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Bell-type nozzle concepts are state-of-the-art technology for expanding gases towards high exhaust velocities. Alternative nozzle concepts have been investigated, although none of them has achieved full-scale flight hardware status. These concepts include altitude adaptive concepts for first stage application, and concepts with reduced length for upper stage application. Both applications have the common requirement that for the thrust chamber design, accurate prediction models for the wall pressure evolution, the wall heat transfer, and the side-load characteristic are of importance. To enhance corresponding design models, the need of well tailored subscale tests at elevated thrust levels has been identified and expressed by the three partners EADS Space Transportation (former Astrium, Space Infrastructure), DLR Lampoldshausen, and Volvo Aero Corporation. Consequently, a joint programme has been formulated, the Calorimeter Nozzle Programme. Within the frame of this Calorimeter Nozzle Programme, three different thrust chamber configurations including actively cooled and film-cooled nozzle extensions are build, tested, and analyzed. Tests are performed with hydrogen-oxygen propellant combination at mixture ratios between 5 and 7.5, and at elevated combustion chamber pressures up to 130 bars.

Nomenclature

Symbols

A	area
ε	area ratio
o/f	mixture ratio
p	pressure
x, y, z	coordinates

Subscripts

a	ambient
c	feeding chamber
e	exit

Introduction

The key demand on future space transportation systems is the continuous reduction of earth-to-orbit launch costs and increase in launcher reliability and operational efficiency. Meeting these demands strongly depend on new engines that deliver high performance with low system complexity. Depending on the engine integration in the first or upper stage of a launch vehicle, high thrust levels and / or high vacuum performance are required. For both applications, practically all of today's rocket engines use classical bell-type nozzle extensions to expand the exhaust gases into the ambience.

Different advanced nozzle concepts have been frequently discussed in the literature.[1, 2] Based on experimental and analytical analyses it could be shown that all of these concepts own certain benefits such as in performance or launcher integration compared to the classical bell nozzles. However, each of these concepts comprises also specific shortcomings which have to be carefully analyzed prior to any full-scale realization.

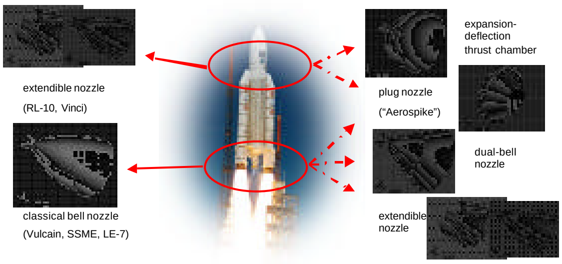

Fig. 1: Rocket nozzle concepts for first and upper stage application.

Figure 1 illustrates existing and flight-proven concepts vs. the above referred advanced nozzle- or thrust chamber concepts. The application for either first or upper stage integration imposes specific demands.[2] For first stage application, stable and controlled operation on ground without uncontrolled flow separation, and high vacuum performance are key requirements. Among these concepts for first stage application there are three altitude adaptive concepts:

- The dual-bell nozzle concept, with single step altitude adaptation;
- The extendible nozzle concept, with single step altitude adaptation, and

- The clustered plug nozzle concept, with continuous altitude adaptation up to its geometric area ratio.

For upper stage application, any nozzle concept will feature instant full flowing during ignition into vacuum. Therefore, flow separation may only impose a constraint in case of a firing during the very first phase of stage separation. This, however, is not the case for civil launchers such as Ariane 4 and 5. Key requirement here is again a high vacuum performance. The only practical limit to reach highest performance values with long nozzle extensions is the available storage compartment, and thus a geometric constraint. For classical bell-type nozzles, the above referred extendible nozzle concept is therefore here already realized, e.g. with the American RL-10 and the future European Vinci LOX/LH_2-engines. Fundamental difference to first stage application is that the deployment occurs prior to engine ignition.

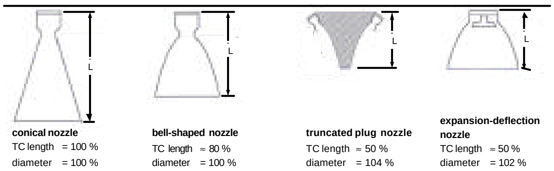

Fig. 2: Comparison of different thrust chamber concepts featuring equal vacuum performance.

For upper stage application, advanced concepts allowing for a significant reduction in geometric size without any moving parts being in closer investigation are the:

- Expansion-deflection thrust chamber concept, and also
- The plug nozzle concept.

The reduced geometric size of above referred thrust chamber concepts is emphasized in Fig.2, sketched for equal vacuum performance values. All above referred nozzle concepts are currently explored by space industry and institutes in Europe, see e.g. Ref.1-3. The investigations concentrate on the

- aerodynamic design, including wall pressure evolution at given back pressures and in vacuum,
- thermal analysis for the cooling layout,
- mechanical design studies,
- manufacturing studies, and
- proof-of-concept by subscale tests, either with cold- and hot firing tests.

For the design of a new rocket engine thrust chamber, accurate prediction models for

a) the wall pressure evolution, including the effect of flow separation at back pressures by the ambiance,

b) the wall heat transfer for attached and separated flow condition, and

c) the side-load characteristic,

are of importance. Especially with regard to future advanced nozzle concepts with actively cooled and/or film-cooled nozzle extensions (which may additionally foresee devices for active or passive flow separation control) the further understanding of physical processes involved near the separation line is of importance.

Despite the different cold gas experiments carried out within the framework of the European Flow Separation Control Device Programme, FSCD, until 2002,[3] hot gas tests are needed for the characterization of the heat transfer, flow separation and side-load behavior in actively and film-cooled nozzle extensions.[*] Furthermore, the experimental data base to be established will be needed for enhancement of engineering models and also for CFD validation.

This need has been identified and expressed by the three partners Astrium, DLR Lampoldshausen, and Volvo Aero Corporation. Consequently, a joint programme has been formulated, the "Calorimeter Nozzle Programme", see Ref. 4 for a detailed description of the programme set-up. Within the framework of this calorimeter nozzle programme, three different thrust chamber configurations, including actively cooled and film-cooled nozzle extensions, are built, tested, and analyzed. Tests are performed with a hydrogen-oxygen propellant combination at mixture ratios between 5 and 7, and at combustion chamber pressures up to 130 bars.

Key objectives of this experimental research programme are the following:

- Characterization of heat transfer, flow separation, and side load behavior in actively and film-cooled nozzles.
- Data base for development / validation of CFD tools and engineering models.
- Demonstration of mechanical integrity of nozzle design.

The status of the calorimeter nozzle programme (abbreviated as "Calo" in the following) is described in this paper. It contributes to the European FSCD programme.

Calo Programme Overview

The Calo programme consists of three campaigns with different nozzle hardwares. All three campaigns use a water-cooled copper combustion chamber manufactured by EADS ST. To this combustion chamber, which also includes the nozzle throat and the divergent portion up to an

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[*] The FSCD Programme investigates flow separation and side-load origins in advanced high area ratio nozzles by means of experiments and numerical analyses, with the following partners involved: European industry (EADS Space Transportation, Snecma, Volvo Aero) and institutes (Cnes, ESA ESTEC, DLR, Onera, LEA Poitiers).

area ratio of e = 4.1, the base nozzle (up to e = 11.1) and the nozzle extension is attached as follows:

- Campaign A: Actively cooled nozzle without film injection; EADS ST-built water-cooled copper base nozzle and nozzle extension, see Fig. 3.
- Campaign B: Actively cooled nozzle with film injection; Volvo-built sandwich base nozzle with integrated film injector and EADS ST-built water-cooled copper nozzle extension, see Fig. 4.
- Campaign C: Nozzle with purely film-cooled skirt: Volvo-built sandwich base nozzle with integrated film injector and Volvo-built film-cooled plate metal skirt, see Fig. 5.

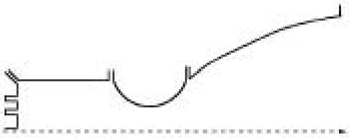

Fig. 3: Calo thrust chamber configuration A.

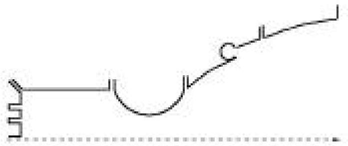

Fig. 4: Calo thrust chamber configuration B.

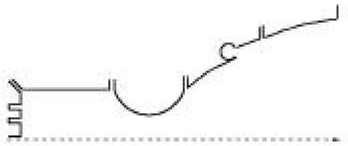

Fig. 5: Calo thrust chamber configuration C.

Test Objectives

The test campaigns with the three different nozzle configurations allow distinguishing

- Vacuum heat flux evolution
- Wall pressure evolution, including separated flow conditions
- Effect of film-cooling on wall heat flux and separation characteristic.

Consequently, the test objectives cover the design requirements for classical and advanced nozzle concepts either for first and upper stage application. An extension of the programme within the frame of FSCD towards hot-firing with the dual-bell nozzle concept within a proof-of-concept phase acting as pathfinder towards full-scale is considered within the hardware design.

The Calo hot-firing tests are accomplished by cold gas tests. Calo hot and cold tests are scheduled for mid of 2003, and are performed on the European P8 facility and P6 facility at DLR Lampoldshausen. First test results gained within this European programme are presented in the following.

Calo P8 Test Campaign

Hardware Description

For the contour design, a truncated ideal profile was selected; see also Ref. 4 for further details:

- Length: $x/r_{throat} = 14.8$
- Area ratio $A_e/A_{throat} = 33.6$

Wall exit pressure is sufficiently high to reach full-flowing with and without film-injection at nominal operational conditions.

The flowfield pattern in terms of Mach number distribution is visualized in Fig. 6. The straight characteristics near the centerline close to the nozzle exit being characteristic for ideal contours are clearly visible.

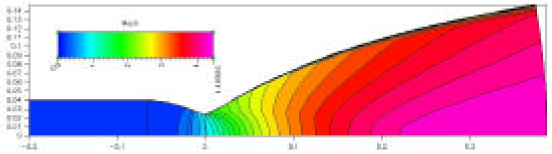

Fig. 6: Mach number field in Calo thrust chamber.

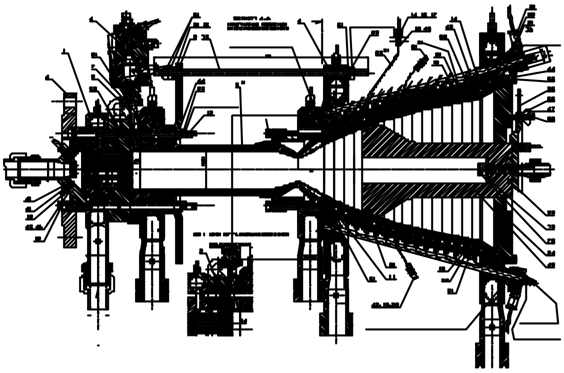

Fig. 7: Thrust chamber assembly for Calo A campaign (including sealing tool for tightness tests).

The manufacturing of all three hardwares has been completed in the first half of 2003. The test-set-up for the Calo A campaign with the actively cooled nozzle extension is illustrated in Fig. 7. Note that a sealing tool for tightness tests at the test facility is included in the Figure.

The assembled Calo nozzle hardware A is shown in Fig. 8 prior to integration into the test facility. Figure 9 displays the thrust chamber integrated into the P8 test facility.

In Calo campaigns B and C, a VAC-designed and manufactured base nozzle is used. The upper part of the nozzle uses a welded Sandwich-design in Inconel 600. As coolant, gaseous hydrogen is used, which is injected into the nozzle by means of an injector that is integrated into the sandwich structure. The downstream portion of the Calo base nozzle is cooled only by the GH2 film from this injector. Calorimeter heat flux information is gained in Calo B testing with a water-cooled design of type A.

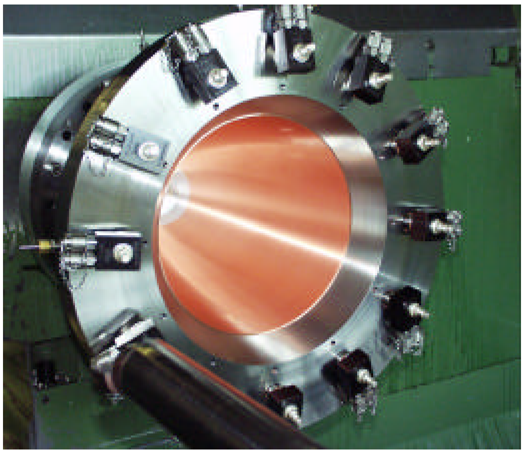

Fig. 8: Calo nozzle assembly A after contouring.

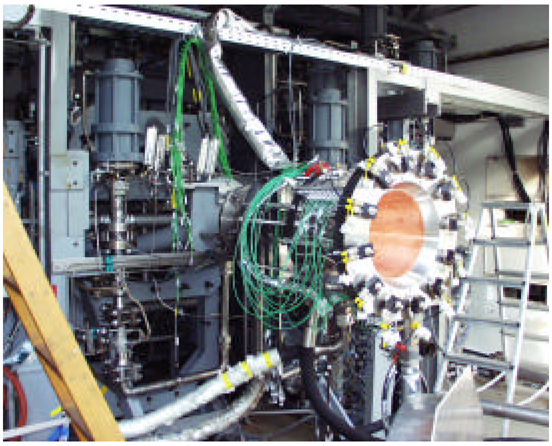

Fig. 9: Calo A thrust chamber integrated into P8 test facility.

In order to withstand the clamping forces from the calorimeter nozzle extension in Calo B, the sandwich nozzle is delivered with a support ring, which gives the nozzle a high axial stability. The base nozzle is displayed in Figures 10 and 11.

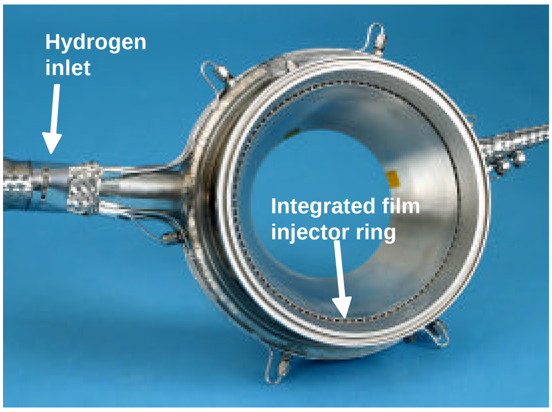

Fig. 10: Calo base nozzle built in sandwich design by Volvo Aero, for campaigns B and C.

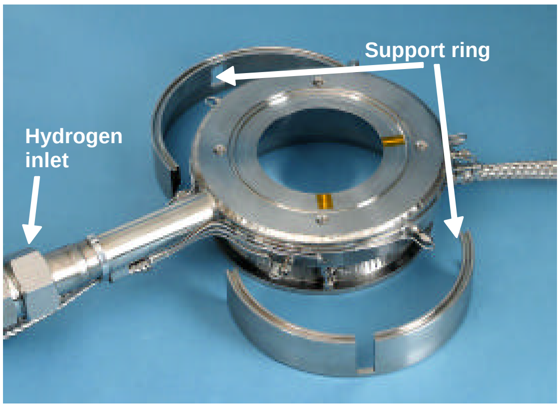

Fig. 11: Base nozzle with support ring.

In the Calo campaign C, the 40 kN thrust chamber assembly resembles the design of real flight hardware. This hardware set-up is sketched in Fig. 12, with the metallic skirt mounted downstream of the base nozzle. It is a sheet metal skirt made of Haynes 188 with straight stiffeners. This skirt is equipped with a lot of measurements, among others numerous specially cooled dynamic pressure sensors and different types of thermoelements. Figure 13 shows a detail of the metallic skirt with micro tubes for high frequency pressure transducers. All tubes are flush mounted on the hot gas side.

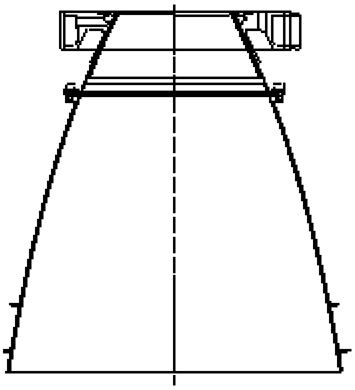

Fig. 12: Calo nozzle assembly C, with actively cooled base nozzle and film-/radiation cooled metallic skirt.

Diagnostics

The following diagnostic methods are applied for the Calo campaign A, B, and C:

- Up to 31 high frequency wall pressure transducers in axial and span wise direction.
- 15 hot gas wall temperature sensors.
- 70 coolant water sensors.
- 15 coolant pressure sensors.
- Acceleration sensors.

Due to the much higher wall temperatures expected with the metallic skirt, infrared thermography will also be foreseen as key technique for hot gas wall temperature recording.

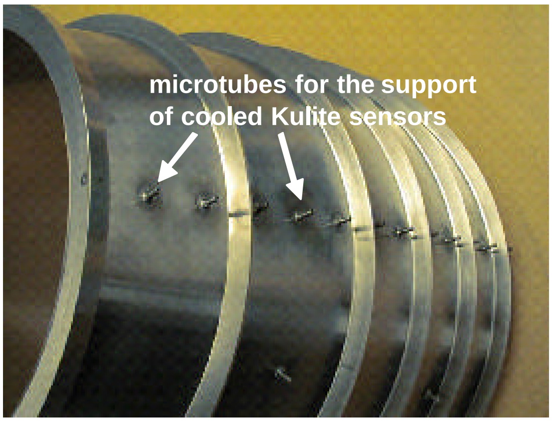

Fig. 13: Metallic skirt for Calo C with diagnostics support

Test Sequences and Results

The hot-firing tests are conducted at the P8 facility; see again Ref. 4 for further details. The tests include the following sequences:

Sequence A:	Incremental increase of chamber pressure.
Sequence B:	Transient change in chamber pressure.
Sequence C:	Incremental change in combustion chamber mixture ratio.
Sequence D:	Incremental change in secondary film mass flow rate.

In these sequences, the combustion chamber is varied in between p_c = 50 to 130 bars. The load points cover the fully separated flow condition up to the fully attached flow condition, with the latter being representative for high altitude and vacuum operation.

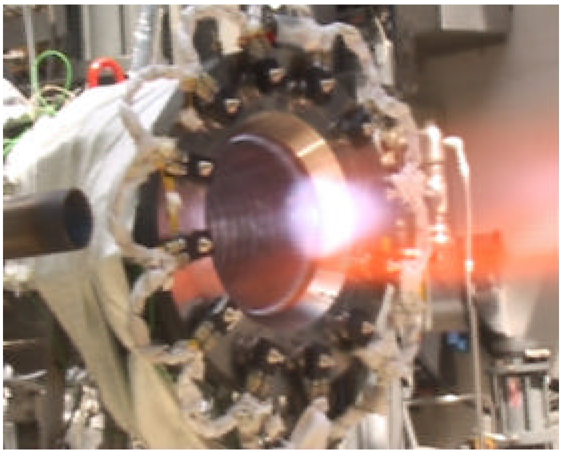

Fig. 14: Calorimeter nozzle extension A within hot-firing test during start-up.

The combustion chamber mixture ratio is varied in between o/f = 5 to 7.5, thereby covering the typical operation conditions of different engine cycles.

Figure 14 shows the exhaust plume of the calorimeter nozzle extension A during start-up. The Mach disk at the centerline is well visible. Note also the symmetric physical separation line at the wall being visualized by the white ring of condensed water vapor.

Figure 15 visualizes a steady state load point. Again, the characteristics for an overexpanded plume, the Mach disk and also subsequent nodes at the centerline further downstream are well visible.

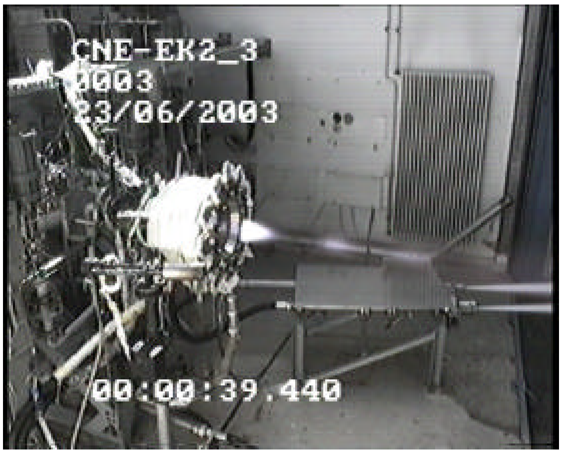

Fig. 15: Calorimeter nozzle extension A within steady-state hot firing.

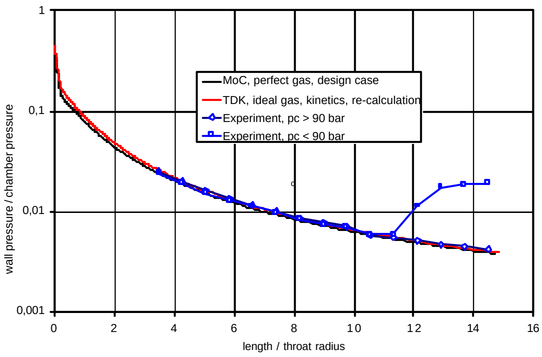

Fig. 16: Numerical and experimental wall pressure evolution.

Figure 16 illustrates the wall pressure evolution for two load points selected for publication. The black line is the vacuum wall pressure profile predicted within the nozzle design with the Methods of Characteristics. The result is gained with perfect gas assumption. The red line results from a re-calculation with the TDK code. For this simulation, ideal gas was assumed being in chemical non-equilibrium state. Thus, gas conditions are closer to the real case within the hot-firing test. Consequently, the experimental wall pressures do agree with the TDK re-calculation. Attached flow condition is achieved for the higher load point with p_c >90 bars, while uncontrolled but steady flow separation is achieved at the reduced chamber pressure of p_c < 90 bars.

Complementary P6 Test Campaign

As reported in Ref. 4, a complementary cold gas test campaign supports the hot-firing tests with cold nitrogen as driving gas. Objectives for the cold gas tests are:

- Investigation of the adiabatic wall temperature evolution in FSS and RSS flow condition, see also Ref. 4.
- Validation of the incipient separation point location prediction with models based on free interaction theory as proposed in Ref. 5, 6.
- Investigation of physical flow phenomena within the incipient separation zone.

Of special interest is the incipient separation domain, in where the wall pressure first deviates from the vacuum profile and approaches the ambient pressure level in a steep gradient. Within this incipient separation domain, the flow is initially still physically attached to the wall, thereby resulting in an increase in heat load compared to the vacuum level.

To determine the location and expansion of the separation zone different flow visualisation techniques were tested, including the ‘Pressure Sensitive Paint (PSP)’ being described in detail in Ref. 7. The optical pressure measurement method PSP uses the physical properties of luminophores. Activated by light of the right wavelength luminophores attain a higher energetic level. They return to their basic level by emitting light (fluorescence). The deactivation can also be caused by collisions with suitable molecules (e.g. oxygen). Then the luminophores react with phosphorescence.

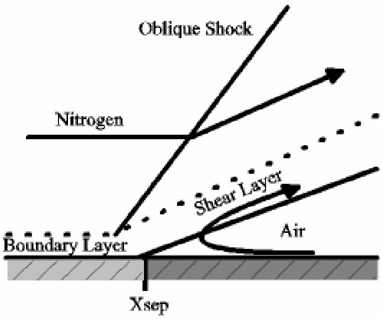

Fig. 17: Intensity change with the pressure sensitive paint; wall color resembles change.

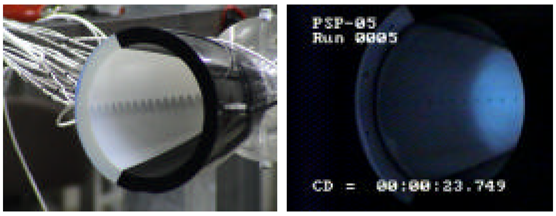

Fig. 18: PSP test specimen (left), and test run (right).

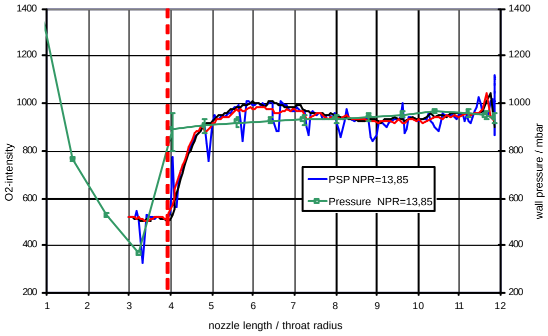

Fig. 19: Wall pressure data measured by PSP and by HF-sensors in cold gas TIC contour.

The test setup uses the PSP property to react with the ambient oxygen but not with the nozzle exhaust driving gas nitrogen. Figure 17 sketches the underlying principle. The attached nitrogen flow pronounces bright fluorescence, while the separated flow region with ambient air appears dark. The presence of oxygen from the ambience will thus lead to a change of the intensity at or near the physical separation point x_{sep}. The intensity is reciprocally proportional to the partial pressure of oxygen and thus allows clearly marking the physical separation line, seeing Fig.18 (right).

Figure 19 gives integrated PSP measurement signals of three adjacent axial contour lines compared with simultaneous wall pressure measurements.[†] The blue line is evaluated along the centreline position of the pressure sensors, while the other two lines were evaluated at axial cross sections to both sides of the sensor line (at +/- 4°). Consequently, the PSP signal along the sensor line shows continuous disturbances at the sensor holes due to expansion and compression at the holes. Upstream the physical separation the PSP signal process is linear, then rises with a strong gradient after the physical separation and follows subsequently the wall pressure profile of the recirculating flow.

The sudden rise of the PSP signal starts slightly upstream of the pressure sensor position at $x/r_{throat} = 4$, and is marked in Fig. 19 with the vertical dashed red line. This position is in line with the end of the incipient separation region, as wall pressure sensor data reveal here already the plateau value being characteristic for the developed recirculation zone. The recorded intensity change of the PSP measurement is caused by sudden rise of the oxygen partial pressure downstream of the incipient separation zone.

Conclusion

A hot-firing test campaign called “The Calorimeter Nozzle Programme” is prepared by

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[†] For the further evaluation, the PSP signal was integrated over 4 seconds due to its low intensity, see also Ref.7.

EADS ST, Volvo Aero, and DLR Lampoldshausen with following key objectives:

- Characterization of heat transfer, flow separation and side load behavior in actively and film cooled nozzles.
- Data base for development / validation of CFD tools and engineering models.
- Demonstration of mechanical integrity of nozzle design.

The proposed test campaigns with the three different nozzle configurations - the calorimeter cooled skirt with and without film-cooling and a purely film-cooled metallic skirt - allow to clearly separating the effect of the TEG-film and the wall temperature on the separation location and connected wall heat flux development. A complementary laboratory cold test programme is performed by DLR to investigate the incipient separation location and the physical processes within the incipient separation zone. Thus, fundamental information for design tools of any new nozzle concept is gained within this joint programme.

The hot-firing tests are performed in the second half of 2003 on the European P8 test facility at DLR Lampoldshausen.

The Calorimeter Nozzle Programme contributes to the European Flow Separation Control Device Programme, FSCD. An extension of the Calo programme towards advanced nozzles with technologies for flow separation control is foreseen in 2004 within the frame of FSCD.

Acknowledgement

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