A BRIEF STUDY ABOUT ADVANCEMENT IN ROCKET NOZZLE USED IN AIRCRAFT SCIENCE

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ABSTRACT

Several nozzle concepts that promise a gain in performance over existing conventional nozzles are discussed in this paper. It is shown that significant performance gains result from the adaptation of the exhaust flow to the ambient pressure. Special attention is then given to altitude-adaptive nozzle concepts, which have recently received new interest in the space industry. Current research results are presented for dual-bell nozzles and other nozzles with devices for forced flow separation and for plug nozzles with external free stream expansion. In addition, results of former research on nozzles of dual-mode engines such as dual-throat and dual-expander engines and on expansion– deflection nozzles are shown. In general, flow adaptation induces shocks and expansion waves, which result in exit pro. Less that is quite different from idealized one-dimensional assumptions. Flow phenomena observed in experiments and numerical simulations during different nozzle operations are highlighted, critical design aspects and operation conditions are discussed, and performance characteristics of selected nozzles are presented. The consideration of derived performance characteristics in launcher and trajectory optimization calculations reveal significant payload gains at least for some of these advanced nozzle concepts.

Nomenclature

A = area

F = thrust

h = • height altitude

I = impulse

l = length

$\dot{m}$ = mass flow rate

p = pressure

$\bar{r}$ = mass ratio oxidizer/ fuel mixture

r = radius

x , y = coordinates

ε = nozzle area ratio

Subscripts

amb = ambient

c = combustion chamber

cr = critical

e = exit plane

geom = geometrical

ref = reference

sp = specific

t = throat

vac = vacuum

w = wall

I. INTRODUCTION

The reduction of Earth-to-orbit launches costs in conjunction with an increase in launcher reliability and operational efficiency are the key demands on future space transportation systems, like single-stage-to-orbit vehicles (SSTO). The realization of these vehicles strongly depends on the performance of the engines, which should deliver high performance with low system complexity. Performance data for rocket engines are practically always lower than the theoretically attainable values because of imperfections in the mixing, combustion, and expansion of the propellants. The examination and evaluation of these loss effects is and has for some time been the subject of research at scientific institutes and in industry. Table-1 summarizes performance losses in the thrust chambers and nozzles of typical high-performance rocket engines:

The SSME- and Vulcain 1 engine shuttle main engine, Rocketdyne hydrogen– oxygen engine and hydrogen–oxygen core engine of European Ariane-5 launcher). Among the important loss sources in thrust chambers and nozzles are viscous effects because of turbulent boundary layers and the nonuniformity of the flow in the exit area, whereas chemical nonequilibrium effects can be neglected in H_2–O_2 rocket engines with chamber pressures above p_c = 50 bar. Furthermore, the nonadaptation of the exhaust flow to varying ambient pressures induces a significant negative thrust contribution (see Figs. 1– 3). Ambient pressures that are higher than nozzle wall exit pressures also increase the danger of flow separation inside the nozzle, resulting in the possible generation of side loads. A brief description of state-of-the-art prediction methods for both phenomena is given.

Table 1 Performance losses in conventional rocket nozzles

Losses	**Vulcain 1, %**	**SSME %**
Chemical nonequilibrium	0.2	0.1
Friction	1.1	0.6
Divergences, nonuniformity of exit flow	1.2	1.0
Imperfection in mixing and combustion	1.0	0.5
Nonadapted nozzle flow	0-15	0-15

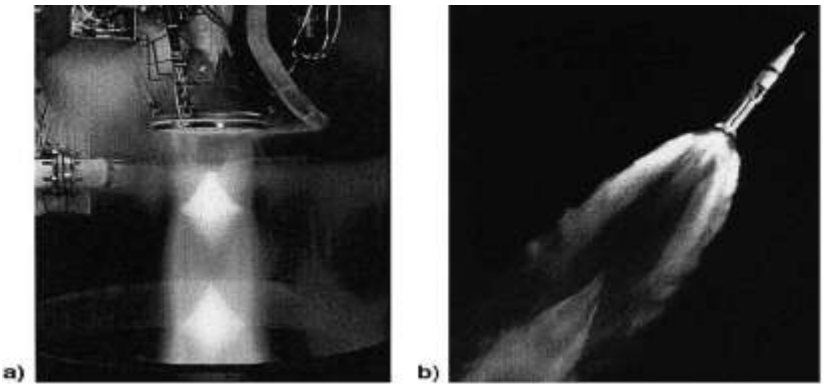

Fig. 1 - Rocket nozzle flow fields during off-design operation

a) Over expanded flow RL10A-5 engine and

b) Under expanded flow Saturn-1B, Apollo-7 (Photographs, United Technologies' Pratt & Whitney, NASA).

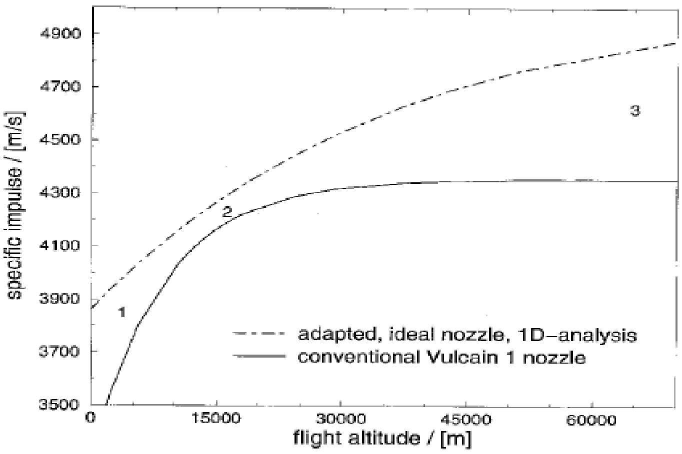

Fig. 2 - Performance Data For Nozzle of Vulcain 1 Engine (Design Parameters of Vulcain 1 Nozzle: $\varepsilon = 45$, $p_c / p_{amb} = 555$, $\bar{r} = 5.89$).

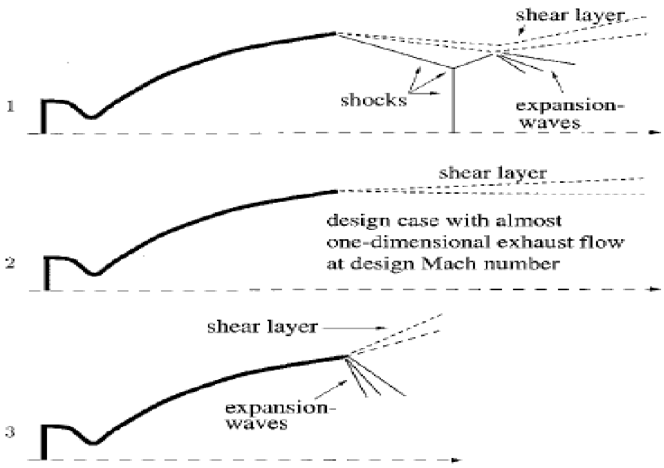

Fig. 3 -Flow Phenomena For A Conventional Rocket Nozzle

II. CONVENTIONAL NOZZLES

Conventional bell-type rocket nozzles, which are in use in practically all of today's rockets, limit the overall engine performance during the ascent of the launcher owing to their fixed geometry. Significant performance losses are induced during the off-design operation of the nozzles, when the flow is over expanded during low-altitude operation with ambient pressures higher than the nozzle exit pressure, or under expanded during high-altitude operation with ambient pressures lower than the nozzle exit pressure. Figure 1 shows photographs of nozzle exhaust flows during off-design operation. In the case of over expanded flow, oblique shocks emanating into the flow field adapt the exhaust flow to the ambient pressure. Further downstream, a system of shocks and expansion waves leads to the characteristic barrel-like form of the exhaust flow. In contrast, the under expansion of the flow results in a further expansion of the exhaust gases behind the rocket. Off-design operations with either over expanded or under expanded exhaust flow induce performance losses. Figure 3 shows calculated performance data for the Vulcain 1 nozzle as function of ambient pressure, together with performance data for an ideally adapted nozzle. Flow phenomena at different pressure ratios p_c/ p_{amb} are included in Fig. 3. [The sketch with flow phenomena for the lower pressure ratio p_c / p_{amb} shows a normal shock (Mach disk). Depending on the pressure ratio, this normal shock might not appear, see, e.g., Fig. 1.] The Vulcain 1 nozzle is designed in such a manner that no uncontrolled flow separation should occur during steady-state operation at low altitude, resulting in a wall exit pressure of $p_{w,e} \approx 0.4$ bar, which is in accordance with the Summerfield criterion. [8] The nozzle flow is adapted at an ambient pressure of $p_{amb} \approx 0.18$ bar, which corresponds to a flight altitude of $h \approx 15{,}000$ m, and performance losses observed at this ambient pressure are caused by internal loss effects (friction, divergence, mixing), as Table 1. Losses in performance during off-design operations with over- or under expansion of the exhaust flow rise up to 15%. In principle, the nozzle could be designed for a much higher area ratio to achieve better vacuum performance, but the flow would then separate inside the nozzle during low-altitude operation with an undesired generation of side-loads. Induce an oblique shock wave near the wall, which leads to a recompression of the flow.

III. ALTITUDE ADAPTIVE NOZZLES

A critical comparison of performance losses shown in Table 1 reveals that most significant improvements in nozzle performance for first-stage or SSTO engines can be achieved through the adaptation of nozzle exit pressures to the variations in ambient pressure during the launcher's ascent through the atmosphere. Various concepts have been previously mentioned and will be discussed in detail in the following text.

3.1 Nozzles with Devices for Controlled Flow Separation

Several nozzle concepts with devices for controlled flow separation have been proposed in the literature, with primary emphasis on the reduction of side-loads during sea level or low-altitude operation. But the application of these concepts also results in an improved performance through the avoidance of significant overexpansion of the exhaust flow.

3.1.1 Dual-Bell Nozzle

This nozzle concept was first studied at the Jet Propulsion Laboratory17 in 1949. In the late 1960s, Rocket dyne patented this nozzle concept, which has received attention in recent years in the U.S. and Europe. Figure 4 illustrates the design of this nozzle concept with its typical inner base nozzle, the wall inflection, and the outer nozzle extension. This nozzle concept offers an altitude adaptation achieved only by nozzle wall inflection. In low altitudes, controlled and symmetrical flow separation occurs at this wall inflection (Fig. 5), which results in a lower effective area ratio. For higher altitudes, the nozzle flow is attached to the wall until the exit plane, and the full geometrical area ratio is used. Because of the higher area ratio, an improved vacuum performance is achieved. However, additional performance losses are induced in dual-bell nozzles,

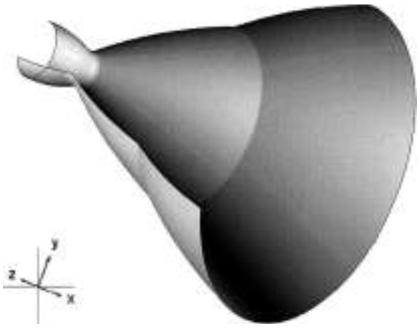

Fig. 4- Sketch of A Dual-Bell Nozzle

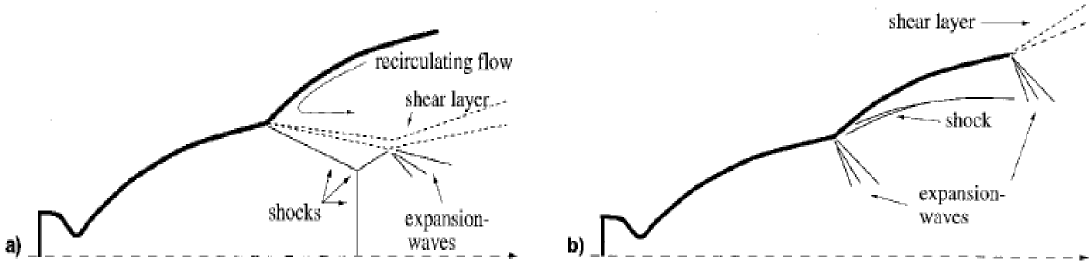

Fig. 5- Flow Field Phenomena In Dual-Bell Nozzles: a) Sea-Level Mode With Flow Separation At The Wall Inflection Point and b) Altitude Mode With A Full-Flowing Nozzle.

3.1.2 Two-Position or Extendible Nozzles

Nozzles of this type with extendible exit cones are currently used only for rocket motors of upper stages to reduce the package volume for the nozzle, e.g., at present for solid rocket engines such as the inertial upper stage (IUS), or for the liquid rocket engine RL10. The main idea of the extendible extensions to use a truncated nozzle with low expansion in low-flight altitudes and to have a higher nozzle extension at high altitudes. Figure 6 illustrates this nozzle concept. Its capability for altitude compensation is indisputable and the nozzle performance is easily predictable. The whole nozzle contour including the extendible extension is contoured for maximum performance at the high-area ratio with either the method of characteristics or a variational method. The area ratio of the first nozzle section is then determined and the nozzle contour is divided into two parts: The fixed nozzle part and the extendible extension. Investigations conducted at the Keldysh Center have shown that this nozzle-contouring method is not only the simplest but also provides a good overall trajectory performance. A minor performance loss is incorporated during low-altitude operations because of the truncated inner nozzle, which has a nonoptimal contour for this interim exit area ratio.

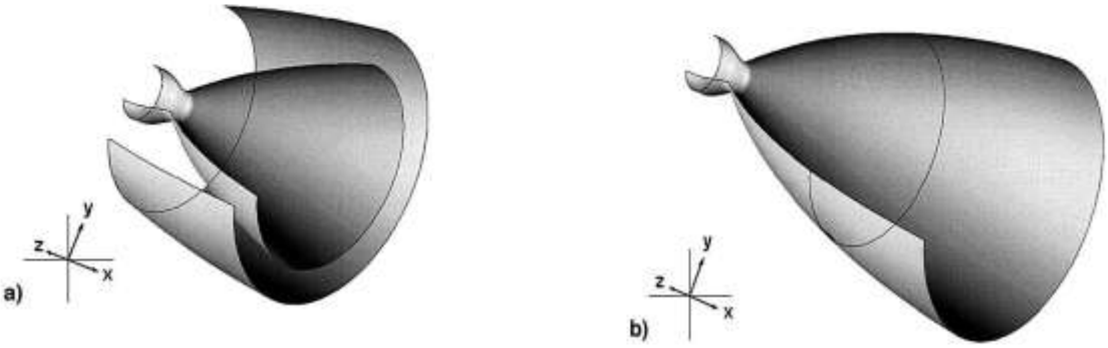

Fig. 6 - Sketch of a two-position nozzle during a) sea-level and b) Vacuum operations.

IV. CONCLUSIONS

Several nozzle concepts that promise gains in performance over conventional nozzles were discussed in this paper, including performance enhancements achieved by slight modifications of existing nozzles, e.g., through cool gas injection into the supersonic nozzle part. It is shown that significant performance gains result from the adaptation of the exhaust flow to the ambient pressure, and special emphasis was given to altitude adaptive nozzle concepts. A number of nozzle concepts with altitude-compensating capability were identified and described. To assist the selection of the best nozzle concept for launch vehicle applications, the performance of the nozzles must be characterized. This can be done using computational fluid dynamics (CFD) and/or cold-flow tests. Existing CFD methods that are in use in the aerospace industry and at research institutes have been verified for a wide number of sub- and full-scale experiments, and provide sufficiently reliable performance determination for the different nozzle types. Theoretical evaluations, numerical simulations, and test results showed that the different concepts have real altitude-compensating capabilities. However, the compensation capabilities are limited and there are some drawbacks associated with each of the concepts. Additional performance losses are induced in practically all of these nozzle concepts when compared to an ideal expansion, mainly because of the nonisentropic effects such as shock waves and pressure losses in recirculation zones. However, these additional performance losses are less than 1– 3%, depending on the different nozzle concepts.

In addition to aerodynamic performance, other technical issue (weight, cost, design, thermal management, manufacturing, system performance, and reliability) must be addressed. Furthermore, before final decision can be made as to which nozzle concept offers the greatest benefits with regard to an effective payload mass injection, combined launcher and trajectory calculations must be performed and compared to a reference launcher concept with conventional nozzles. Different nozzle efficiencies, which account for the additional losses of advanced rocket nozzles and are extracted from numerical simulations and experiments, must be taken into account. At least for some of these nozzle concepts, the plug nozzle, the dual-bell nozzle, and the dual-expander nozzle, benefits. Ts with regard to lower overall launcher masses have been demonstrated in the literature. Furthermore, the plug nozzle concept will be the first in flight of all these advanced nozzle concepts, with the X-33 demonstrator vehicle.

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