LOX-Kerosene Oxidizer-Rich Gas-Generator and Main Combustion Chambers Subscale Testing

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Experimental technology demonstration testing has been performed in cooperation between Astrium GmbH/Germany and KBKhA/Russia Liquid oxygen and kerosene have been chosen as propellants based on previous studies addressing the potential of hydrocarbon fuels for future launch vehicle applications. In a first steps three oxidizer-rich gas-generator subscale injection systems have been designed and manufactured. These three injection systems were then hot-fire tested in Russia. The different injection systems were evaluated by temperature variations and by combustion roughness. In a second step three main combustion chamber injection systems for oxidizer-rich staged-combustion cycle conditions have been designed and manufactured. Both gas-generator and main combustion chamber were then hot-fire tested as integrated subsystem. The subscale main chamber injectors were evaluated in terms of performance, chamber wall heat transfer, and combustion roughness.

Nomenclature

CC	=	Combustion Chamber
GG	=	Gas Generator
LRE	=	Liquid Rocket Engine
TC	=	Thrust Chamber
c_D	=	pressure drop coefficient
η_{c*}	=	combustion efficiency

1. Introduction

In the past years considerable activities have been performed to identify the advantages and drawbacks of the application of hydrocarbon fuels for rocket engines for launcher stages[1]. First testing on subscale level has been performed with LOX-Methane and LOX-Kerosene in cooperation between EADS Astrium, Propulsion and Equipments, in Germany and the Chemical Automatics Design Bureau (KBKhA) in Voronezh[2]. In that previous phase of the cooperation injection elements were tested under conditions which are typical for open cycle gas generator engines.

Based upon the experience gained in this previous phase injection elements for closed cycle staged-combustion conditions were designed and tested on subscale level. The operational conditions were derived from system analyses of potential engine concepts. The testing was performed using an oxidizer-rich gas generator (or preburner) in order to achieve realistic conditions for the main chamber injector.

A number of staged-combustion cycle engines with an ox.-rich preburner have been developed and are in use in several Russian launchers. This heritage is currently also used in the Russian RD-180 engine which powers the first stage of the US Atlas 5 launcher. The NK-33 engine is foreseen to be used as main propulsion system of the Kistler launcher project. The Russian company KBKhA is currently developing a new LOX-Kerosene ox.-rich staged combustion cycle upper stage engine RD-0124 for the uprated third stage of the Soyuz launcher. While a lot of experience has been acquired in Russia and in the Ukraine, only very few experience exists in Western Europe for this kind of rocket propulsion technology. A small LOX-Kerosene demonstrator engine, the P111, had been developed in 1956-1967 at Bölkow (today EADS Astrium) featuring an oxidizer-rich staged-combustion cycle with. After this project was completed no such activity was conducted in Germany for about 35 years.

To be prepared for future thrust chamber developments the extension of the newly acquired experience from gas generator cycle conditions to staged-combustion cycle conditions was the primary goal of this German-Russian cooperation.

2. Baseline Operating Conditions and Injector Concepts

2.1. Operating Conditions

The reference operating conditions for both the preburner and the main chamber injection heads were derived from previous system studies. The nominal conditions used for the design of the subscale engine including the preburner and the main chamber are given in Table 1.

The preburner temperature is set to 750 K, while the temperature of the simulated turbine exhaust gas is nominally 680 K. These temperatures are realized by preburner mixture ratio of 50.3 and 56 resp. in the tests of the preburners without the main chamber.

As the objective was to test the gas generator together with the main chamber in a staged-combustion assembly, the term preburner is used herein.

2.2. Preburner Concept

Three injection heads were designed and manufactured for the preburner. Figure 1 shows one of these injection heads. All three preburner injection heads were equipped with 7 coaxial injection elements. These elements realized in different ways a two-zonal atomization and mixing of the oxygen flow in order to create an initial combustion zone with mixture ratio around 20 and thus a combustion temperature above 2000 K. In the second zone the remaining oxygen is mixed into the combustion products from the first zone to achieve the desired high mixture ratio and flow conditions as homogenously mixed as possible. For example the numerous holes in the faceplate seen in Fig. 1 form the second zone while the first zone is inside the injection elements. Another tested injection element type implemented both zones inside the element.

Table 1. Reference Operating Conditions.

Preburner	
Combustion pressure	130 bar
Mixture ratio	56
LOX inlet temperature	~105 K
Kerosene inlet temperature	~300 K
Total propellant flow rate	6.0 kg/s
Main Chamber	
Chamber pressure	80 bar
Mixture ratio O/F	2.94
PB-gas inlet temperature	~680 K
Kerosene inlet temperature	~300 K
Total propellant flow rate	8.0 kg/s

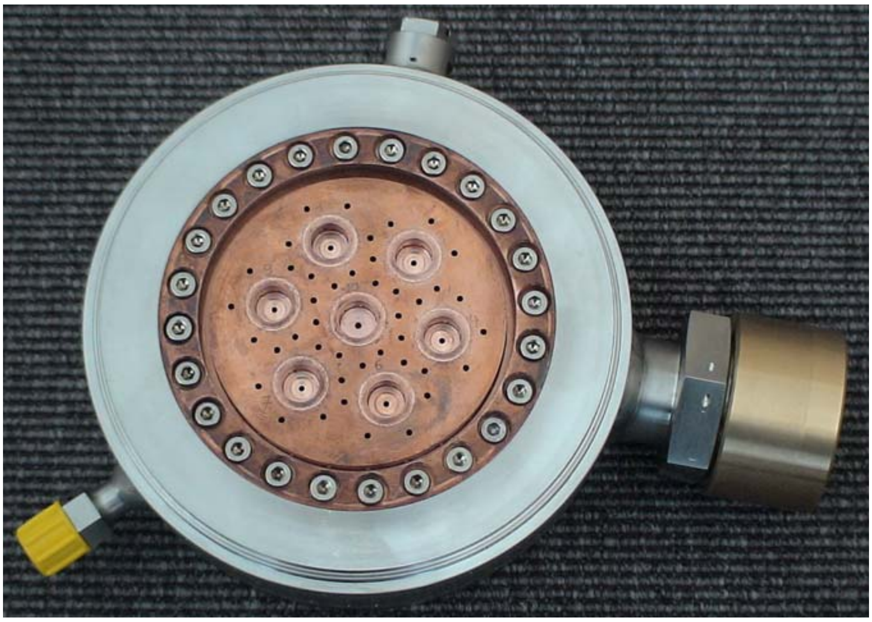

Figure 1. Subscale Preburner Injection Head.

The preburner has a chamber cylinder and a converging and diverging throat section, see Fig. 2. A flow straightening grid is mounted at the end of the cylinder. Ports to install temperature sensors are provided upstream and downstream of this grid as well as in the diverging section in order to obtain measurements of the temperature field.

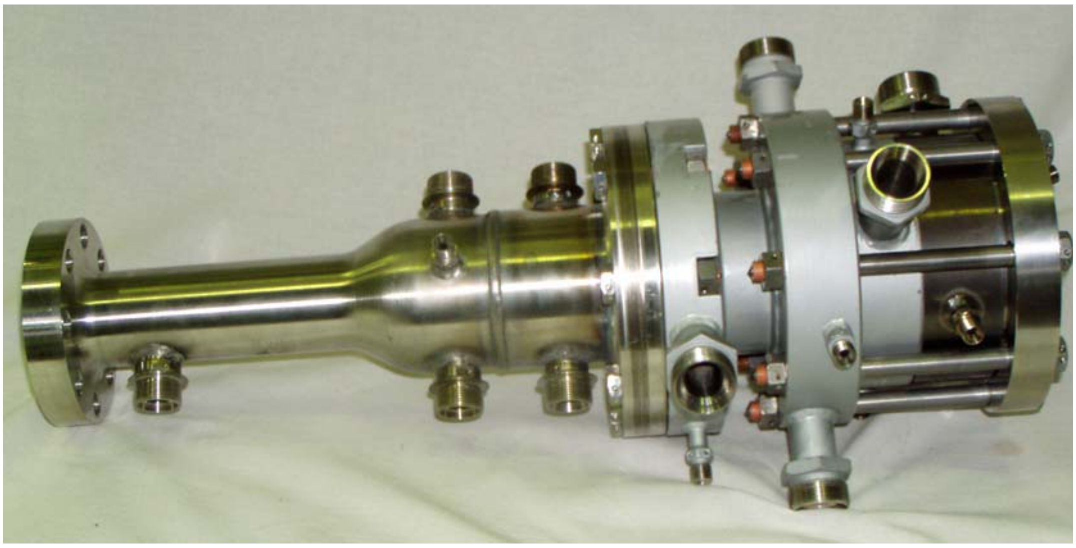

Figure 2. Preburner with Injection Head and Throat

All injection heads were tested with water to verify the flow pattern and to obtain the hydraulic characteristics. Figure 3 shows the flow pattern of the kerosene flow in the elements on the left side, while the flow pattern of the second oxidizer injection zone is shown on the right side.

Figure 3. Preburner Cold Flow Tests: Kerosene-Side (left); Oxygen Faceplate Flow (right).

2.3. Main Chamber Injector Concept

Three injection heads were designed and manufactured for the main combustion chamber. Figure 4 shows one of these injection heads. The three main chamber injector variants were equipped with 7, 19, or 37 coaxial injection elements. All elements realized an axial inflow of the oxidizer-rich preburner gas and a kerosene swirl. Two of the injection heads had protruding elements as shown in Fig. 4. All injection heads were tested with air and water to visualize the flow pattern and to obtain the hydraulic characteristics. The 19 element head was also flow checked with air and kerosene separately.

Figure 4. Subscale Main Chamber Injectors with 7 (left), 19 (center), and 37 (right) Elements

The main combustion chamber features a lateral connection to the preburner, two short segments for a dynamic pressure sensor and the igniter, a cylindrical section, and a converging and diverging throat section. The chamber sections are cooled by water except the first ring at the injector, which was cooled by kerosene.

3. Subscale Preburner Testing

3.1. Test Bench

The subscale preburner used to test all three preburner injection heads was mounted laterally to the oxidizer-dome of the main combustion chamber injection head, see Fig. 5. During the GG testing a CC simulator in the form of a tube with orifice was used to create the relevant counter pressure of the oxidizer-dome. Five sets of four temperature sensors were mounted upstream and downstream of a flow straightening orifice plate and in the expansion cone downstream of the critical section. Further instrumentation was used to measure the propellant inlet pressure and temperature as well as static and dynamic pressure in the preburner chamber.

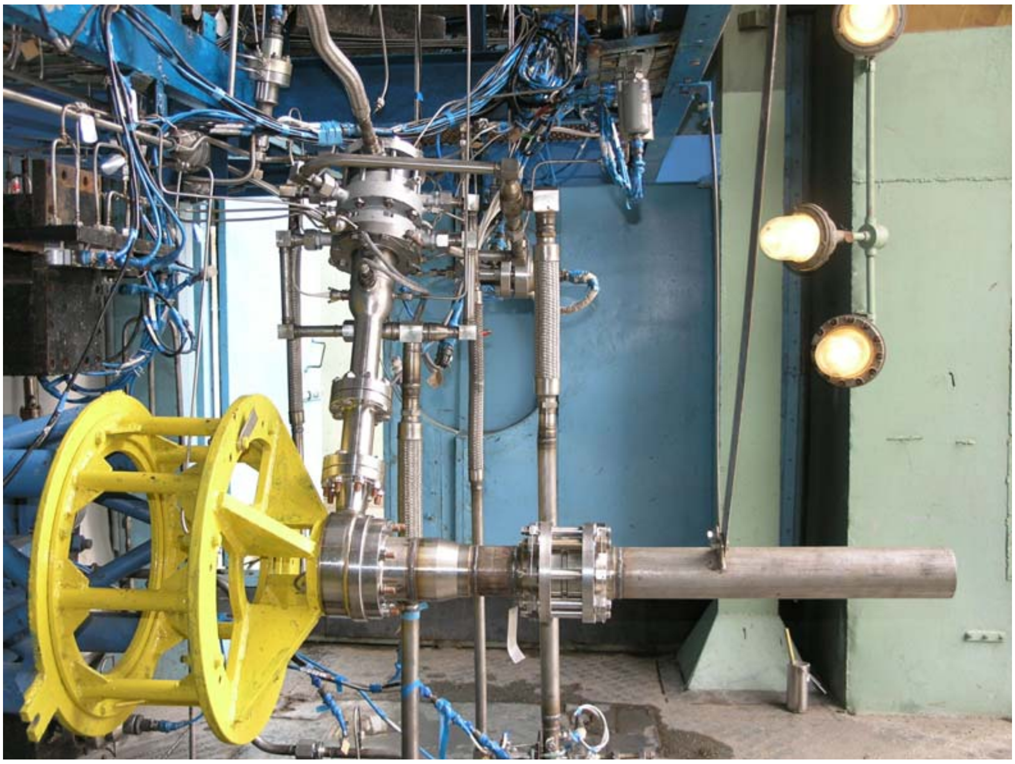

Figure 5. Preburner Installed on Test Bench with CC Simulator

LOX was fed at a temperature of 110 K ±2 K, while kerosene was fed at room temperature of 300 K ±8 K. Orifices in the feedlines were used to establish the planned flow rates according to the scheduled mixture ratio and chamber pressure, considering the predicted pressure drops of the injection elements. Ignition was achieved by a GOX-kerosene electrical spark igniter.

3.2. Preburner Testing

A total of six tests were performed with the three preburner injection heads. Each test was 30 seconds long and three load levels at 60%, 80% and 100% of rated chamber pressure were achieved. The mixture ratio was aimed at 50.3 and at 56. The pressure drop characteristics of the injection heads were predicted based on results from cold flow tests with water. However, due to an additional pressure drop under hot-fire conditions, generated by the reaction in the recess of the injection elements, the realized mixture ratio deviated from the target values. A comparison of the prediction to the test results is given below.

3.3. Preburner Performance and Test Results

The achieved preburner gas temperatures are compared in Fig. 6 to the theoretical predictions using the NASA code CEA2 for the nominal LOX-temperature of 110 K. The test results agree well with the prediction. The deviations are caused partly by the scatter of the LOX-temperature.

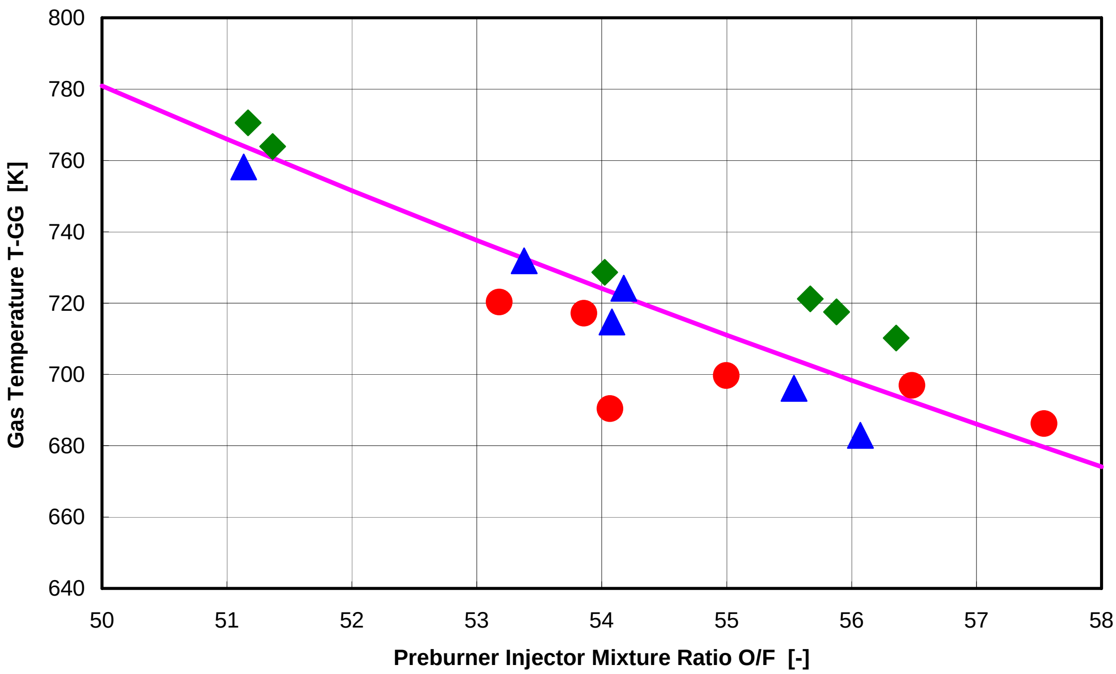

Figure 6. Gas Temperature achieved in Preburner Tests Compared to Thermodynamic Prediction

The injector flow coefficient c_D was evaluated using the measured pressure drops and flow rates. Figure 7 compares the pressure drop coefficients for both LOX and kerosene as a function of the Reynolds number (three connected solid symbols per test) with the results from the water flow checks (single open symbols).

The Reynolds number realized in the water flow checks is significantly lower than the Reynolds number obtained with LOX in the hot tests. Nevertheless, two of the three injection heads showed a good agreement between flow check and hot-test. A higher pressure drop (lower c_D) in the hot-tests on the LOX side was observed for third injection head (red symbols) compared to its flow check. This is most probably caused by an additional pressure drop due to pre-reaction of the two propellants in the element recess zone.

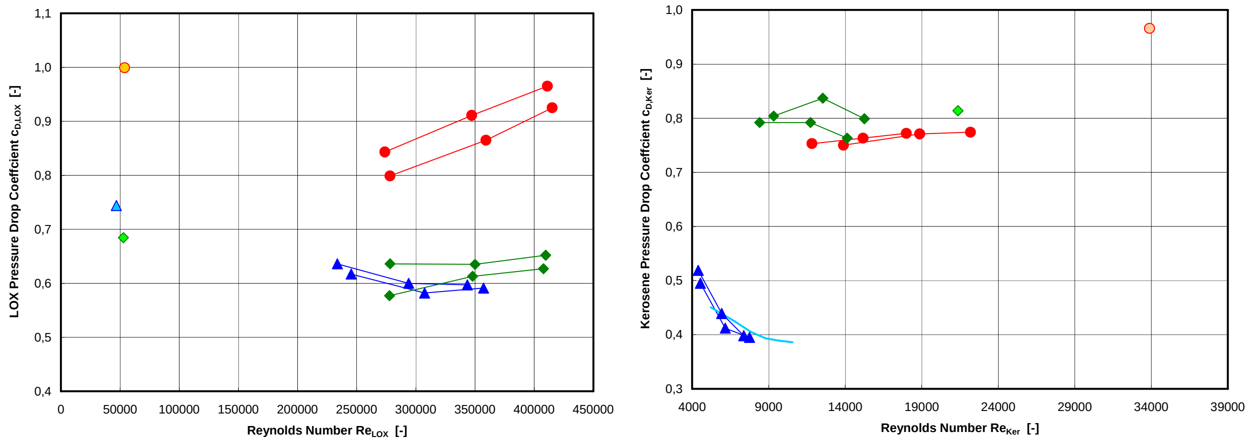

Figure 7. Preburner Injection Pressure Drop Coefficients for LOX (left) and Kerosene (right)

On the kerosene side the same two injectors show a good agreement between the water flow checks and the hot-test with kerosene. The additional pressure drop in the recess of the third injection head apparently affects both the LOX- and the kerosene-pressure drop characteristics.

4. Subscale Main Chamber Injector Testing

After successful completion of the preburner tests, the testing of the fully integrated hardware consisting of preburner and the main combustion chamber followed. In these tests the pre-combusted oxidizer-rich gas from the preburner was fed into the main injector together with additional kerosene.

4.1. Test Bench

The set-up of the main combustion chamber and the preburner on the test bench is shown in Fig. 8. The preburner is connected by rods to the movable thrust frame (yellow structure in Fig. 8) in the same way as for the autonomous preburner tests, see Fig. 5. This thrust frame is connected to a thrust measurement device, thus small movements have to be enabled.

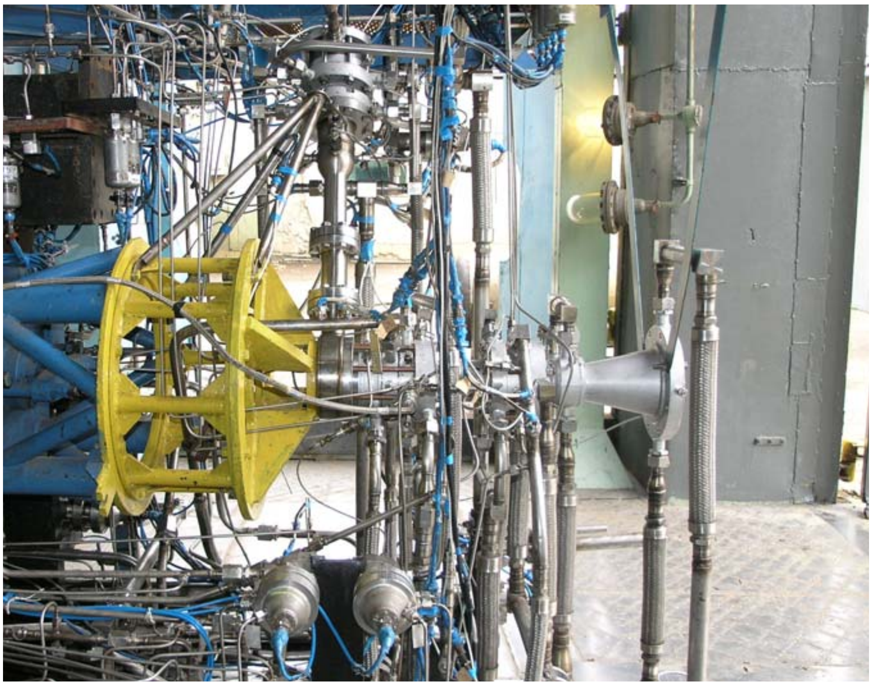

Figure 8. Subscale Main Combustion Chamber and Preburner Installed on Test Bench

The segments of the main combustion chamber and of the preburner were cooled with water except the small segment near the main chamber injection head which was cooled by kerosene. The feedlines for the cooling water were all equipped with flexible connections in order not to disturb small axial movements of the complete chamber – preburner assembly for thrust measurement. The water flow rate and the propellant flow rates were measured by flowmeters.

4.2. Main Chamber Testing

One preburner injection head was selected for testing together with the main combustion chamber heads. A temperature of 680 K of the simulated turbine exhaust gas was realized by fixing the preburner mixture ratio to 56.

A total of seven tests were performed with three injection heads. Each test was 30 seconds long accomplishing two load levels at 60% and 100% of the reference chamber pressure. The main propellant inlet pressures and the chamber pressures for the preburner and for the main combustion chamber are plotted in Fig. 9 for a typical test.

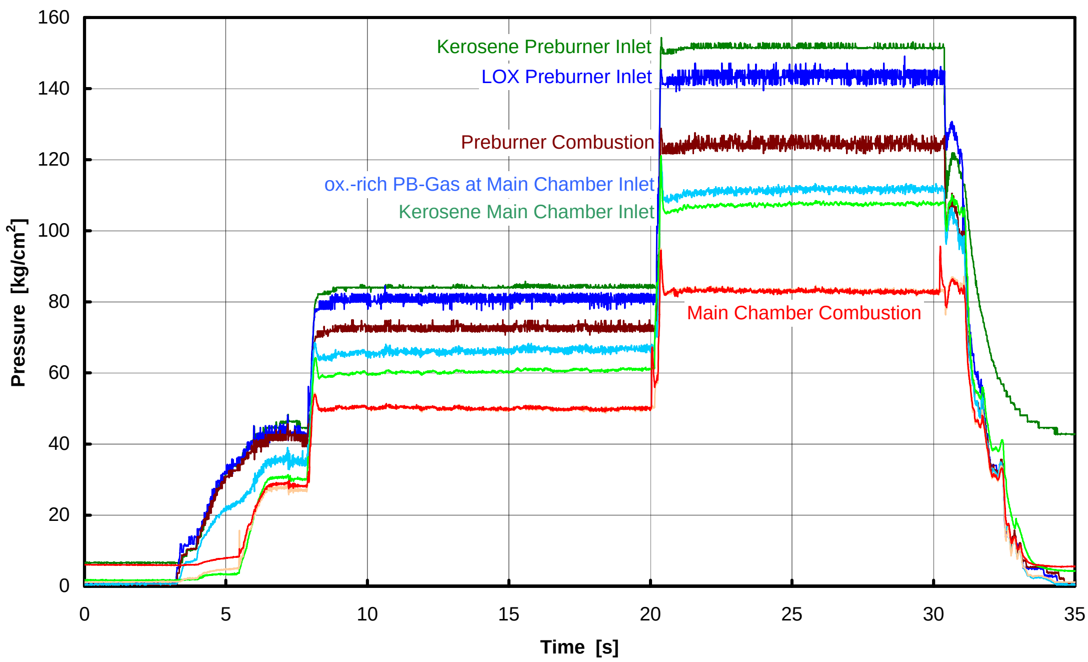

Figure 9. Main Chamber and Preburner Pressures during a Hot Test

Combustion instabilities occurred in the first test with the third injection head throughout the 30 s long test, causing overheating of the attachment of a dynamic pressure sensor in the chamber. It was decided to put the test program temporarily on hold and to modify the unstable injection head.

4.3. Main Injection Head Modification

The injection head, which exhibited severe instabilities in its first test, was modified by variation of the injection elements. In preparation a single-element test program was run at the technical University of Munich with GOX and kerosene. Several potential modifications were tested. It was then decided configure the elements in the center and in the outer row differently. Figure 9 compares the initial status of the injection head with the modification. Tangential oxidizer injection was added to the inner elements. Eight resonators in the oxidizer dome were trimmed to the unstable frequencies measured in the hot-test.

Three tests were performed with the modified injection head, which showed the stable operation and an increased performance compared to the unstable test. With these successful tests the test campaign was concluded.

Figure 10. Main Injector in Initial (left) and Modified Configuration (right)

4.4. Injector Performance and Test Results

The combustion efficiency of the main chamber was evaluated from the test data considering the mean temperature of the preburner gas and the inlet temperature of the liquid kerosene. Corrections were made to account for the enthalpy loss from the hot gas to the water cooling as well as for the two-dimensional flow profile in the chamber throat. For the latter correction the flow coefficient was calculated by the TDK code for the relevant operational conditions.

The combustion efficiency evaluated from the tests is shown in Fig. 11 as a function of the mixture ratio. For each injection head the dark symbols are related to 100% power level whereas the light symbols are related to 60% operation. The efficiency of the injection head operated with instabilities was found to be significantly lower than the efficiency of the two stable injection heads. A short stable operation was seen immediately after the transient to the 100% load point for about 0.3 s in the first test of the third injection head, which causes the efficiency to increase to 96% compared to only 92% during the unstable operation. The tests of the modified injection head confirm the high efficiency in stable operation. A slight trend of increasing combustion efficiency towards higher injection mixture ratio can be observed.

4.5. Combustion Stability

The combustion stability of the main chamber was evaluated from dynamic pressure measurements in the ox.-dome, in the kerosene cavity upstream of the injectors, and in the combustion chamber. Fig. 12 compares the amplitude of the chamber pressure oscillations up to 10 kHz as percentage of the mean static chamber pressure of the tests of all injection heads. A short stable operation for about 0.3 s was seen in the first test of the third injection head, when the dynamic chamber pressure drops from 38% to about 12%. The modifications of the third injection head result in stable combustion with chamber pressure oscillations comparable to the two other injection heads, thus proving the effectiveness of the modifications.

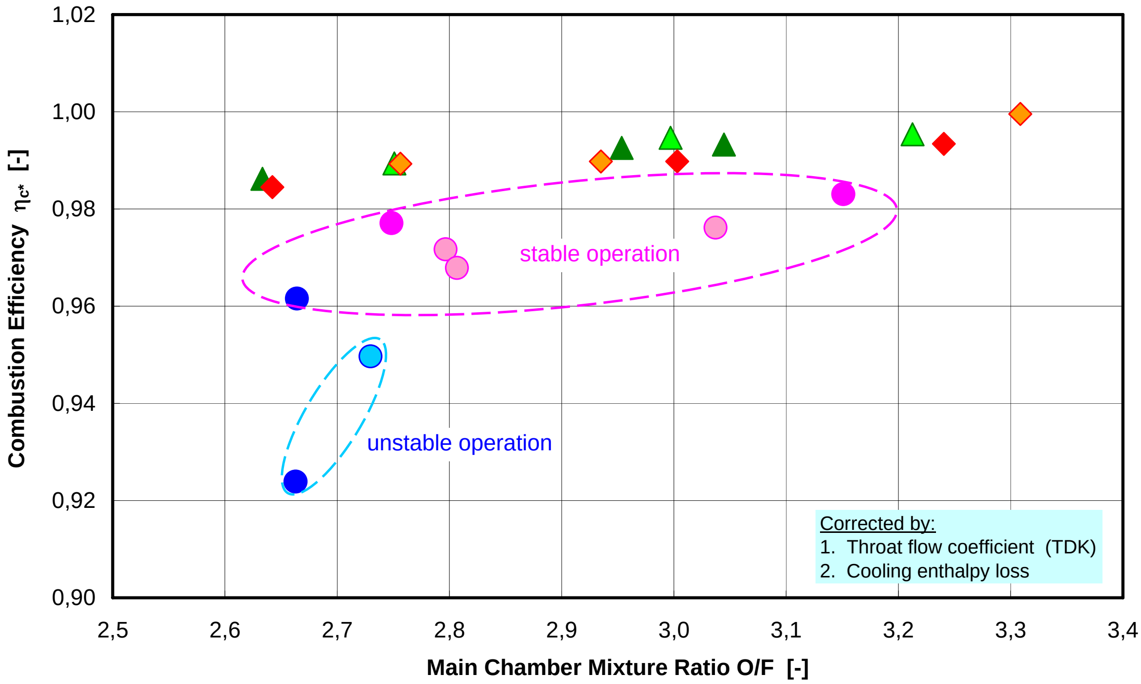

Figure 11. Main Chamber Combustion Efficiency

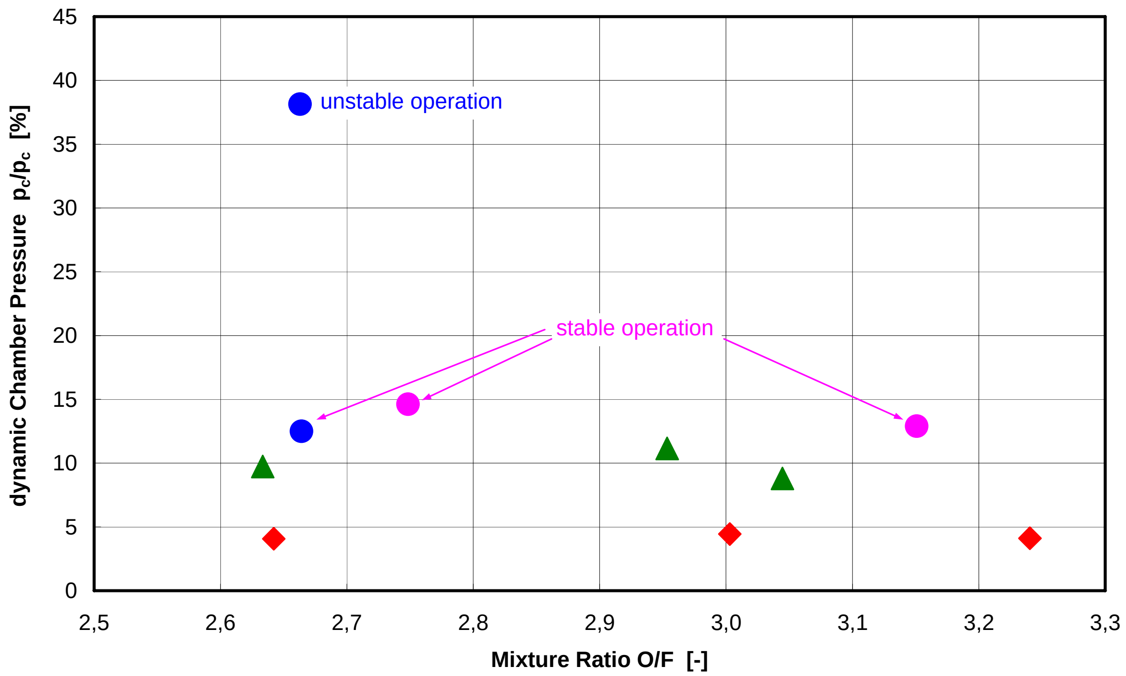

Figure 12. Main Chamber Combustion Pressure Roughness

5. Conclusion

Three different subscale preburner injection heads were successfully tested with LOX-kerosene propellants at oxidizer-rich mixture ratios. The best candidate was then selected for integration with the main combustion chamber and for subsequent testing of three main chamber injection heads under staged-combustion cycle conditions. Whereas two of those main chamber injectors were operated under stable conditions with combustion efficiencies around 98% to 99.9%, one injector exhibited unfavourable instabilities during hot-firing. Upon this, a single injection element test program has been defined to evaluate the burning characteristics of different element types in more detail. Based upon these results, certain element modifications were implemented at subscale level before returning to hot-fire testing in early 2007. The tests of these modifications confirm the stable operation of the injection head at high efficiency.

The experience of this testing programme with preburner and main chamber coupled will be helpful for similar testing with LOX-H2 and LOX-Methane planned in frame of the European FLPP programme.

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