Optimization of Actuation and Cooling Systems for Advanced Convergent-Divergent Nozzles of Combat Aircraft

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1. SUMMARY

The system or components of a convergent-divergent (CON-DI) nozzle that offer better perspectives for improvement and optimization are the actuation and cooling systems.

Performance offers little margin for a direct improvement, and the utilization of advanced materials in many components of the nozzle presents no specific problems as compared with those of other parts of the engine, with the exception of the petals, in which the introduction of ceramic materials has a direct influence on cooling and performance, and it will be included in the cooling optimization.

The introduction of a thrust vectoring capability is a major improvement, though not the subjet of this paper.

The problem of the optimization of the actuation system was preliminary discussed in ref. 1, mainly in connection with the utilization of one versus two parameters actuation system. Since that time, SENER and ITP have carried out many studies and tests on actuation systems and on cooling optimization. They have also accumulated experience by means of theoretical and experimental studies on the utilization of ceramic petals.

Some results and the main conclusions of these studies and tests are presented in the present work.

2. ACTUATION SYSTEM

Conceptual design of nozzles involves primarily a device optimization based on a set of missions for which the whole weapon system is to be designed. Optimization of the actuation mechanism is closely linked with the nozzle concept itself, and therefore is one of the main issues established during the conceptual design phase.

Basically the function of the nozzle as an engine component is the air flow and back pressure control. It can be covered in a military engine by means of a simple variable convergent nozzle. However this type of devices are far of being optimum regarding the produced thrust. The second function of the nozzle is to convert as much thermal energy as possible into thrust. As the supersonic flight capabilities of fighter airplanes seem more and more important, thrust at high nozzle pressure ratio starts to be one of the limiting constraints for sizing the engines. That is the case of the following typical design cases:

-Supersonic cruise & escape dash.
(M = 1.5, h = 30kft, R = 130 n.mi., Max dry)
-Weight specific excess power at high Mach num.
(M = 2.0, h = 40 kft, Max reheat)
-Accelerations to supersonic.
(0.8 ≤M≤1.6, h=30 Kft, t<50s, Max reheat).

A convergent nozzle working in the first condition is producing 6% less thrust than the optimum convergent - divergent nozzle, or in other words, aircraft is requiring 0,5% WTO to perform the supercruise missions phase (5% of the typical payload of an air to air figther-AAF). For the weight specific excess power at high Mach number the loss of thrust relative to the optimum convergent divergent is in the order of 7% which represents roughly the required excess power.
For comparison purposes the optimum CON-DI nozzle will be used as a baseline. Optimum CON-DI nozzle means an axisymmetric convergent-divergent nozzle with a fixed aircraft interface producing the highest thrust for a giving total thermodynamic conditions of the exhaust gases. Convergent and divergent petals length are kept constant as well as the required cooling flow.

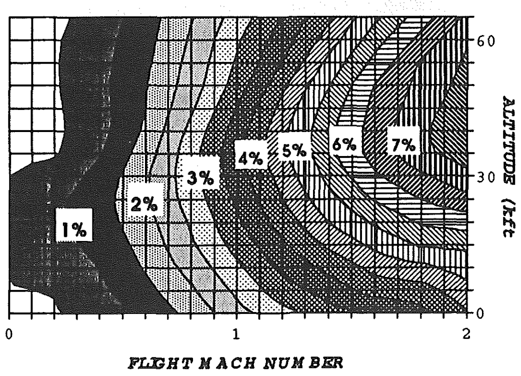

Fig.1.- Thrust losses of a convergent nozzle (dry)

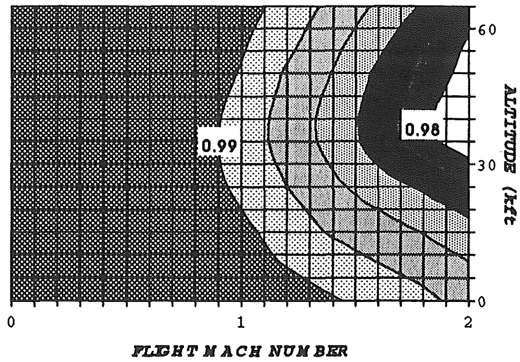

Fig.2.- Optimum thrust coefficient for a CON-DI nozzle (dry)

Figure 1 shows the thrust losses of a convergent nozzle relative to the optimum CON-DI operating in dry conditions, and the optimum thrust coefficient contours attainable with the described CON-DI nozzle are plotted in figure. 2. Nozzle optimization has been performed based on a typical engine for an AAF operating up to Mach number 2 an 65 kft altitude. Exit to throat area ratios (A9/A8) corresponding to optimum thrust coefficients are included in Figs.3. Optimum A9/A8 ratios vary from 1 to 1.9 for this kind of applications.

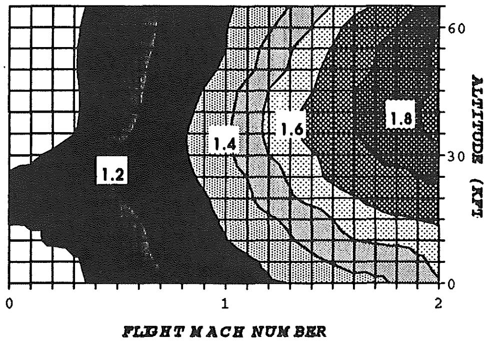

Fig.3.I.- Optimum exit to throat area ratio (dry)

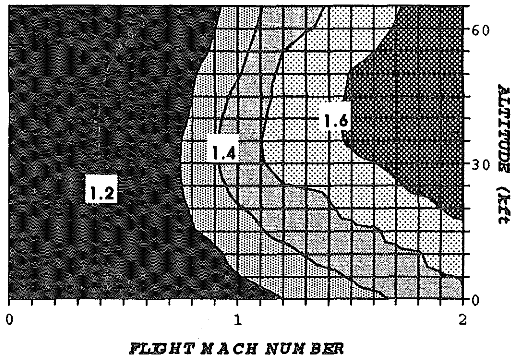

Fig.3.II.- Optimum exit to throat area ratio (reheat)

From figures 3.I. and 3.II. above, where the mentioned A9/A8 relationship for dry engine rating and reheated operation respectively are shown, the following conclusions can be derived:

- -Best A9/A8 ratio for supercruise mission phase is ~1.6. (Fig. 3.I).
- -Optimum A9/A8 for weight specific excess power requirement at M=2.0/40 Kft is again around 1.6. (Fig.3.II).

It has been mentioned that supercruise or excess power at high Mach number are the limiting constraints at high speeds, but on the other hand there is another fundamental constraint at low speed: the take off requirements. Preferred solutions for A9/A8 ratio for take off conditions are around 1.1. That introduces one of the main problems of the nozzle actuation system. Nozzle performance demands a system capable of producing variations of A9/A8 ratio from 1.1 to 1.6, independently of the throat area value, this means, a two degrees of freedom mechanism or biparametric CON-DI nozzle. But all the other aspect to be taken into account in the design optimizations indicate the opposite. Weight, Maintainability and Reliability considerably worsen when a biparametric nozzle is studied.

Classical CON-DI nozzle designs are based on the articulated struts construction, where A9/A8 relationship is kinematically linked to actual throat area. Large A8 produces high A9/A8 ratio, when reheated engine operations is required at supersonic Mach number. Lower A8 implies low A9/A8, suitable for continuous subsonic operations.

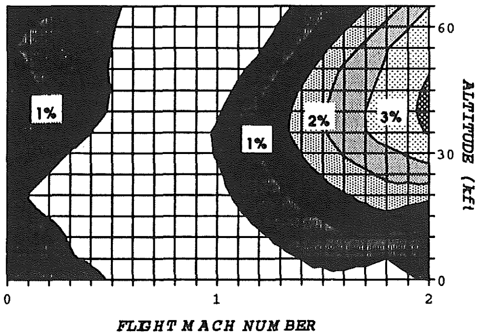

Fig.4.I.- Thrust losses for a monoparametric nozzle (dry)

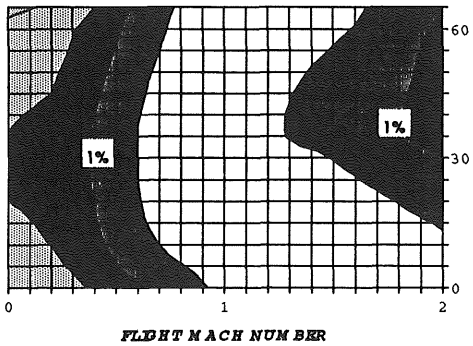

Fig.4.II.- Thrust losses for a monoparametric nozzle (reheat)

In figures.4.I and 4.II the thrust losses contours for a typical monoparametric nozzle are presented. For take off conditions 1.5% of the available thrust is lost. At supercruise flight conditions the thrust losses are approximately 2%. For excess power requirement point the thrust loses are around 1%.

Figures 5, 6 and 7 present the thrust losses, at dry power, for a nozzle with fixed exit to throat area ratios of 1.2, 1.55 and 1.9 respectively, with the reheat losses being very similar to the dry ones.

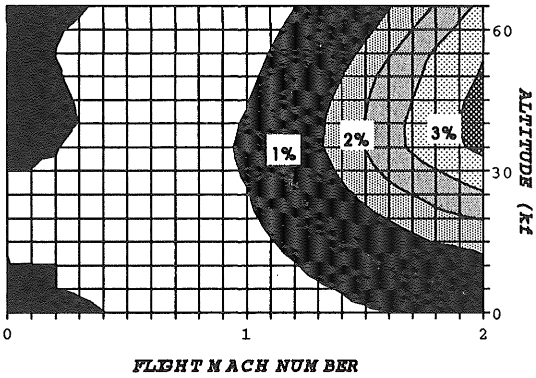

Fig. 5.- Thrust losses for a a CON-DI nozzle with A9/A8=1.2 (dry)

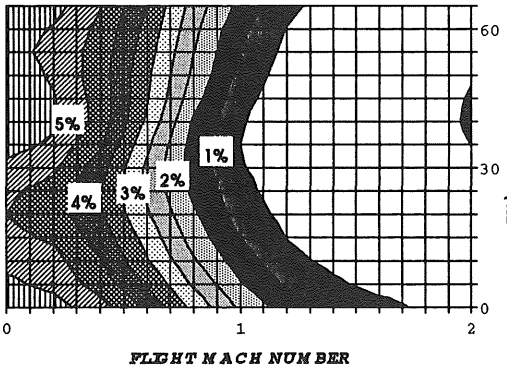

Fig.6.- Thrust losses for a a CON-DI nozzle with A9/A8=1.55 (dry)

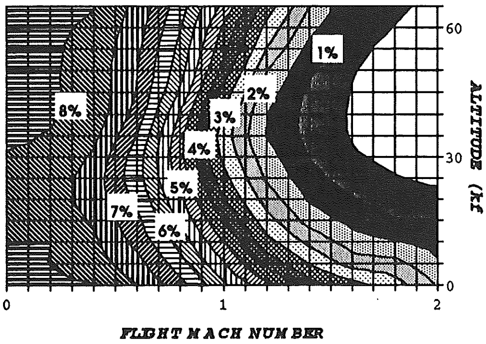

Fig. 7.- Thrust losses for a a CON-DI nozzle with A9/A8=1.9 (dry)

An important conclusion arises from the previous figures. The whole speed-altitude range, from Mach number 0 to 2, and from sea level to 65 kft, can be flown with thrust losses below 0.5% using a nozzle with two fixed A9/A8 relationships, 1.2 for subsonic flight and 1.55 for supersonic flight, either in maximum dry rating or maximum reheat operation. This kind of bistate CON-DI nozzle is being currently investigated for future applications. Bistate nozzle can be nearly as efficient as the biparametric ones, but lighter an more reliable provided that the change between the two expansions ratios could be done using the appropriate system, such as electrical micro actuators.

Up to this point missions phases involving maximum thrust requirements have been discussed. To finalize with the optimization of the actuation mechanism some attention must be paid to the cruise conditions. A substantial part of the fuel required for a mission is spent in cruise conditions. Typical subsonic cruise phases are:

-Subsonic cruise climb	~40 Kft/M=0.9, 150 n.mi.
-Loiter	10 Kft/M=0.65.

Engine pressure ratios for these flight cases are well below 3. The most critical case is the loiter mission phase. Performance of a perfectly sealed CON-DI nozzle as described in previous paragraphs is very poor. The reason of such a bad behavior is due to the large A9/A8 employed for the actual cruise nozzle pressure ratio. Discharge static pressure Ps_9 is lower than the ambient pressure, and this nozzle over-expansion causes a rapid descent of thrust coefficient. A method to alleviate the mentioned effect is to leave the divergent part of the nozzle floating. As static pressure inside the nozzle is lower than the ambient pressure there is a moment relative to the hinge at the throat plane which tends to close the divergent part of the nozzle. Hence over-expansion can be drastically reduced leaving the divergent petals floating up to a position where the moment of external pressure forces is in equilibrium with the one generated by the internal ones. That device has been called floating nozzle. Figure 8 (solid line) shows the increase in thrust, when the floating system is employed, relative to a nozzle with a fixed A9/A8 ratio of 1.2.

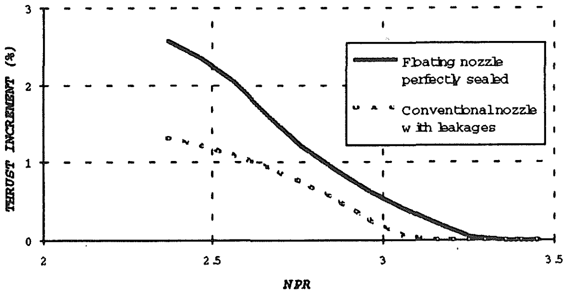

Fig. 8.- Thrust increment for a CON-DI nozzle with floating and leakage

However floating mechanisms present some problems difficult to overcome. Pressure oscillations in the divergent part of the nozzle induce vibrations at low A9/A8, when the floating nozzle could give the biggest benefits. Moreover, load maneuvers in flight would induce nozzle ovalization. Pressure fluctuations in the external cavity, between nozzle and the flaps, in a twin engine aircraft installation, would produce in flight vibrations.

Fortunately real nozzles are not perfectly sealed, specially at low NPRs where pressures inside the nozzle are below the ambient pressure. In that situation slave divergent petals tend to be separated from the master ones. External air is really being ingested through the existing gaps between master and slave divergent petals. This incoming flow reduces the effective exit to throat area ratio, hence diminishes over-expansion producing an increment in thrust coefficient. Fig. 8 (dashed line) gives the thrust increment due to the described effect. At least half of the benefit theoretically recoverable by means of a floating nozzle can be obtained from the real geometry of a conventional CON-DI. For that reason, nozzles with floating mechanism have been discarded, because the potential benefits can not compensate the problems that it introduces.

3. COOLING

The simplest way to cool a CON-DI nozzle is to take the air needed for the cooling at the end of the reheat liner. This air flows downstream as a film protecting the walls from the high temperature of the main flow. The cooling effectiveness decreases with the distance from the injection due to the mixing of the (cold) film cooling layer with the (hot) main stream.

There are alternative ways to cool a CON-DI nozzle but with a high mechanical complication in the design of the nozzle petals and/or mass penalty not compensated with the possible increment on thrust due to the hypothetical reduction on cooling.

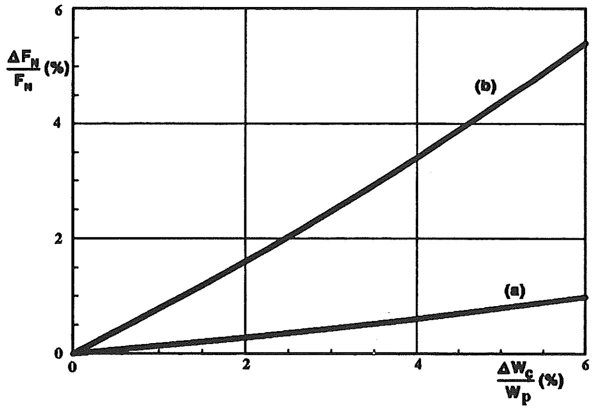

Fig. 9.- Delta thrust vs. delta cooling reduction. (a) with decoupled R/H system; (b) with coupled R/H system.

The appropriate nozzle cooling has to be obtained as a compromise with the jet pipe cooling. For example, a reduction on nozzle cooling flow does not implies an equivalent increment on engine thrust if there is not an appropriate coupled design of the complete reheat system as can be seen in Fig. 9. The reason to have the difference between curves a and b of Fig. 9 is because , for a given reheat configuration, the reduction on nozzle cooling implies a redistribution of the cooling flow across the reheat system and only a small part of the reduced cooling is utilized (burnt in the reheat system) to increase the thrust. Nevertheless, if the reduction is complemented with a coupled design of the reheat system the increment on thrust can be as high as given in curve b of Fig. 9.

3.1. THROAT COOLING

Independent of the thermal design is the passive cooling that can be obtained in some flight conditions, i.e. for some nozzle pressure ratios, throughout the gaps between petals left for mechanical reasons.

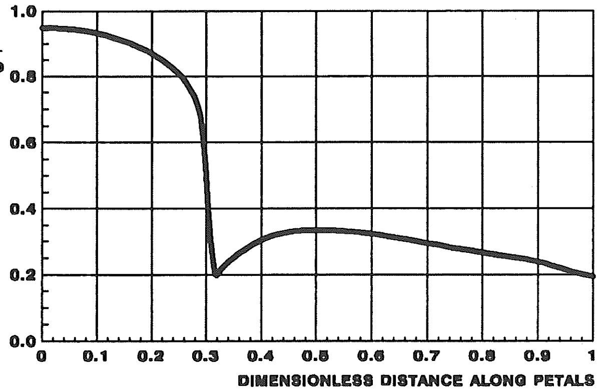

Fig. 10.- Typical pressure distribution along the petals of a CON-DI nozzle

A CON-DI nozzle with a sharp throat produces a local expansion downstream the throat, as sketched in Fig. 10, when the nozzle is choked. The pressure at the nozzle wall suddenly decreases down to approximately 50% of the one-dimensional value immediately downstream the throat, followed by a gradual increasing up to the one-dimensional value in a petal length of approximately 20% of the throat diameter as pointed out by experimental results.

The local expansion around the throat region could be utilized to introduce some amount of cold air from the surrounding nozzle cavity to the nozzle main flow. This cold air can be used as extra-cooling air for the divergent petals. To pump the cold air from the cavity, a slot in the throat is needed. The flow originated downstream the throat near the nozzle wall is complicated to analyze in a theoretical way because there is a supersonic flow at distances sufficiently apart from the nozzle wall, together with a shear layer starting at the throat slot in presence of the boundary layer originated upstream of the nozzle throat.

It is clear that to have positive flow from the cavity to the nozzle, the cavity pressure, p_c, must be larger than the local pressure inside the nozzle near the wall just downstream the throat slot, but this pressure depends on the local geometry of the nozzle around the throat and on the main flow characteristics.

The slot in the throat area of a CON-DI nozzle is inherent to its design unless special features are provided so as to seal that region. Nevertheless, the slot is of small dimensions compared with the throat diameter, so that the local flow can be considered two-dimensional.

Let us assume the simple two-dimensional configuration of Fig. 11 when the nozzle is choked. The flow at the throat is sonic an the sonic line starts perpendicular to the end of the convergent petal. The relative angle between the convergent and the divergent petal is $\alpha+\beta$, being α and β the convergent and the divergent petal angles, respectively, with respect to the symmetry axis of the nozzle. In the case of an ideal flow, a tangential discontinuity separates the nozzle flow from the cavity air. For a value ψ of the angle of this tangential discontinuity with the divergent petal, the total turning of the flow is $\alpha+\beta+\psi$. As the pressure across the tangential discontinuity must be continuous, the total flow turning is function of the ratio p_c/P_0, P_0 being the total pressure of the main flow. On the other hand, the velocity at both sides of the discontinuity can be different but its component normal to this surface must be zero, and therefore the mass flow is zero.

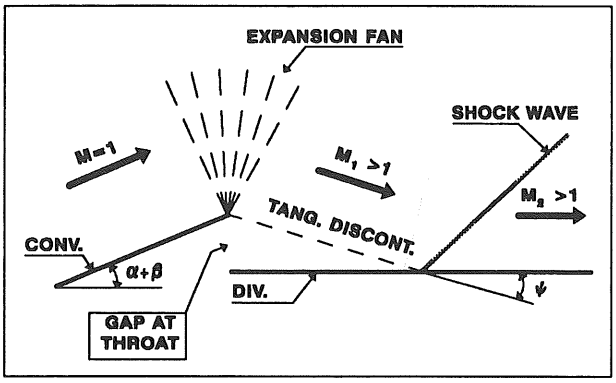

Fig. 11.- Sketch of the ideal flow in the region close to the throat slot and the nozzle petals.

In a real flow the tangential discontinuity does not exist, being instead a layer where the viscous effects take place and some amount of flow goes inside or outside the cavity as sketched in Fig. 12.

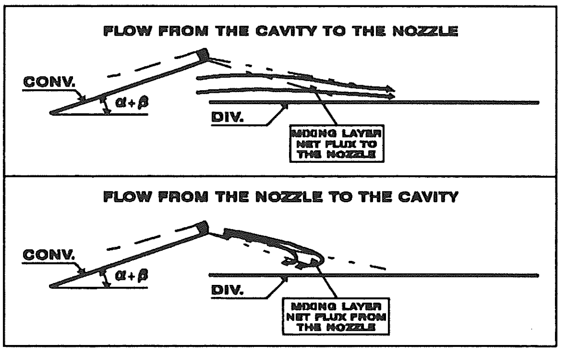

Fig. 12.- Sketch of the real flow in the region close to the throat slot and the nozzle petals

From the analysis of this layer, the additional condition comes that determines the cavity pressure as a function of the mass flow. The analysis of this layer is complicated, but if we are looking for small values of the mass flow (compared with the main flow) ejected from and to the nozzle, the mixing layer is narrow and can be taken as a discontinuity when we are calculating the expansion fan. Using the method described in Ref. 4, it is possible to obtain the angle ψ of the effective separation surface between the nozzle and cavity (see Fig. 13) as a function of the cavity pressure p_c.

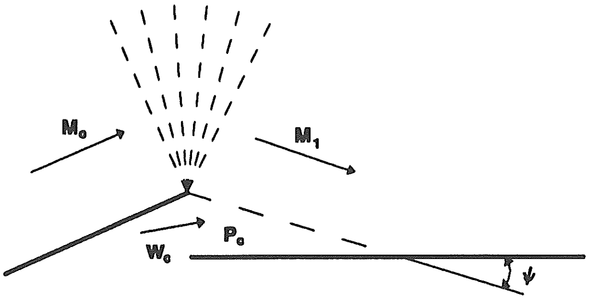

Fig. 13.- Sketch to obtain the mass flow ejected from or to the nozzle

Once the angle ψ is known as a function of p_c, the Mach number M_1 downstream the expansion fan is also known. As the angle ψ can also be written as (see Ref. 4),

$$\psi(M_1,C_w)=f_1(M_1)+C_w\cdot f_2(M_1)$$

where C_W is the dimensionless mass flow (positive or negative) and $f_1(M_1)$ and $f_2(M_1)$ are known functions of the Mach number M_1, the dimensionless mass flow can be obtained from the above relation. The definition of C_W is given in terms of the mass flow ejected W_c, the density ρ_1 and the velocity v_1 (both known) and the boundary layer momentum thickness before the expansion fan (also known from the analysis of the flow field in the convergent nozzle). Therefore, the ejected mass flow can be obtained.

The mass flow W_c shall be positive (to the nozzle) or negative (from the nozzle). The important point is to know what is the nozzle pressure ratio, NPR_0, for which W_c is zero. When $NPR<NPR_0$ we have a positive value of W_c, that means an extra-cooling for the divergent petals. On the other hand if $NPR>NPR_0$, W_c is negative and there is a loose of cooling for the divergent petals.

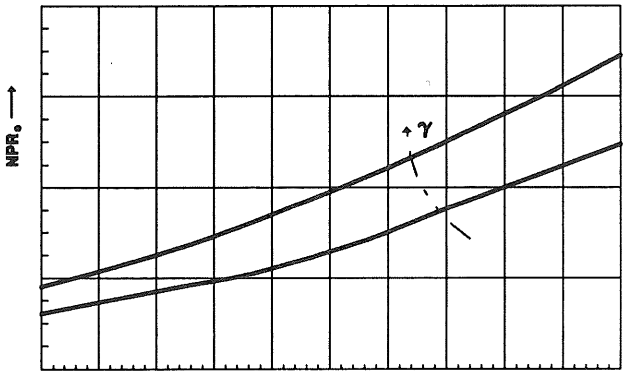

Fig. 14.- Nozzle pressure ratio for zero cooling flow throughout the nozzle slot.

Tests have been performed with a nozzle throat ejector in order to determine the ejection capability and the value of NPR_0 (see Refs. 6 and 7). The experimental data can be easily correlated using the method of Ref. 4 above described. The value of NPR_0 is a function of the total turning angle

$\alpha+\beta$ and the specific heat ratio γ, for fixed values of the total cavity pressure (assumed to be equal to ambient pressure) and slot geometry. The results are given in Fig. 14.

The operating NPR of a CON-DI nozzle can be, in some flight conditions, higher than NPR_0 and, as mentioned above, the nozzle will loose some amount of cooling flow throughout the gap. As it can be seen in the sketches of Fig. 12, for W_c to have negative values, a reversal flow pattern needs to be generated at the throat, this meaning that the value of the NPR to loose an appreciable amount of cooling mass flow is too high, outside of the operating values. This was confirmed with the ejector tests and also with engine tests measuring petal temperatures distribution for NPR´s lower and higher than NPR_0 (see Fig. 15).

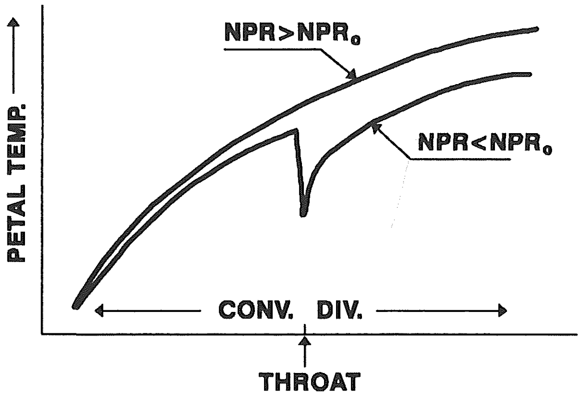

Fig. 15.- Effect of throat cooling on petal temperature.

3.2. CERAMIC PETALS, COOLING REDUCTION.

CON-DI nozzle will benefit from the general development of advanced materials, as in the field of advanced titanium alloys (actuation ring, struts); polyamides composites (external fairing flaps), and specially ceramic matrix composites for the petals.

The development of ceramic composite materials have progressed steadily, but rather at a slow pace. This development is being hampered by the size of the potential market, which is rather small. As a consequence the high cost of these materials will probably continue to be a problem.

AVERAGE SiC/SiC CHARACTERISTICS		
Density	T ~ 20 °C 2.3-2.5 gr/cm^3	T ~ 1400°C -------
Tensile strength	180-340 MPa	~150 MPa
Flexure strength	300-550 MPa	~280 MPa
Shear strength	35-45 MPa	
Thermal difussivity	$\sim 6\times10^{-6}\ m^2/s$	$\sim 2\times10^{-6}\ m^2/s$
Total emissivity	0.75 - 0.80	-------

Table 1.

The most advanced type is the ceramic composite silicon carbide matrix and silicon carbide fiber (SiC/SiC). Some of its more important characteristics (averages values from several manufacturers) are shown in Table 1.

The utilization of SiC/SiC petals up to temperatures of about 1200°C is feasible. Above this temperature a protective coating would be needed, or else the utilization of other carbon matrix materials, such as the C/SiC, not yet sufficiently developed. However , at such high temperature, radiation form the petals might originate serious problems in other nozzle components, specially in the actuation system and fairing flaps.

The value of the cooling flow is usually determined by the maximum admissible temperature in the divergent petals. Therefore the utilization of SiC/SiC in these petals would permit reduction of cooling flow up to the limitation in the temperature now imposed by the convergent petals. Reductions of the order of a 5% are possible (fig. 16) with a thrust increase of about 4% (fig. 9). In addition , SiC/SiC divergent petals could reduce the total mass of the nozzle by about a 5-6%. However, the introduction of this ceramic matrix continues being hampered not only by its high cost, but by a certain insufficient knowledge of some mechanical properties specially with relation to life.

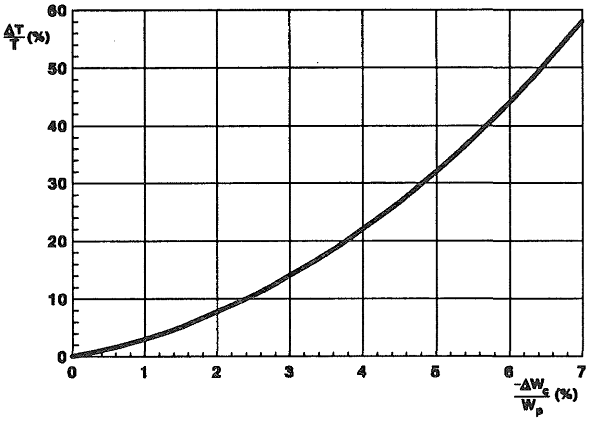

Fig. 16.- Petal temperature increment vs. nozzle cooling reduction

The utilization of SiC/SiC in the convergent petals would allow a further reduction of the cooling flow, with a total reduction of the order of a 6% and a thrust increase of about a 5% (fig. 16 and 9); assuming maximum temperature of 1400°K. However it would imply that the master convergent petals would require a new configuration, with a SiC/SiC surface plate in contact with the hot gases and the rest of the petal of a metallic material with a minimum contact with the SiC/SiC.

Finally, another factor to be considered is that a high temperature ceramic petals nozzle would have a much higher infrared emissivity than that of a metallic petals nozzle.

3.3. SYMBOLS.

NPR Nozzle pressure ratio (P_o/P_a)

A_8	Nozzle throat area.
A_9	Nozzle exit area.
C_w	Mass flow coefficient.
F_N	Net thrust.
M	Mach number.
P	Pressure.
P_o	Total pressure at nozzle entry.
P_a	Ambient pressure.
P_c	Cavity pressure.
W_p	Total engine mass flow.
W_c	Cooling mass flow.
α	Convergent petal angle.
β	Divergent petal angle.
ψ	Angle of effective separation (see Fig. 13).
γ	Specific heat ratio.

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Paper 26: Discussion

Question from K Bradbrook, BAe Defence Ltd, UK

You referred to thrust losses for convergent nozzles. Were these losses for installed or uninstalled nozzles?

Author's reply

The losses are for the uninstalled case. For a pure convergent nozzle the installed losses will be higher. However, in the case of an ejector nozzle they will be lower because it forms an aerodynamic convergent-divergent nozzle. In most cases such a nozzle will be larger than a conventional single parameter nozzle.