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L75 LOx Ethanol Engine: Current Status of Thrust Chamber and Turbopump Cooperative Development

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In 2011, the German Aerospace Center and the Brazilian Space Agency started to cooperate in the field of liquid rocket engines. They agreed to jointly develop the L75 engine which is using Liquid Oxygen and Ethanol as propellants. Within the last year, the first hot-firing test campaign with pre-development models of the thrust chamber assembly successfully took place. Furthermore, important milestones in the development of the turbomachinery of the L75 engine, as run-in of test facilities and spin testing, have been achieved. This paper details the progress of the project, concentrating on the description of the joint activities of the consortium.

Nomenclature

F	Thrust, N
I_{sp}	Specific Impulse, s
$\dot{m}$	Mass flow, kg/s
p	Pressure, MPa
ϵ	Nozzle area ratio, -
c^*	Characteristic velocity, m/s
P	Drive power, kW

I. Introduction

The *German Aerospace Center* (DLR) and the *Brazilian Space Agency* (AEB) have successfully cooperated in the field of sounding rockets for more than 30 years. In 2011, Brazil and Germany jointly agreed to extend their existing cooperation to the development of the L75 liquid rocket engine (LRE). The L75 engine[1,2,3] shall produce a thrust of 75 kN in vacuum and uses the propellant combination of Liquid Oxygen

(LOx) and Ethanol (ETOH). While AEB authorized the Brazilian *Institute of Aeronautics and Space* (IAE) to develop the L75 engine, DLR uses own facilities and resources as well as is contracting German industry, such as *ArianeGroup* formerly *Airbus Safran Launchers*, to fulfill dedicated tasks.

Each involved party contributes to the development according to their past experiences: IAE gained experience with LOx/ETOH combustion by performing activities for small engines. At the end of the 1990s, ArianeGroup was tasked by the *National Aeronautics and Space Administration* (NASA) to operate the existing *Ariane 5* upper stage engine *Aestus* with the propellant combination LOx/ETOH.[4] The program was carried out jointly with the American company *Rocketdyne*. Tests of the customized *Aestus* engine were performed at *Rocketdyne's* Santa Susanne test facility. The tests have been performed very successfully providing good results with respect to performance and combustion stability. NASA's idea had been to get rid of storable propellants due to their toxic behavior and high turn around operation cost within the *Space Shuttle* program. In early 2000, NASA declared to retire the shuttle and thus the initiative was put on hold. The experience of DLR with LOx/ETOH originates from the steam generators[5] in use for vacuum facility operation at the engine test center in Lampoldshausen, Germany.

During the first phase, the development concentrated on developing, manufacturing, and testing of the L75's main subsystems: thrust chamber assembly (TCA) and turbopump assembly (TPA). To support the design activities, several test facilities were modified or newly built on both sides of the Atlantic Ocean. Here, Brazil concentrated on cold flow test as well as turbine and pump test stands while Germany enlarged the capabilities of the existing research and technology test stand for rocket propulsion systems. According to the engine's development plan, first pre-development models (PDM) of the TCA were built and tested, which provides a sound basis to start the next development steps.

For the TPA, joint efforts in design, manufacturing and testing were performed. The work covered engineering efforts such as *Computational Fluid Dynamics* (CFD) analysis, structure mechanical and thermal investigations as well as development and verification of new processes for manufacturing and hardware integration.

After successful execution of the first project phase, development activities on component and subsystem level will follow. In parallel, project activities will continue to finalize engine system design.

II. The L75 Engine

The L75 is an open cycle engine using the Gas Generator (GG) principle and the propellant combination LOx/ETOH. L75 shall develop a thrust of 75 kN and is designed for an upper-stage engine application for satellite launchers. The stage layout allows for approximately 400 s of burning time. Table 1 summarizes the foreseen characteristics of the L75 engine.

Figure 1 presents the flow schematic of the current L75 operational concept. Existing databases from previous programs were used for initial engine components layout. Verification and validation activities for combustion devices and power pack components are ongoing to extend the database and to allow for improvement in mathematical models. Functional models for engine steady state and transient operating conditions are available.[6] The steady-state model has been used to define the engine operational envelope

Table 1. L75 engine and GG characteristics

Parameter	Value	Unit
Thrust in vacuum F	75.0	kN
Specific impulse in vacuum I_{sp}	315	s
Thrust chamber LOx flow $\dot{m}_O$	14.1	kg/s
Thrust chamber ETOH flow $\dot{m}_{ETOH}$	8.85	kg/s
Chamber pressure p_C	5.85	MPa
Nozzle area ratio ϵ	147	-
GG pressure p_{GG}	4.82	MPa
GG LOx flow $\dot{m}_{O,GG}$	0.31	kg/s
GG ETOH flow $\dot{m}_{E,GG}$	1.0	kg/s

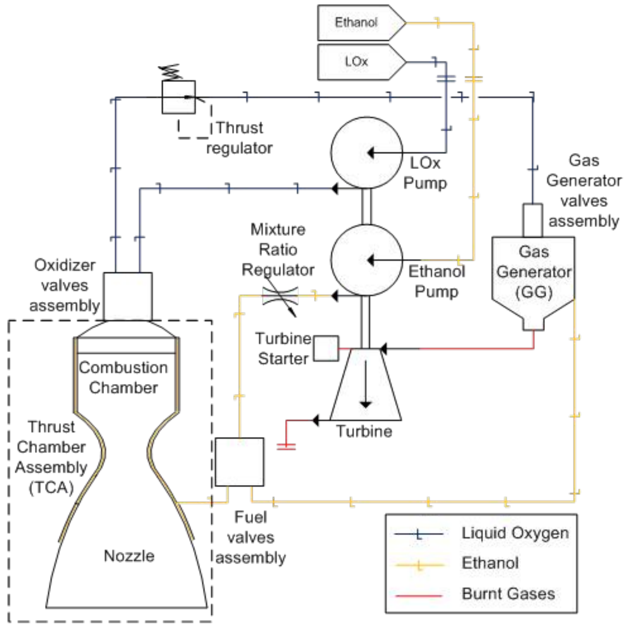

Figure 1. L75 flow schematic

and for preliminary definition of subsystem requirements. Within the next development steps, the same model will be used for engine performance prediction and tuning.
The propellant feeding to the combustion chamber is performed by turbomachinery. The pumps are driven by a turbine which is fed by the exhaust gases of the gas generator. The turbomachinery is of a single shaft overhang design. Combustion chamber and gas generator ignitions, as well as turbomachinery start-up, are provided by pyrotechnical devices.
The TCA design consists of a regeneratively cooled combustion chamber with a copper alloy liner and a stainless steel outer shell. The Brazilian injector head consists of 91 double swirl injection elements. The nozzle extension is built up of an regeneratively and radiation cooled section. Engine control is provided by an engine controller commanding the valves. A thrust frame is implemented to carry the loads.

III. Status of General Cooperation Activities

During the first phase of the cooperation on the L75 project (2011-2016), the main objectives have been to design, manufacture, and to test TCA and TPA components. According to their previous experience, each cooperating party contributed to meet the objectives: On the one hand, Brazil concentrated on the design and manufacturing of their capacitive thrust chamber (CTC), while Germany took care of the preparation, conduction, and evaluation of the test campaign, as well as for an alternative injector head design. On the other hand, both parties jointly performed CFD analyses on the LOx pump, designed and manufactured LOx pump rotors, and spin tested ETOH as well as LOx rotors. Each year, there have been joint workshops, during which the latest design approaches were presented, discussed, and as appropriate adapted accordingly. For the second phase of the L75 project, it was agreed to work on a German design of the TPA components (turbine, LOx pump, ETOH pump) and subsequent tests in Brazil in the coming years. Further potential cooperation activities such as system engineering studies and regenerative test campaigns with Brazilian hardware are under discussion. Table 2 summarizes the past and the upcoming joint activities already agreed and assigns ownership.

IV. Test Facilities

During the development of an LRE, multiple tests on system, as well as subsystem, and component level are performed, to demonstrate that the design meets the requirements. The activities presented in this paper

Table 2. Agreed joint activities in L75 development and classification of responsibility

L75 Project Phase	Component	Activities	Responsible
First Phase (2011-2016)	TCA and components	ArianeGroup CTC design	Germany
		ArianeGroup CTC manufacturing	Germany
		ArianeGroup CTC testing	Germany
		IAE CTC design	Brazil
		IAE CTC manufacturing	Brazil
		IAE CTC Testing	Germany
	TPA	LOx pump CFD analysis	Germany and Brazil
		LOx pump rotor manufacturing	Germany and Brazil
		LOx and ETOH pumps rotor spin testing	Germany and Brazil
Second phase (from 2017)	TPA Components	ArianeGroup components design	Germany
		ArianeGroup components manufacturing	Germany
		ArianeGroup components testing	Brazil

concentrate on the test of the PDM of the TCA and on TPA component testing. In the following, the test stands used in the past years are described in more detail.

A. Cold Flow Test Stand - Brazil

A cold flow test stand was build at IAE to support liquid engine project development activities. The facility uses water as a working fluid and serves for:

- Injector resistance measurements,
- valve flow checks, and
- combustion chamber hydraulic characterization.

The data gained from cold flow tests as shown in Figure 2(b) provide additional inputs for modeling activities. Test facility can handle pressure levels of up to 35 bar at a mass flow of 30 kg/s provided by water pumped by 140 kW electrical pumps (Figure 2(a)). This facility is also expected to be used for acceptance tests in the production phase.

B. Turbine and Pump Test Stand - Brazil

Within the L75 project, the pump and turbine test stand (BTBH) was designed and built as IAE's turbopump facility at their premises in Sao Jose dos Campos, Brazil (Figure 3). This facility was used to fulfill the project goals of phase 1, e.g. to determine pump and turbine performance curves, pump cavitation curves, and pump and turbine vibration and sealing characteristics of the TPA components.

Currently BTBH allows only the performance mapping of the components using water as model fluid to simulate the propellants in the oxidizer and fuel pumps and gaseous nitrogen to simulate hot gases in the turbine. Modifications of the test bench to use liquid nitrogen in order to simulate the cryogenic fluid in the oxidizer pump are ongoing.

For the future, it is planned to run the original GG at the BTBH, too. The main parameters of BTBH are presented in Table 3.

(a) Water supply of the hydraulic test bench driven by electrical pumps

(b) L75 PDM 1 injector head flow tests

Figure 2. Cold flow test stand at IAE's premises: Water supply of the hydraulic test bench driven by electrical pumps on the left and an illustration of the injector head flow tests of the first CTC PDM on the right

Figure 3. BTBH at IAE's premises

C. P8 Research and Technology Test Stand - Germany

The P8 Research and Technology Test Stand at DLR Lampoldshausen (Germany), shown in Figure 4, was used for the tests starting in June 2016 and ending in December 2016. A high-pressure ETOH supply was added to the facility directly preceding the test period.* This upgrade enlarges P8's portfolio which encompassed LOx, GH2/LH2 and GCH4/LCH4/LNG high pressure propellant supplies, so far. The feed systems provide mass flows of up to 16 kg/s of LOx and nearly 10 kg/s of ETOH, and feed pressures of up to 80 bar in the LOx inlet and up to 115 bar in the ETOH inlet. These supplies allow for accommodating L75 test hardware on full scale level which is a significant advantage during this development phase. Further details on P8's test facility history and capabilities,[7] as well as on the ArianeGroup's (Ottobrunn/Germany) test heritage[8] can be found in the respective publications.

*The modifications have been partly funded through an the *European Space Agency* (ESA) contract wihtin the *Future Launcher Preparatory Programme* (FLPP)

Table 3. Main parameters of BTBH

Parameter	Value	Unit
Drive power P	550	kW
Max. rotational speed U_R	33	krpm
Max. water flow $\dot{m}_W$	24	kg/s
Max. liquid nitrogen flow $\dot{m}_{N,L}$	20	kg/s
Max. nitrogen gas flow $\dot{m}_{N,G}$	6	kg/s
Number of data channels	500	-

Figure 4. P8 test bench at DLR's test facilities in Lapoldshausen/Germany during operation

V. Capacitive Thrust Chamber Activities

In the first phase of the cooperation, PDM have been designed, manufactured, and tested. One PDM consists of:

- An injector head,
- a cavity ring, and
- a combustion chamber.

The components of the PDM are of modular design and are bolted together to assure easy handling of the hardware; including easy exchangeability during test. This allows for using different designs throughout the hot-firing test campaign

A. IAE's Hardware Description

Most important in this early phase of engine development was the proof of concept, especially for the injector head. Using short-term tests, the injector head could be characterized with respect to transient, ignition, and stability behavior. Considering this, IAE decided to use a capacitively cooled TCA, the CTC. It was defined to use the same inner contour as the L75 flight configuration TCA for the CTC. Figure 5 shows a schematic view of the CTC assembly on the left and a photograph of the assembled Brazilian PDM hardware prior to shipping to Germany.

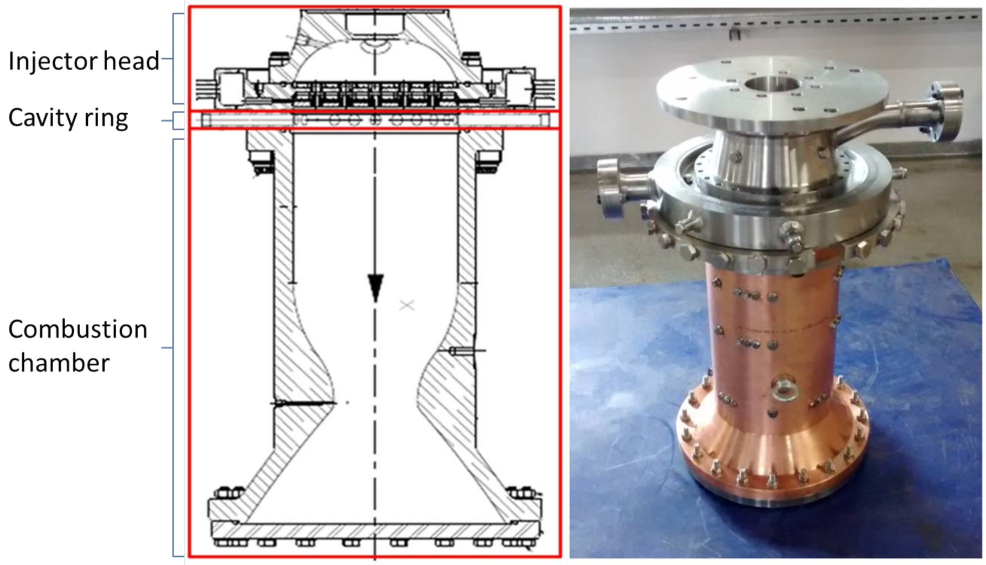

Figure 5. Brazilian CTC hardware with the injector head on the top, the combustion chamber at the bottom, and the cavity ring in between: Schematic view on the left and CTC assembly prior to shipping

1. *Injector Head*

The IAE injector head consists of a LOx dome, a base plate and a faceplate. It is equipped with 91 bi-propellant double-swirl-coaxial type elements. The element design was derived from the Russian engine RD0109 working with LOx/Kerosene. The inner element diameters were modified to cope with the propellant ETOH. The outer row elements were trimmed to achieve a low mixture ratio to assure chamber hot gas wall cooling for overall heat load reduction. All other injection elements were designed for optimum performance and stability. The LOx dome, as well as the ETOH feedline, are equipped with static and dynamic pressure sensors for characterization of coupling between gas and fluid side during transients (filling process, shut down) and steady state operation.

2. *Cavity Ring*

The cavity ring is mounted between the injector and the combustion chamber. It is equipped with 21 radially oriented quarter wave acoustic absorbers. The cavity ring was implemented for fast reaction in case combustion stability problems would occur. The layout of the cavities in terms of frequency/mode adjustment was done by performing tests under ambient conditions in IAE's acoustic laboratory. Loudspeakers were used for acoustic excitation and microphones could be set to different radial and axial positions inside the chamber volume for acoustic mode and frequency measurements. The cavity ring is also used to carry the igniter.

3. *Combustion Chamber*

During the first phase of the L75 project, three different combustion chamber development models were manufactured in Brazil. To cope with the goals of the test plan, all three models were equipped with sufficient instrumentation to allow for best test result analysis and characterization. Static and dynamic pressure sensors were mounted at different cross sections and different circumferential positions. A number of 30 temperature pick ups were integrated on the chamber outer surface as well as inside the chamber wall at different radial positions to allow estimating the heat load. Three thermocouples are located in the cavity ring boreholes and three are welded on the hot gas side of the injector faceplate. The measurements are used to understand the interaction between injectors and chamber wall in the vicinity of the faceplate. The test data are used to collect information about chemical reactions and faceplate cooling performance.

B. ArianeGroup's Hardware Description

In 2014, DLR contracted ArianeGroup located in Ottobrunn/Germany to perform the L75 test campaign. It was commonly agreed, that ArianeGroup will provide an alternative injector head. Thus, two injector heads were available as back up for each other in order to use the test slot as efficiently as possible and allow for hardware modifications or adaptations, e.g. cavity ring tuning or necessary detailed data analysis without losing valuable test time during the running campaign.

1. Injector Head

The design of the alternative injector head (see Figure 6) was based on identical L75 operational specifications. ArianeGroup selected a design for their injection elements which is based on best practice elaborated within years of operating storable propulsion systems, as well as, on know-how gained during their activities related to the usage of green propellants for orbiting maneuvering systems (OMS) together with *Rocketdyne*. The injection element is characterized by a swirl / slot design. The injector head's general design allows for implementing classical baffles or liquid baffles in case of any instability issues.

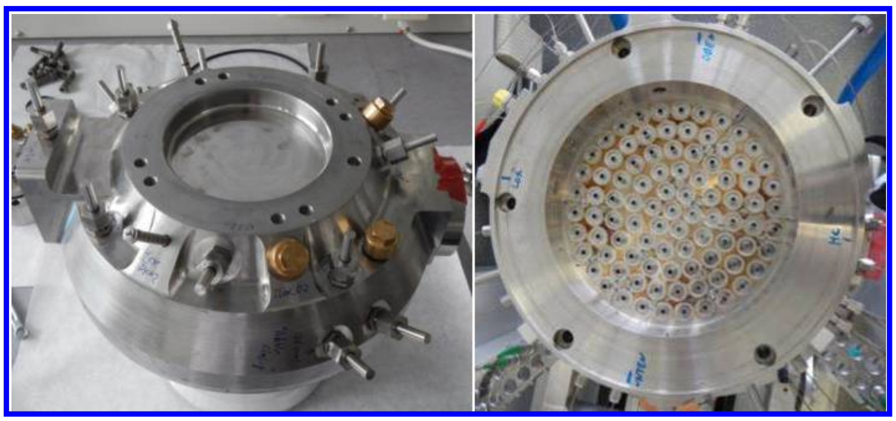

Figure 6. Alternative injector head: ArianeGroup's injector head with measurement ports on the left and faceplate equipped with structural temperature measurement on the right

2. Combustion Chamber

Complementary to the capacitively cooled chambers provided by IAE, a water-cooled chamber was manufactured and operated within one of ArianeGroup's hardware set-ups during the last phase of the P8 test campaigns. Due to its actively cooled chamber wall, this configuration allows for longer test duration. Once ignited, the test hardware was operated at several test points in the steady state regime during one single burn. By doing so, both the accumulated run time for the ArianeGroup injector and the number of tested load points increased significantly. Considering the fact that test facility commissioning effort and test preparation for each test run remained constant, this approach improved the testing efficiency. Additionally, the longer run times lead to thermal steady state conditions inside the specimen improving the data base for the assessment of the heat load on the chamber walls (integral heat load measurement).

C. TCA Full Scale Test Campaign

The main objectives for the L75 thrust chamber full-scale test campaign was to get first indication of:

- Engine transient behavior - start up, shut down,
- engine ignition behavior,
- engine stability behavior,
- preliminary definition of the c*-performance (characteristic velocity), and
- first assessment on chamber heat load.

Next to different injector head designs, four different thrust chambers had been designed and manufactured to allow for differing test objectives and test durations. These chambers are in particular:

- A steel chamber with capacitive cooling for flow checks and ignition tests allowing for a test duration of up to one second,
- two capacitively cooled chambers of copper material (one with limited and one with full instrumentation) which allows for an extension of the test duration to up to 6 seconds, and
- a water-cooled chamber for test durations of approximately 30 seconds.

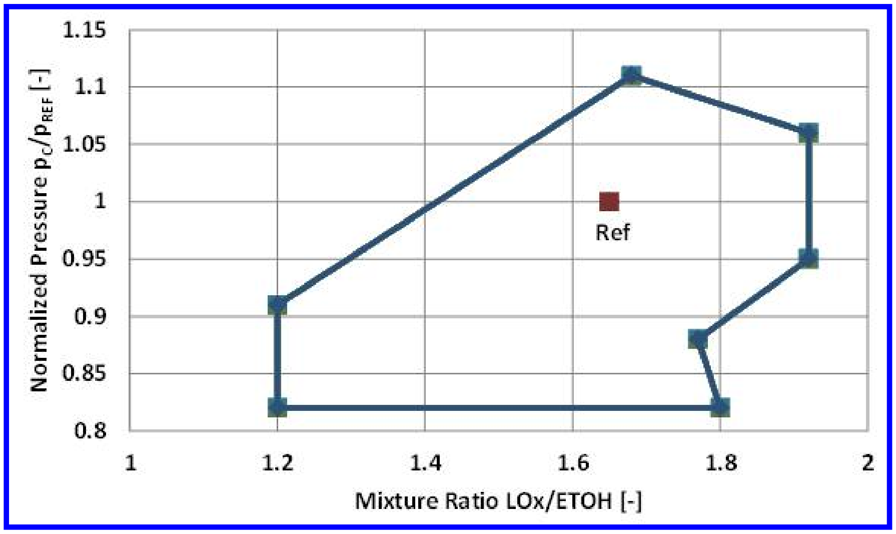

Figure 7. Operational envelop for CTC testing: One operational point is defined by the normalized chamber pressure p_C/p_{REF} and the mixture ratio LOx/ETOH.

The test campaign with LOx/ETOH at P8 test facility for both injector heads took 22 test days with two test days dedicated to P8 facility acceptance and ten test days for each injector head design. During the first testing phase the uncooled steel chamber was used. Even though it allowed only short burns, this more robust configuration was selected for ignition tests and ramp-up development. The importance of this phase was obvious, since both the test facility installations and the test specimens were operated for the first time. Consequently, the facility conditioning, the valve sequencing for the injector's domes filling processes, as well as the sequencing of the igniter operations were in the focus. The conditions at ignition and the first start-up transient were oriented according to the envisaged conditions during L75 engine operations. However, also alternative conditions were investigated (e.g. variations of LOx lead versus fuel lead) to enhance the knowledge of this critical phase. Additional to the elaboration of ignition and transient sequence, the obtained test data could be used to adapt the final definition of redline logics and their respective threshold values. In this context, it should be mentioned that also the shut-down sequence was optimized.
Once all necessary data for safe and reliable test operations were gained, the next test phase was initiated. The injector head was now mounted to a capacitive copper chamber. With this configuration it was possible to increase the burn time and thus to achieve the reference point (REF) as presented in the Figure 7. While extending the run time with the cooper chamber to a few seconds in steady state combustion, the different envelope load points were tested subsequently.

The Brazilian injector was tested using the steel and copper chambers, with a total of 21 successful ignitions; accumulating 67.0 s of run-time. An impression of the hot-firing tests is given in Figure 8. Based on the operational experience gained during the first two phases of the test campaign, the run-in period of ArianeGroup's injector was kept short. Once again, the steel combustion chamber was operated to obtain the injector's filling characteristics. These values were used to adapt the existing start-up, ignition and transient sequences. Thanks to the positive results so far, it was decided to directly switch to the water-cooled combustion chamber configuration. In total, the German injector head was tested during 21 test runs with an accumulated runtime of 235.4 s. Thus, each injector head design performed 21 successful ignitions out of 21 ignition attempts. Thanks to the longer test duration (and, as a consequence, the possibility for

Figure 8. CTC hot-fire test with Brazilian injector head and copper chamber (left: start-up, right: steady state combustion)

several test points during one single burn) it was possible to operate the specimen not only in the nominal envelope but also outside of this box. Valuable test data were created at load points inside and outside the envelope; especially as combustion stability characteristics are concerned.
It is well known that propellant combinations like LOx/ETOH have a tendency to some unstable combustion behavior (during transients but also in the steady state regime). In order to cope with this challenge, a ring with adjustable quarter-wave acoustic cavities and instrumentation was mounted between the injector and the combustion chambers in all tests. The acoustic cavities were closed at the beginning of the test series but their presence would offer a quick response in case some instabilities might occur during the tests.
However, the tests of both injectors presented stable combustion without the need of making use of the acoustic damping devices. The first Brazilian injector configuration tested was damaged because of high frequency combustion oscillations during ramp-up at the very first phase of the facility's run-in operations. The injector was replaced and the ramp-up procedure was modified and no high frequency was observed ever since. However, low frequency oscillations were present with the Brazilian injector during the ramp-up and shut-down phases in all tests, but they were damped out naturally in milliseconds with change of chamber pressure.

VI. Turbopump Activities

The details of the current status of L75's turbopump development are presented in another paper.[9] In order to provide a complete overview of the current status of the L75 project, this chapter also summarizes the progress in TPA development.

A. IAE's Hardware Description

The TPA is a highly integrated part of the L75 engine feed system. It is responsible for pressure regulation in the fuel and oxidizer feed lines and for providing the required pressures and flow rate for the combustion chamber and gas generator. The chosen turbopump design satisfies the required performance and mass, while retaining relative simplicity and cost effectiveness. The L75 TPA consists of a single shaft configuration as it is illustrated in Figure 9. On one side, an overhanging head-on floated LOx pump with an axial inducer and a radial impeller is mounted. A seal package separates the oxidizer and ETOH using an additional purge fluid. The ETOH pump is centrally mounted between two double back to back angular ball bearings cooled by ETOH and also consists of an axial inducer and a radial impeller in the same inflow direction as the LOx pump. A second seal package separates the ETOH part of the pump from the fuel rich hot environment around the overhanging single stage impulse turbine. Manufacturing constraints have been taken into account during the design process of the components.
Furthermore, in a joined effort with DLR/ArianeGroup, IAE performed CFD analysis prior to the first LOx pump test campaign. A detailed comparison between CFD calculations and tests results is ongoing and part of the cooperation.

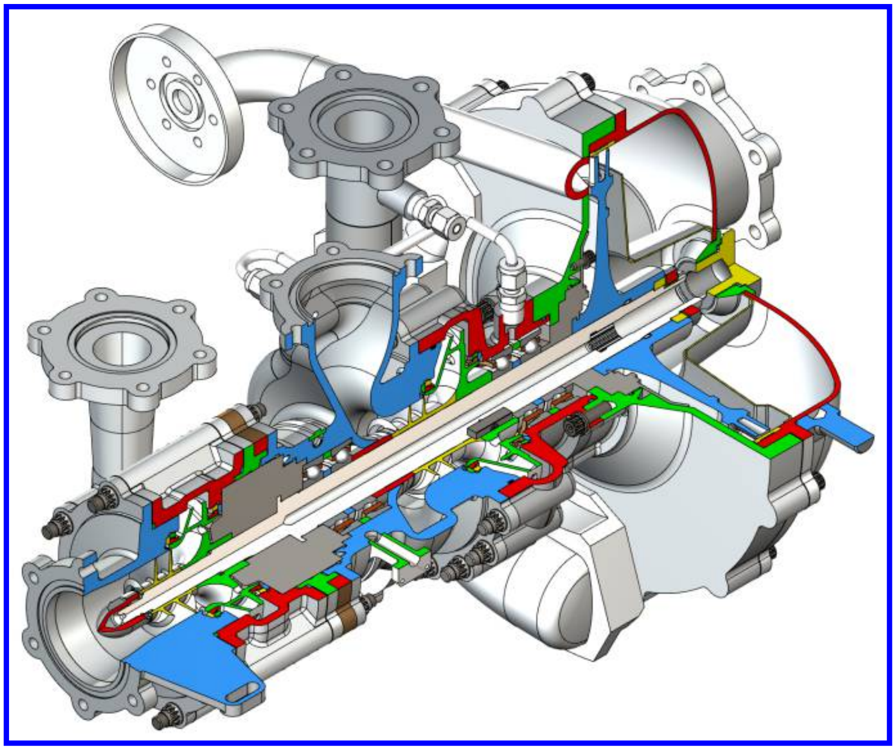

Figure 9. L75 TPA design illustration

B. Rotor Manufacturing and Spin Testing

In order to evaluate different production techniques, IAE and DLR manufactured the LOx pump impellers by four different processes:

- Electric discharge machining (EDM) and milling followed by brazing, developed by IAE and
- additive layer manufacturing (ALM) and welding (rotor machined/blades welded) processes developed by DLR.

To proceed with validation of manufacturing processes, the Brazilian and German impellers were subjected to spin testing (see Figure 10, followed by burst tests. First, all impellers were submitted to rotation at

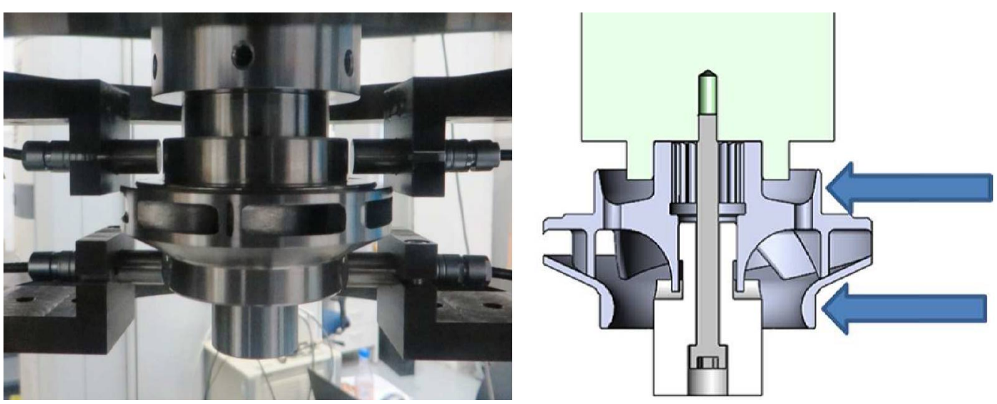

Figure 10. Impeller at spin test stand: Lox impeller testing with expansion measurement on the left and measurement points on the right

120% of nominal speed (28,800 rpm) for 400 s. Second, the rotation speed was elevated to 60,000 rpm. No cracks or plastic deformation were recorded.

C. ArianeGroup's Design Approach

DLR/ArianeGroup and AEB/IAE agreed to follow a similar cooperation approach for TPA activities, as had been implemented for combustion chamber activities already. The currently agreed programmatic framework includes the design, manufacturing and test of German TPA demonstrator hardware based on the identical specifications derived from engine design requirements. The TPA component demonstrators shall use the same housing as well as interfaces to ensure easy exchange of components especially for test purposes. In addition, this approach allows for a direct comparison of both design solutions. The project code name for the activities is UBATuBa.
The AEB/IAE and DLR/ArianeGroup test campaign activities on component level will use the BTBH facility at IAE's premises in Sao Jose dos Campos. The project work is planned to be performed within the next three years and will be done in parallel to IAE's nominal L75 turbopump development work. Test of an integrated power pack assembly are foreseen for a future project phase and are planned to be performed at DLR's facilities in Lampoldshausen, Germany.
The UBATuBa activity will lower the total development risk of the L75 engine and enlarge the party's technical knowledge. The development of different technical solutions shall proceed in parallel with the ongoing standard design work, as it is described above.
The first phase of the TPA alternative design will include the design of a PDM in Germany, as well as, manufacturing and testing of this design at subassembly level in Brazil for early characterization of performance criteria e.g. efficiencies and pressure rise of the chosen design.

VII. Conclusion

This paper presents the status of the cooperation of DLR and IAE for the development of the L75 engine. First TCA PDM had been designed, manufactured and tested. The hot-firing tests have been successfully performed on fullscale level. All test objectives have been achieved for both injector head designs. Using the evaluation of the test results and their implemention into the design of the TCA, a significant step in the L75 development has been taken. Furthermore, the necessary test facilities to proceed were built up and operated. Additionally, the TPA design is advancing. Special attention was put on the rotor design and the related mechnical testing. In the next years, Germany will also deliver dedicated TPA component designs and test them in Brazil. With that, all partners are well prepared to proceed with the development.
The activities and results achieved within the last years of Brazilian/German cooperation have proven that the team is capable to design and qualify a liquid rocket engine. The combination of heritage on both sides turned out to be beneficial providing an efficient and cost effective approach. Facilities on both sides of the Atlantic Ocean are and will be used in order to make best use of available installations. Due to some budget constraints that drives our environment worldwide, combining activities by bilateral cooperation is an appropriate measure to fulfill challenging tasks.
Next steps will include system and subsystem design, subsystem testing as well as launcher system engineering tasks. Discussions on cooperating on those topics are ongoing.

Acknowledgments

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