluid to close this knowledge gap.

The cooperation between CNES and DLR will take into account the year-long experience in testing by CNES and the expertise in fundamental research (water-hammer, cavitating orifice, super-critical flashing) by DLR. The objective of the cooperation is to reach a better understanding of phenomena and induced anomalies, e.g. vibrations or performance losses and an improvement of the design tools available. Cavitation testing with LNG will be performed by CNES and the data is shared between the partners. This way DLR and CNES can use their tools and experience on a common data set and exchange on the results and findings. The exact framework of this work package is still under discussion with both partners.

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