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EUROPEAN COOPERATION
ON FLOW SEPARATION CONTROL

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Introduction and History

Most of today's launch vehicles use parallel staging with two or more strong solid rocket boosters and a core stage engine; the latter is ignited at ground and operates up to high altitudes, where the ambient pressure is close to vacuum. During take-off and the first phase of flight, the strong boosters make up most of the thrust, whereas the contribution of the core stage is comparably small. After booster separation, which usually takes place in altitudes where the ambient pressure is very low, the core stage alone accelerates the launcher. Therefore, the vacuum performance of the core stage engine has a considerable influence on the payload, whereas its sea-level impulse is of minor importance. An obvious way to enhance the payload of such launchers is hence to increase the area ratio ε of the core engine nozzle.

If a rocket engine is operated under strongly over-expanded conditions with the ambient pressure considerably higher than the nozzle exit pressure, the flow separates from the wall. Flow separation in rocket nozzles is undesired because it can lead to high lateral forces, the so-called side-loads, which can damage the nozzle and engine. In order to prevent flow separation and side-loads, the core stage nozzles of today's launch vehicles use area ratios that are far below the optimum, but ensure full-flowing and thus safe function at sea-level conditions. Hence, allowing flow separation in the core stage engine with reduced side-loads would considerably improve the launcher's payload.

In the 1940s, flow separation in rocket nozzles was for the first time investigated in detail [1]. It was understood that the boundary layer separated from the nozzle wall for wall pressures below a value of about one third of the ambient pressure and that the flow continued as a free stream. Today, this flow phenomenon is referred to as “Free Shock Separation”, FSS, see Figure 1 left. During the development of the J-2S engine in the early 1970s [2], a second kind of flow separation was observed, where the separated flow reattached to the nozzle wall, thereby forming a closed recirculation bubble, see Figure 1 right. The name “Restricted Shock Separation”, RSS, was chosen for this phenomenon, which was however only observed in sub-scale cold-gas tests and not completely understood. Independently of the flow separation pattern, the amplification of existing side-loads due to an aeroelastic coupling between flow and structure was believed to play a considerable role for the side-load development [3].

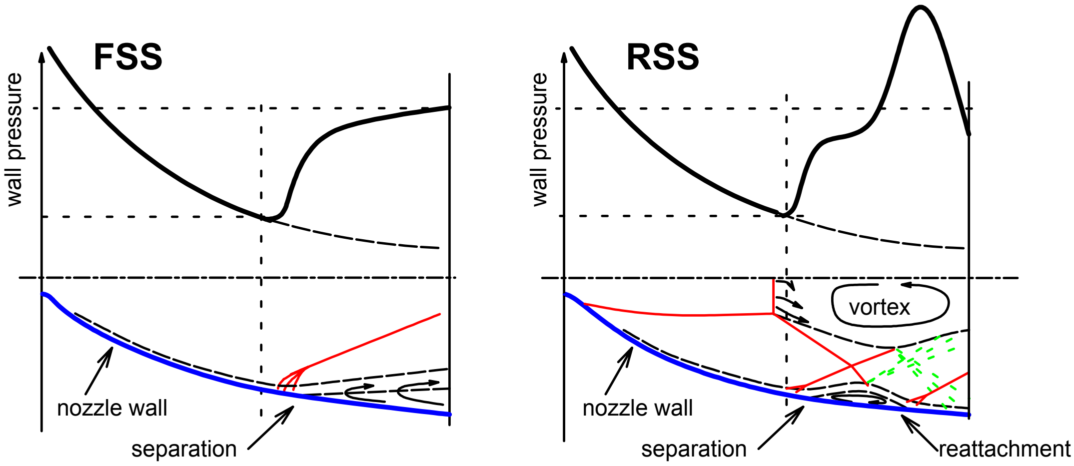

Figure 1: Free Shock Separation (FSS, left) and Restricted Shock Separation (RSS, right) –- wall pressure distribution and flow phenomenology

In Europe, activities on flow separation and side-loads were initiated in the early 1990s after high side-loads had been observed in a Vulcain engine. Sub-scale tests in a truncated ideal nozzle were carried out at LEA Poitiers, including dynamic wall pressure measurements [13]. At ONERA, a planar nozzle flow was investigated, where either a symmetrical or unsymmetrical shock could form [30]. Wind tunnel tests with a sub-scaled Vulcain nozzle performed by Volvo Aero [21] showed the occurrence of RSS over a wide range of pressure ratios. It could be shown that huge side-loads were induced when the flow changed from FSS to RSS and vice versa [21]. By analysing different nozzle design methods, DLR [7] showed that a weak shock exists inside thrust-optimised nozzles, originating from the beginning of the divergent nozzle section. This internal shock causes a plume pattern very different from the expected Mach disk and was called “cap shock pattern”. At low pressure ratios with flow separation, the cap shock pattern can cause the separated flow to reattach to the wall and thus cause RSS, even in full-scale engines as the Vulcain and the SSME [7].

In 1998, the European industrial partners Snecma (at that time called SEP), Astrium (Dasa) and Volvo Aero together with the research institutions DLR, ONERA, LEA Poitiers and somewhat later also ESTEC focused their research efforts in the European FSCD group, which is organized by CNES. An important part of the work consists in cold sub-scale tests, which are performed at four different test facilities at FOI (Sweden) [40], LEA Poitiers (France) [24], DLR Lampoldshausen (Germany) [19] and ONERA Meudon (France) [31, 32]. Furthermore, extensive numerical studies as well as analytical considerations were used to understand the physical phenomena connected to flow separation and side-loads in rocket nozzles.

This paper gives an overview over the work done by the group members during the past four years.

Plume investigations

Investigations of the flow downstream of the nozzle exit were initiated by the observation that two different shock patterns could exist in the Vulcain plume [7]: At higher chamber pressures, the well-known Mach disk was visible, while the so far unknown cap-shock pattern was observed for lower load-points, see Figure 2.

The transition between the two different patterns takes less than 2 milliseconds, and the pressure ratio at which it occurs shows a clear hysteresis [8].

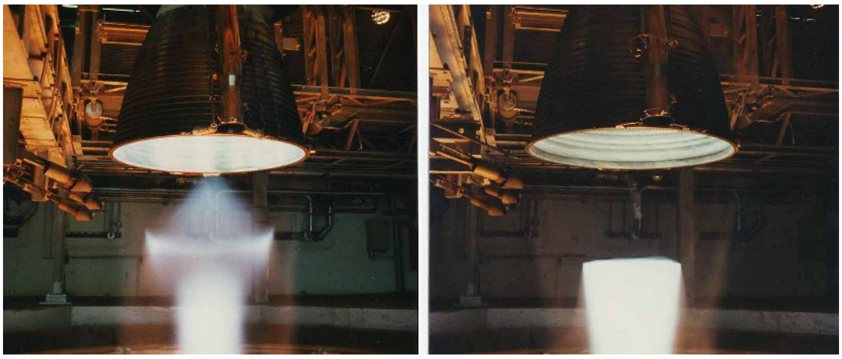

Figure 2: Cap shock pattern (left) and Mach disk (right) in the plume of the Vulcain engine [7]

A condition for the existence of the cap-shock pattern is the existence of an internal shock about parallel to the nozzle axis. Such a shock is formed if the wall curvature downstream of the throat is stronger than the one of an ideal nozzle with identical wall angle; it can be observed in thrust-optimised (both parabolic and Rao-optimised) and compressed truncated ideal nozzles. The cap shock pattern occurs as the internal shock is reflected at the centreline as an inverse Mach reflection [10]. It consists of a strong shock near the centreline, an oblique shock (called "cap shock") leading from the triple point in radial direction and the over-expansion or separation shock coming from the nozzle wall, see Figure 3. The interaction between the cap shock and the over-expansion shock can either be a regular one (as shown in Figure 3), or a bridge interaction in the manner of a Mach stem is formed [29, 31]. Downstream of the strong shock, a trapped vortex with backflow at the centreline is expected by numerical simulations [21, 7, 37, 35]

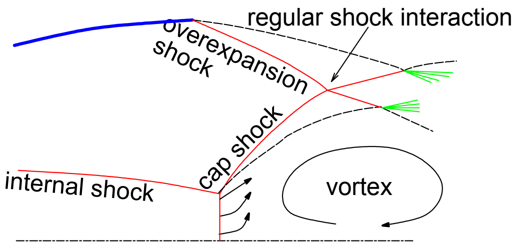

Figure 3: Cap shock pattern with regular interaction between cap shock and over-expansion shock – flow phenomenology

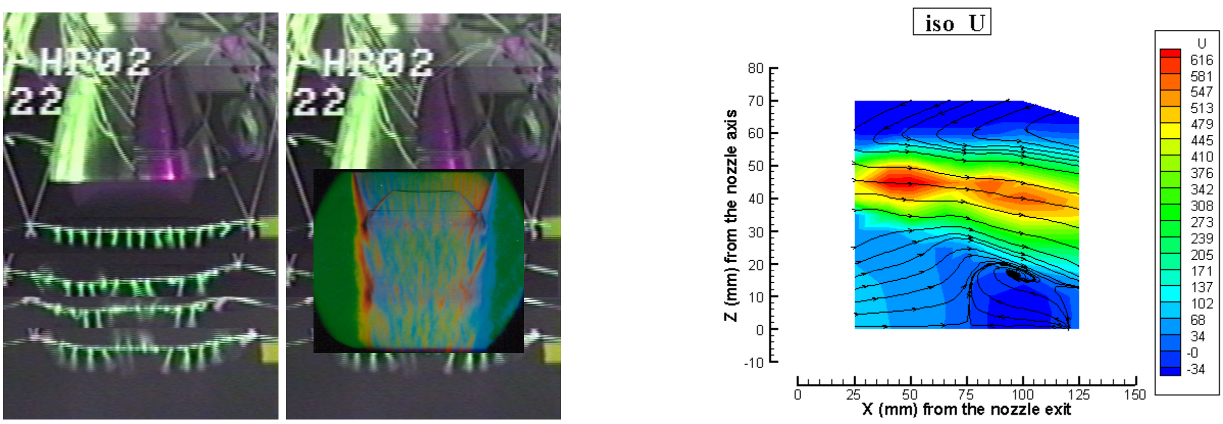

Figure 4: Visualisation of the cap shock pattern by cotton threads [37] (left), Schlieren photographs [12, 37] (centre) and LDV [35] (right)

Different visualisation techniques have been applied to the cap shock pattern in sub-scale tests. Schlieren pictures [26, 12, 31] give a good overview over the general flow field, but allow no statement about the flow direction. The classical cotton thread method shows a backflow at the nozzle centreline [37], while the quantitative confirmation of the backflow is reached with LDV measurements [35], see Figure 4.

Free Shock Separation (FSS)

One of the main problems with FSS is the prediction of the separation location. This is, inspired by early works from the 1940s and 1950s [1], usually done by describing the ratio between wall and ambient pressure p_{sep}/p_a at which flow separation occurs.

Within the FSCD group, several attempts were taken to improve the accuracy of separation prediction. They all have in common that they treat the two independent physical processes separation and recirculation as separate problems and hence split the usual separation criterion p_{sep}/p_a into two parts, p_{sep}/p_p and p_p/p_a, as earlier suggested by Lawrence [4]. A possibility to increase the accuracy for the prediction of the pressure rise over the separation shock is to use the oblique shock relations and to describe the behaviour of the shock angle rather than the one of the pressure rise [7, 28]. However, the higher accuracy can be reached with separation models that take into account the contour [34, 28]. These models use the Generalized Free Interaction Theory by Carrière [5] to predict the pressure distribution in the separation region. Over the recirculation zone, a momentum conservation is applied [34]. Figure 5 shows the good agreement of this type of model with sub-scale test results.

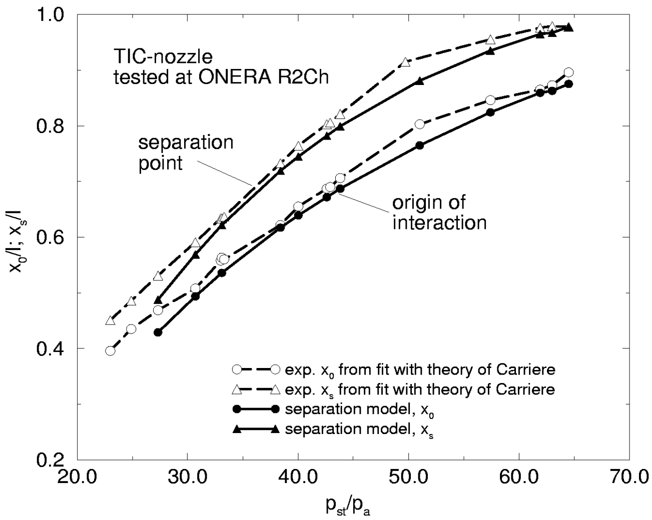

Figure 5: Comparison of a FSS separation model with experimental data [34]

In the case of FSS, side-loads are created by asymmetric pressure fluctuations in the separation and recirculation regions. The analysis of different sub-scale tests [6, 39, 28, 31] shows only very low pressure fluctuations in the attached boundary layer, high values in the separation region and intermediate values in the recirculation region, see Figure 6. These different levels are caused by the oscillating separation shock: In the separation region, where highest fluctuations are measured, the pressure oscillates between the value of the undisturbed boundary layer and the plateau pressure, which is in the range of the ambient pressure, see Figure 7. Based on this knowledge, side-load models for FSS have been developed and validated to sub-scale test data [27, 34].

In general, the side-loads in nozzles where only FSS occurs do not show any peaks at special pressure ratios [12, 6, 32]. However, a distinct side-load activity at pressure ratios below $p_c/p_a = 10$ has been detected in some sub-scale tests with different nozzle types [20]. Infrared visualisations showed a local and very unsteady reattachment of the separated jet to the wall [20].

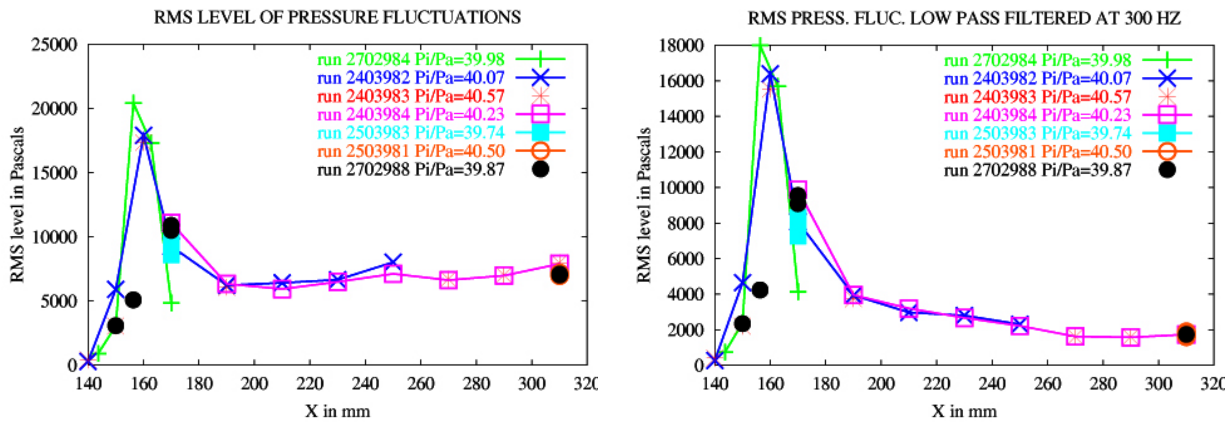

Figure 6: Pressure fluctuations in a truncated ideal nozzle with FSS [6]

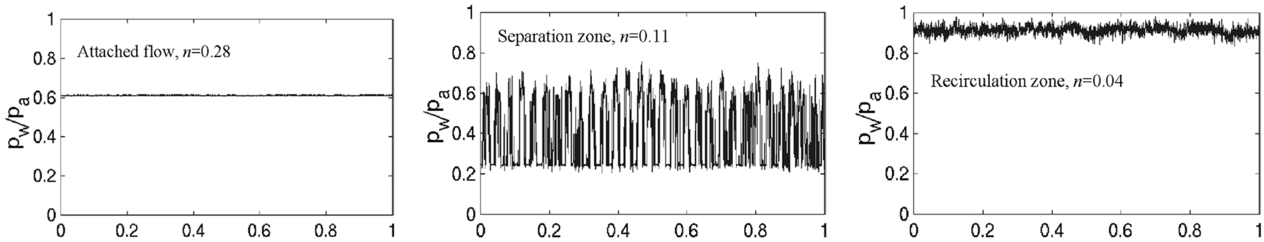

Figure 7: Wall pressure over one second at same location, but different pressure ratios [27]

It is important to note that a nozzle is a mechanical system, to which the aerodynamic side-load is applied as an exciting force. The system response is therefore not only a function of the side-load's magnitude, but also of its frequency. Typical FSS side-loads can be recalculated from the system response by using the forced response theory [27].

A nozzle deformed by a lateral force changes its wall pressure distribution, which results in either an amplification or a weakening of the original force. This effect is called aeroelastic coupling and was believed to be one of the main causes for the side-load problems with the Vulcain engine [3]. It was shown by experiment that aeroelastic amplification indeed can occur in nozzles, but that its effect is limited to very weak nozzle structures and furthermore depends on the nozzle contour [27]. The high Vulcain side-loads were not caused by this phenomenon.

Restricted Shock Separation (RSS)

If the pressure ratio is lowered in nozzles showing a cap shock pattern in full-flowing conditions, this shock pattern moves into the nozzle according to the movement of the separation location. Located inside the nozzle, this pattern deflects the separated flow towards the wall, and a stable and mainly axisymmetric reattachment can occur, referred to as Restricted Shock Separation, RSS, see Figure 1 right. The separation and subsequent reattachment can e. g. be visualised by oil flow visualisations [22] or infrared imaging [20], see Figure 8.

RSS can only occur for intermediate pressure ratios; for lower and higher area ratios, FSS exists or the nozzle is full-flowing. Therefore, two distinct changes in flow pattern occur as such a nozzle is started: At lower pressure ratios, the transition FSS-RSS, where the separated flow reattaches to the wall and at higher pressure ratios the opening of the recirculation bubble as it reaches the nozzle exit. Both transitions cause clear side-load peaks [21, 7] and are well visible on Schlieren films [12, 28] see Figure 9. If the aerodynamic excitation is a single pulse rather than a steady oscillating force, the shock excitation theory must be used instead of the forced response theory in order to calculate the system response [27].

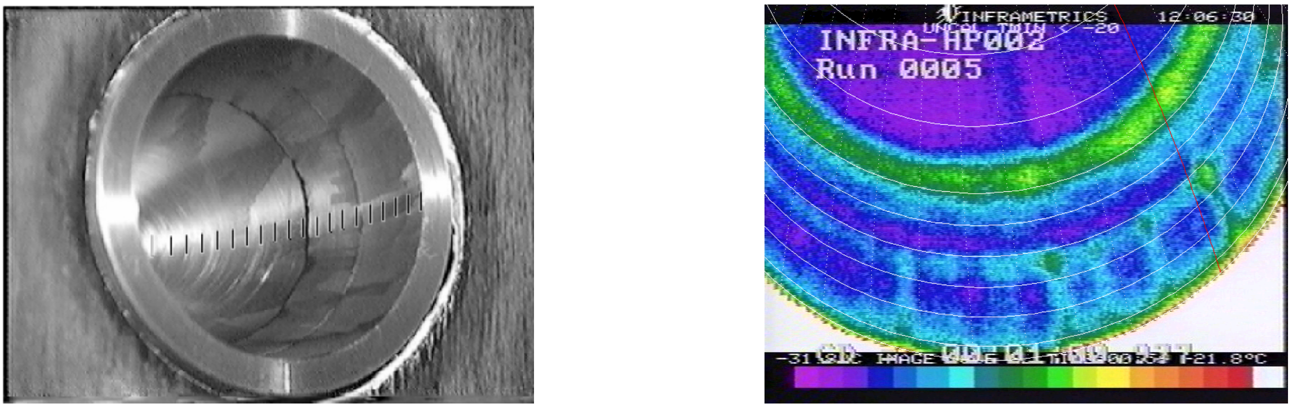

Figure 8: Visualisation of the separation and reattachment lines in sub-scale tests by oil flow (left) [22] and infrared imaging (right) [20]

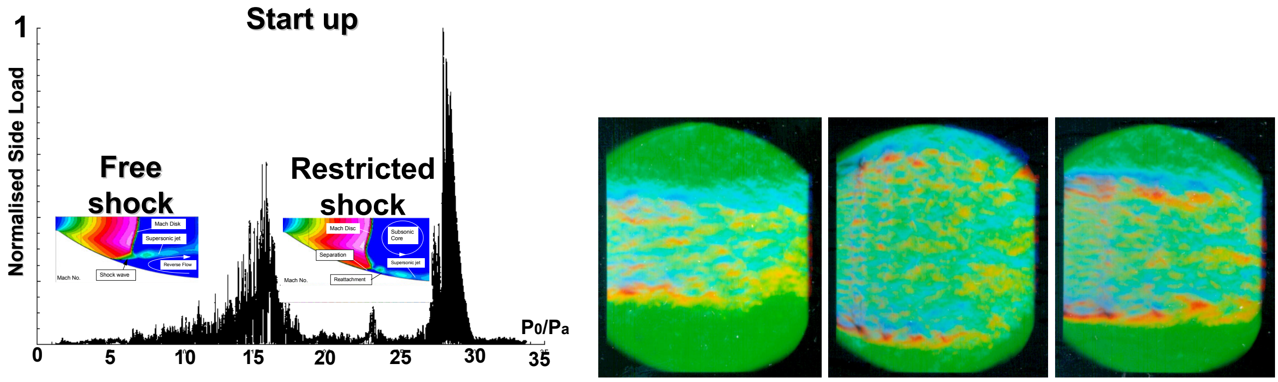

Figure 9: Left – side-loads in a parabolic nozzle with change of separation pattern [21]; right – Schlieren pictures of a parabolic nozzle flow with increasing pressure ratio from left to right (FSS - RSS - FSS near exit), flow from left to right, nozzle exit at left side [12]

Different models have been developed to predict the pressure ratio at which the transitions occur and the side-load magnitude of the transition loads [10, 26, 29], one of them using the method of characteristics to trace the shock location [29]. The results are in good agreement with experimental data.

The duration of the transition FSS-RSS was measured to be shorter than 50 ms in a cold-gas test [22]. Increasing side-loads are induced already before the transition itself, because the turbulent shear layer of the free jet approaches the nozzle wall and causes high pressure fluctuations at the wall. The opening of the closed separation bubble at higher pressure ratios can occur as a periodic pulsation [10, 21] or as a random process [6], but is in any case the source of high side-loads. This peak can be reduced by the attachment of a high-pressure gradient extension to the contour [26].

The early observation of a hysteresis concerning the pressure ratio at which the transition FSS-RSS occurs [2] was confirmed by both tests [21, 12, 6, 28] and computations [11, 25, 6].

Scaling considerations

Cold gas tests allow relatively inexpensive investigations of nozzle flows with diagnostics that are hard to apply in hot rocket nozzles [28]. However, the direct scaling of the results to hot flows represents a serious problem due to the different specific heat ratio, which causes a fundamentally different expansion behaviour. Nevertheless, direct scaling from cold to hot flows is possible within certain limits if the cold-gas contouring is done very carefully and if the right values are used for normalisation [28]. Of course, cold-gas test results can always be used to understand the physical phenomena and establish prediction tools, which can be applied to hot full-scale applications [15, 28].

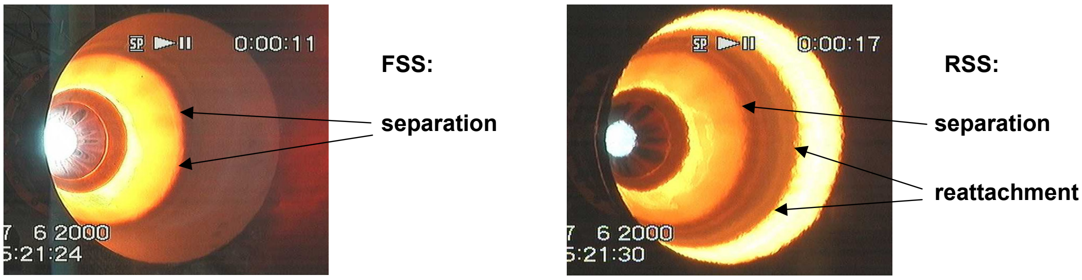

Figure 10: FSS (left) and RSS (right) in a hot sub-scale test with a ceramic nozzle [15]

Since Reynolds number and chemical non-equilibrium effects only play a minor role in H_2O_2-combustors, direct geometric scaling can be applied to hot sub-scale tests with identical gas. This has been demonstrated with a Vulcain sub-scale nozzle, where the transitions between FSS and RSS and vice versa were observed at exactly the same pressure ratios [15]. Moreover, the hot ceramic nozzle wall allows an excellent visualisation of both separation and reattachment point, see Figure 10. Hot sub-scale tests represent therefore a very useful intermediate step in order to minimize development risks.

Buffeting

In the transonic regime of space vehicle trajectory, flow instabilities as well as pressure pulsations develop along the body of the vehicle and cause a highly instationary flow in its wake, where the engines are located. If the nozzle is not full-flowing, a dangerous interaction between fluctuating ambience and nozzle flow can occur, resulting in high side-loads.

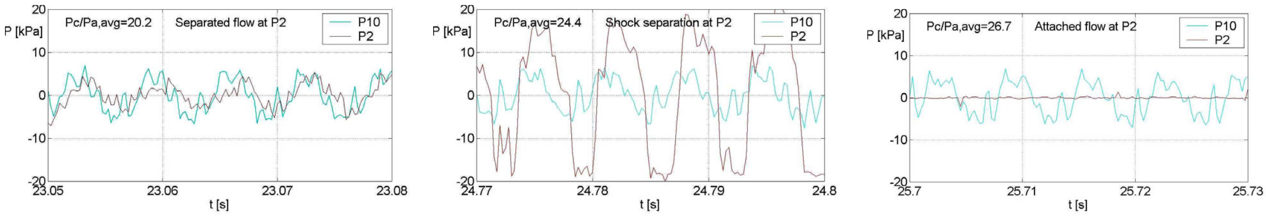

Figure 11: Wall pressure (sensor P2) measurements in a nozzle disposed to ambient pressure (sensor P10) pulsations [40, 36]; sensor downstream of separation point (left), in the region of the moving separation shock (centre) and upstream of separation point (right)

In a wind tunnel experiment, a separated nozzle flow has been disposed to a pulsating ambient pressure [40], and a coupling between the pulsating atmosphere and the separation line has been detected, which varies with frequency and amplitude, see Figure 11. Numerical simulations of the same nozzle reveal a resonance between ambient fluctuation and internal flow in so far as for a certain exciting frequency, the movement of the separation location is much stronger than it would be the case for a slow change of the ambient pressure. For lower frequencies, a quasi-static behaviour is seen whereas for very high frequencies, the fluctuation of the separation location tends to zero [36].

Dual-bell nozzles

One example for a nozzle with flow separation control is the dual-bell nozzle. Its most noticeable property is the sharp contour inflection in the divergent portion, which divides the nozzle into two parts, the base nozzle upstream of the inflection and the nozzle extension downstream, see Figure 12 left. In low altitudes with high ambient pressure, the nozzle flow separates at this point (sea-level mode), and the effective area ratio corresponds to the one of the base nozzle. In high altitudes with low ambient pressures, the whole nozzle is full-flowing (altitude mode). This change of effective area ratio provides an altitude adaptation and hence increases the specific impulse [9] over wide ranges of the trajectory. Moreover, the side-load activity during sea-level mode is reduced, because the separation location is locked at the wall inflection. This reduces also the side-loads during the dangerous buffeting phase.

A very critical item for the realisation of the dual-bell concept is how the flow changes from sea level to altitude mode. During this mode transition, the separation point is located somewhere between the wall inflection and the nozzle exit, and huge side-loads can be induced. However, certain contouring methods allow to reduce the mode transition duration drastically [9, 16].

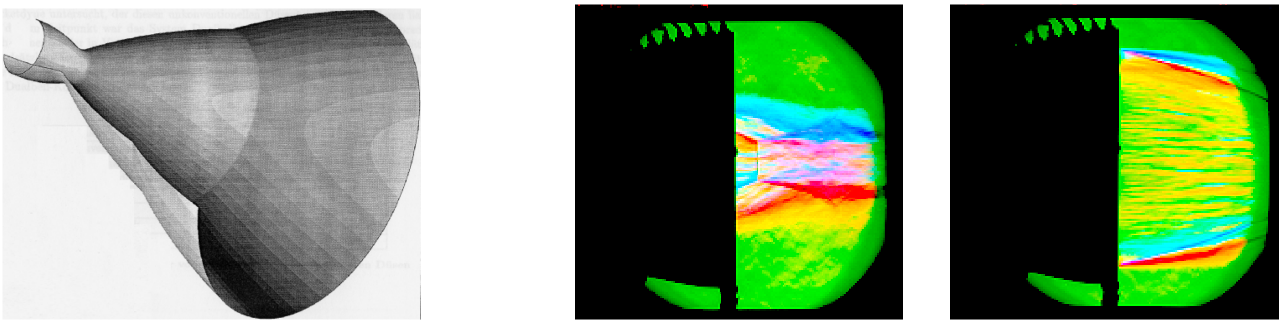

Figure 12: Artist's view of a dual-bell nozzle (left); Schlieren photographs of a dual-bell nozzle flow – sea level mode (centre) and altitude mode (right) [16]

In the framework of FSCD, cold sub-scale tests with dual-bell nozzles have been performed at two different test facilities [26, 16]. The desired fast mode transition without any occurrence of RSS was only reached if a truncated ideal contour was used as base nozzle and the wall pressure gradient in the nozzle extension was equal to or greater than zero. For one specific nozzle, the transition duration was measured to be in the range of 10 milliseconds [16] – possibly short enough to prevent any dangerous effect on the engine. Schlieren pictures of this nozzle are shown in Figure 12 centre and right. Furthermore, it was shown that the mode transition occurs at different pressure ratios at start-up and shutdown. This hysteresis effect stabilizes the modes and prevents multiple transitions.

The mode transition in the same nozzle has been modelled by CFD, where different ramps of the driving nozzle pressure ratio were simulated, which were however much faster than in reality. Nevertheless, a sensitivity of the transition duration with respect to ramping speed and the final pressure ratio of the ramp was detected [42].

Conclusion

During the past four years, the European research group for flow separation, FSCD, has studied flow separation and side-loads in rocket nozzles. To get an insight into the related flow phenomena, cold and hot sub-scale tests were carried out, full-scale tests were analysed and numerical simulations were performed.

Major progresses are described on the field of nozzle plumes as well as in the analysis of both Free Shock Separation (FSS) and Restricted Shock Separation (RSS). Different scaling approaches are presented for the application of cold sub-scale results to full-scale. Flow problems during the critical buffeting phase are analysed, and the altitude-compensating dual-bell nozzle is investigated, which could reduce the problem of interaction between flow separation and ambient pressure fluctuations.

The FSCD group has given rise to a good coordination of the European research and technological activities related to nozzle flows. A high efficiency has been attained in Europe by allowing industrial partners to present the challenges they face to scientific institutions and by enhancing the coordination of the scientific and technological effort by space agencies at a European scale.

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