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Performance Aspects of Plug Cluster Nozzles

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Plug and plug cluster nozzles are said to have superior performance compared to that of conventional nozzles. A preliminary comparison of different nozzles at an identical area ratio shows that at the nozzle design point the plug cluster nozzle performs slightly worse than a conventional or an extendible bell nozzle. However, for certain applications, such as atmospheric flight or the realization of high area ratios at short nozzle lengths, advantages of the plug cluster nozzle may exist. Any plug-cluster-nozzle performance model must include the effects of the merging stream tubes emanating at the module exists as well as a reliable determination of the pressure acting on the base area of the truncated plug. The fundamental performance elements of a general plug-cluster-nozzle performance model are discussed, and, as far as already elaborated, solutions are presented. A theory for base pressures of truncated cylinders is adapted to plug nozzles and shows good agreement with the few available cold-flow test data.

Nomenclature

$A_{t,\text{ges}}$	= total throat area, m^2
D	= diameter, m
F	= thrust, N
I_{sp}	= specific impulse, s
L/L_{id}	= fraction of ideal plug length
M	= Mach number
N	= number of modules
p	= pressure, bar
γ	= ratio of specific heats
ε	= nozzle area ratio
θ	= module tilt angle, deg

Subscripts

a	= ambient environment
b, B	= plug base
c	= combustion chamber
E	= geometric plug exit
e	= module exit
M	= module
P	= point where the module touches the plug
rec	= recirculation zone between module jets and plug
1	= exit of truncated plug

Introduction

IT is widely accepted that performance gains over conventional nozzles are obtained by expanding the rocket exhaust gases along a contoured plug. The external expansion allows an adaptation to the ambient pressure at any instant of the flight trajectory, eliminating overexpansion losses at altitudes below the nozzle design point. Because the plug can be truncated to a fraction (typically 10–30%) of its ideal length without causing excessive performance losses, high overall area ratios can be achieved at very short nozzle lengths. The truncated part of the plug contour is replaced by an aerodynamic spike where the pressure acting on the base area of the truncated plug also contributes to the overall engine thrust. If a plug or plug cluster nozzle instead of two or more conventional bell nozzles is integrated into a launch vehicle, the complete vehicle base area can be utilized for expansion and very high area ratios can be realized, resulting in a slightly superior performance.

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However, there are many unsolved problems in the manufacture and operation of ideal annular plug nozzles. Apart from the well-known cooling problems of an annular throat and the problem of maintaining a consistent throat gap width during all operating conditions, there are mainly the issues of engine throttleability and thrust vector control to be resolved. A promising solution to these problems that realizes the benefits of plug, or aerospike, nozzles is to circumferentially cluster a set of conventional engines around a central plug. This method avoids the problems of an annular chamber, but retains the principal advantages of a plug nozzle, i.e., altitude adaptation, short nozzle length, and utilization of the complete vehicle base area for expansion. Additionally, the modular concept allows a stable combustion during throttling, the switching off of modules to limit vehicle acceleration, and, possibly, thrust vector control by means of differential throttling.

This paper summarizes the points to be considered and the problems to be dealt with for the derivation of a plug-cluster-nozzle performance model. The solutions found so far for certain performance elements are discussed. The foundation of the performance model, including the underlying assumptions, and the open issues to be clarified in the further course of the study will be described. The questions of cooling, engine mass, operating cycle, and propellant feeding of the modules are not dealt with in the present study.

Design Parameters of Plug Cluster Nozzles

The underlying design philosophy for a plug cluster nozzle is equivalent to that of the annular counterpart despite the profound differences in the respective flowfield. The nozzle design condition results from looking at the ideal flowfield at the nozzle design point. The flow performs a Prandtl–Meyer expansion between the exit of the internal expansion shroud and the tip of the full-size plug, ensuring parallel flow at the ideal full-length nozzle exit. If, however, the plug is truncated, the ideal contour for a maximum thrust design is slightly different.[1–3]

An easy way to estimate the overall performance of such a truncated-plug annular nozzle is to apply the laws of conservation of mass and momentum, with the control surface between the shroud exit and the exit of the truncated plug being defined by an expansion wave of the Prandtl–Meyer expansion. This expansion wave represents a line of constant Mach number and constant pressure, and so the ideal thrust coefficient can be calculated easily. After determining the boundary layer and divergence losses and accounting for the usual engine efficiencies resulting from energy release and kinetic losses, the intrinsic nozzle performance can be obtained. Downstream of the exit of the truncated plug, the core flow encloses the base region where a recirculating base flow forms. The pressure within this flow region acting on the plug base area results in an additional thrust contribution, which essentially compensates for the performance lost due to truncating the plug. An increase in base pressure is achievable by small amounts of base bleed.

Now, if the annular throat is replaced by a set of discrete modules with circular exit cross sections, the Prandtl–Meyer theory would be roughly valid only in the module center planes, which include both the plug axis and the respective module axis. Only for module exits shaped in a way to provide a quasiannular flowfield can the external expansion be treated essentially as for the annular case. The definition of such minimum-loss contoured modules requires complex three-dimensional numerical calculations and is not considered here but has been treated elsewhere.[4,5]

For the investigations described, a plug cluster design is assumed that relies on a number of existing small engines or bell nozzles arranged around a central plug. In the module exit plane, the area between the modules and the plug is assumed to be covered by a closure plate to avoid an outflow of gases between the modules and a resultant thrust loss. A recirculating flow will form in the region between this closure plate, the plug, and the module jets.

It becomes obvious that the ideal annular design theory is no longer valid for this type of plug cluster engine because of the nonannular three-dimensional flowfield. The assumption of the flow being turned according to the Prandtl–Meyer condition and the applicability of an expansion wave as control surface between the module and the plug exit can no longer be supported. Consequently, the total thrust is composed of the contributions from the tilted modules, the pressure distribution along the plug contour and closure plate, and the pressure acting on the plug base. Unless in vacuum, the counteracting force due to ambient pressure also has to be accounted for.

However, if the modules are tilted according to the Prandtl–Meyer condition derived for the annular case, the tilt angle will increase for lower module area ratios and thus for an increasing number of modules. The initial expansion is the most effective one; thus, performance will decrease slightly for an increasing number of modules. The increased external expansion along the plug surface cannot quite compensate for the losses due to the tilting of the modules. On the other hand, the flowfield for a higher number of modules more closely resembles that of the annular case, which directly translates into better clustering efficiencies. Thus, a range for an optimum number of modules can be expected.

The characteristics of the three-dimensional plug cluster flowfield can be approximated by considering the core flow expanding around the module exit and impinging either on the plug wall or on the neighboring stream tube farther downstream. As long as no better condition for the adaptation of the plug contour to the core flowfield has been elaborated, the assumption of an ideal Prandtl–Meyer expansion between the module exits and the full-length plug tip will be maintained and the module tilt angle determined accordingly. It will further be assumed that there is an ideal parallel flow at each module exit, and that a conical plug with a half-angle equivalent to the module tilt angle is employed.

The primary plug cluster nozzle design parameters are the overall engine area ratio, the module area ratio, the number of modules, the module tilt angle, the gap distance between neighboring modules, the shape of modules, and the length fraction of the truncated plug. An analytical performance model has to describe thrust and performance as a function of these design parameters, the optimum combination of which depends on the chamber pressure and on the desired thrust level.

Altitude Adaptation

The thrust of a truncated plug nozzle is dependent on ambient pressure in two ways: 1) by acting on the engine cross section and 2) by influencing the nozzle external expansion flowfield. The first influence can easily be accounted for in the same manner as for any conventional nozzle, but the second one is more difficult to describe.

The reason for suggesting a plug cluster nozzle in atmospheric flight is the adaptation of the external flowfield to ambient conditions. The gases of a conventional nozzle can only be expanded to a certain level below ambient pressure to avoid flow separation. The advantage of the plug cluster nozzle is that the module nozzles can be adapted to sea-level conditions with the flow increasingly attaching along the plug surface with decreasing ambient pressure.

This altitude adaptation only occurs during open-wake conditions, when base pressure is roughly equivalent to ambient pressure. The achievable nozzle area ratio continuously increases from that at the module exit to the effective one at the edge of the truncated plug. By assuming an isentropic expansion from the module exit to the plug exit, according to Fig. 1, the effective area ratio of the truncated plug is defined as

$$\varepsilon_1 = \frac{\pi\left(D_P^2 - D_B^2\right)}{4A_{t,\mathrm{ges}}} + \varepsilon_M \tag{1}$$

The actual conditions along the plug surface depend on how the ambient environment influences the core flowfield by communicating with the recirculation zone between the merging jets either through the open base area or directly by penetrating at the module exits. This process has to be modeled carefully, because it determines the grade of the additional expansion of the module jets along the plug contour.

As soon as the wake closes, the core flowfield completely surrounds the base region and secludes it from the ambient environment, resulting in a constant base pressure that is determined by the conditions within the core flowfield. A further decrease in ambient pressure then only changes the outer flow boundary, but conditions along the plug surface and within the base region remain unchanged. The plug nozzle then behaves essentially like a conventional nozzle. A detailed description of the plug nozzle flowfield is available.[6,7]

Experiments[8–11] indicate that the wake of the base region closes at pressure ratios (chamber to ambient pressure) that are between 20

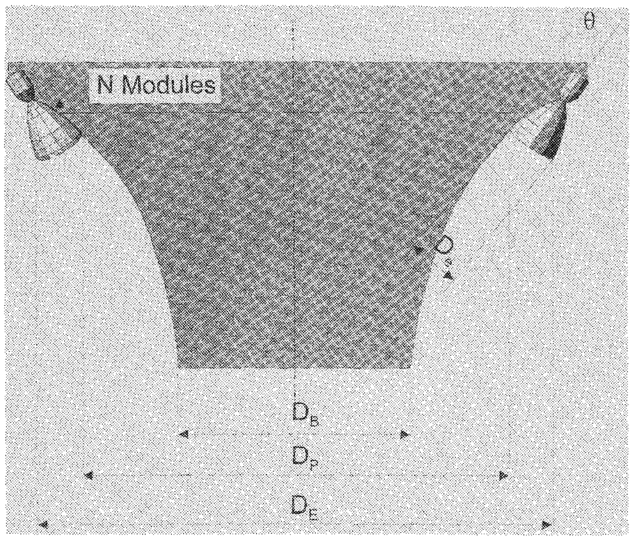

Fig. 1 Geometry and nomenclature for truncated plug cluster nozzles.

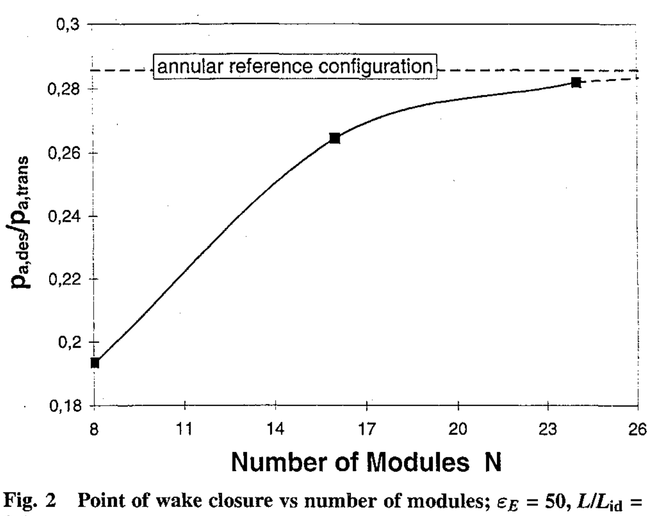

Fig. 2 Point of wake closure vs number of modules; ε_E = 50, L/L_{id} = 0.16.

and 50% of the nozzle design pressure ratio. For a higher number of modules, the flowfield generally more closely resembles that of an annular nozzle, which explains the asymptotic approximation of the closing condition to that of the annular counterpart for an increasing number of modules, as shown in Fig. 2.[8]

The point of wake closure is essentially dependent on two counteracting effects: For a shorter plug, the pressure level of the core flow at the plug exit increases, leading to a wake closure at lower pressure ratios. The plug exit wall pressure equals ambient pressure at a lower altitude. On the other hand, the total base area increases, leading to a bigger volume to be secluded by the core flowfield, which tends to become more difficult, thus leading to a wake closure at higher pressure ratios. A prediction of the effect that prevails is presently not possible. Experiments with different configurations in Refs. 8 and 9 on the one hand and Refs. 10 and 11 on the other hand showed opposite results.

Base Pressure and Base Bleed

During open-wake conditions, the base region is directly connected with the ambient environment, and the pressure acting on the plug base area is roughly equivalent to ambient pressure. As soon as the wake closes, a recirculating flow forms within the base region, and base pressure becomes independent of ambient pressure. The core flow expands around the plug exit with the expansion angle being determined by the pressure within the base region. The base pressure, on the other hand, is a function of geometry (flow angle with respect to the base plane normal, and absolute size of the base area) and of the core flow conditions (pressure, Mach number, boundary layer) immediately upstream of the expansion around the plug edge.

Detailed base-pressure models have been described in literature,[6,12–14] but even the most advanced theory does not adequately predict the experimentally determined base pressures.[15] Empirical base-pressure models[2] according to Eqs. (2) and (3) also failed to produce reliable results:

$$p_b = \frac{0.846 p_1}{M^{1.3}} \tag{2}$$

$$p_b = p_1\left(1 - 0.715\gamma \frac{M^{2.3} - 0.92M^2 - 0.03}{M^{2.7}}\right) \tag{3}$$

A comparison with the few available measurements showed differences of up to an order of magnitude (Table 1). Slightly better agreement of the base-pressure predictions and data for 12–16% plug lengths resulted by assuming a base pressure lying halfway between the core-flow pressures at the truncated plug exit and at the geometric area ratio (exit of a hypothetical full-length plug)[16]:

$$p_b = \frac{p_E + p_1}{2} \tag{4}$$

A recent empirical base-pressure model for cylinders and cones[17] also failed initially to show agreement with the base-pressure measurements of tested nozzle configurations. However, there is a disagreement in the underlying assumptions, because the flow of a plug nozzle is directed toward the nozzle axis and thus opposite to the direction on which the empirical model for a supersonic flow around the cone is based. The flow angle is accounted for in an exponent in a way that negative flow angles, as would be required for a plug nozzle, are not defined. If, however, for cold-flow tests ($\gamma = 1.4$) the exponent is set constant at 0.35, agreement with the measured base pressure seems to be attainable (Fig. 3) with

$$p_b = p_1\left[0.025 + \frac{0.906}{1 + 0.5(\gamma - 1)M_1^2}\right]^{0.35} \tag{5}$$

The empirical model derived for a cylinder embedded in supersonic flow[16] almost duplicates most of the measured data for cold-flow tests ($\gamma = 1.4$), if an additional factor made up of the reference Mach number M_1 and a sonic pressure ratio is introduced:

$$p_b = p_1 M_1 \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)}\left[0.05 + \frac{0.967}{1 + 0.5(\gamma - 1)M_1^2}\right] \tag{6}$$

Figure 3[8–11] shows the comparison of these theoretical curves with the measured base pressures for the available nozzle configurations, and Table 1 summarizes the exact values.

Base pressure can be increased by injecting a small amount of mass flow into the base region. This, in turn, will lead to an increase of the base thrust contribution and, thus, of total thrust. A higher thrust would translate directly into a higher performance, but, because the specific impulse is defined as the ratio of thrust to total mass flow, the additional mass flow injected through the plug base area causes exactly the opposite effect. A performance gain due to base bleed is thus only possible if the increase in total thrust exceeds the increase in mass flow. Experimental results for a configuration with 16 modules,[8] evaluated for the changes in total thrust and specific impulse, are shown in Fig. 4. With beginning base bleed there is a high base-pressure increase. But, with a further increase, the slope of the curve diminishes, and the additional mass flow severely reduces the specific impulse.

Experimental results[8,9] indicate that a performance gain due to base bleed may be possible only for an ideal annular flowfield, and at certain ambient pressures, especially in the range where the wake begins to close. Possibly, a plug cluster nozzle with a high number of

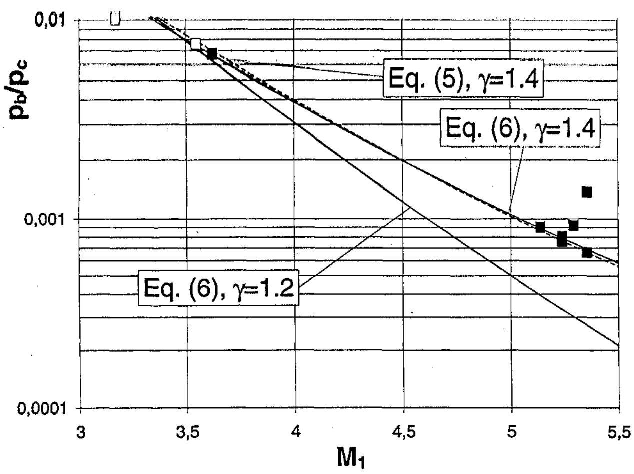

Fig. 3 Modified empirical base-pressure models [Eqs. (5) and (6)] in comparison with test data.

Table 1 Measured and predicted base pressures

					Normalized base pressure $p_b/p_c \times 10^3$					
Ref.	ε_E	N	L/L_{id}		Measured	Eq. (2)[a]	Eq. (3)[a]	Eq. (4)[b]	Eq. (5)	Eq. (6)
8	49.8	8	0.12	air	0.799	0.141	1.110	1.066	0.763	0.791
8	49.8	8	0.16	air	0.911	0.131	1.047	1.025	0.717	0.744
8	51.4	16	0.16	air	0.890	0.163	1.249	1.140	0.868	0.894
8	48.3	point exp.	0.16	air	1.364	0.121	0.976	0.995	0.664	0.691
8	48.3	annular	0.16	air	0.660	0.121	0.976	0.991	0.664	0.691
10	15.02	24	0.094[c]	air	6.840	1.770	8.643	7.558	7.086	6.748
11	24.75	24	0[c]	H_2/O_2	10.296	3.144	13.419	10.041	12.525	14.671
11	24.75	24	0.094	H_2/O_2	7.637	1.381	6.793	5.956	6.106	7.451

[a]Ref. 2. [b]Ref. 16. [c]Referenced to location of module exit.

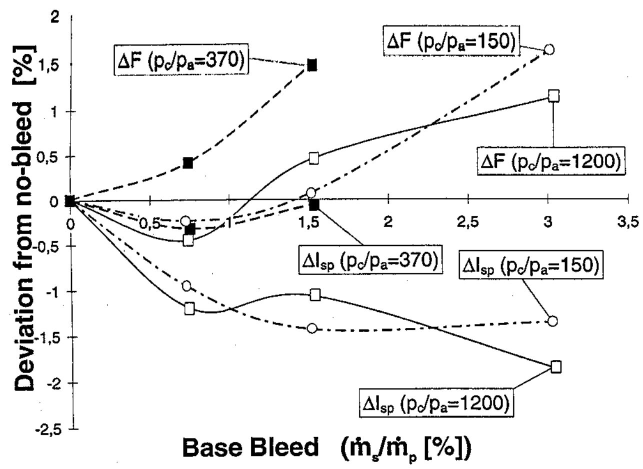

Fig. 4 Change in thrust and I_{sp} with base bleed.

modules will behave comparably. The modeling of the base pressure in the presence of base bleed requires a modification of the detailed base-pressure models that had been derived for the no-bleed case. Presently, no reliable empirical model that also accounts for the effects of base bleed is known.

Plug-Cluster-Nozzle Loss Effects

For a definition of the optimum range of the nozzle geometry and design parameters, the interaction of the merging module stream tubes with each other and with the plug must be understood. A detailed plug-cluster-nozzle performance model must account for the internal expansion within the modules, the expansion around the module exit, the merging of the module jets, the flowfield's internal structure, and the external flow boundary during adaptation to the local ambient pressure. Additionally, the influences of boundary layers, three-dimensionality of the external expansion process, flow divergence, and general geometry must be considered. The effects of truncating the plug to a small fraction of its ideal isentropic length on the nozzle flowfield and the resulting pressure distribution along the plug base area have to be modeled as well as the point of wake closure.

As long as conventional nozzles are utilized as modules, their total efficiency accounting for energy release, kinetic, two-dimensionality, and boundary-layer losses can be readily determined. Plug boundary-layer losses can be accounted for during the integration of the pressure distribution along the plug surface. So-called slipstream effects due to an external flow around the engine have been discussed[8,9] and are not treated here. Because slipstream effects are dependent on the external-flow Mach number, ambient pressure (open or closed wake), the core-flow gas properties, and the vehicle base geometry, they would eventually have to be considered separately from, and independent of, a fundamental plug-cluster-nozzle performance model. Slipstream has essentially no influence during closed-wake conditions, but it shifts the point of wake closure to lower chamber-to-ambient pressure ratios and causes a performance degradation for open-wake conditions.

The most difficult problem, however, is the determination of the clustering efficiency, which accounts for the effects of clustering discrete modules around the plug compared with an equivalent annular design. The resulting losses depend primarily on the deviation of the flowfield from the ideal annular case, which is expressed primarily as a three-dimensional flow of merging stream tubes including recirculating flow regions between the jets, and a nonuniform outer diameter of the core-flow jet boundary. The core flowfield itself is interlaced with shocks due to the redirection of the flow when it impinges on the plug surface or on the neighboring stream tube. The flowfield has to be modeled as a function of the plug-cluster-nozzle design parameters in a way that allows reliable prediction of the pressure distribution along the plug surface. Therefrom, the plug thrust contribution can be obtained. A comparison with an equivalent annular nozzle providing an internal expansion to ε_M then yields a value for the clustering efficiency. Also, a gap efficiency can be defined by comparing the performance obtained for a configuration having a gap between modules with the standard configuration where the neighboring modules touch each other.

Performance Model

A detailed performance model of a plug cluster nozzle has to account for the flowfield properties between the module exit and the plug exit. To allow a general understanding and description of the conditions determining the pressure distribution along the plug, the following assumptions have been made for a convenient derivation of a preliminary performance model: touching modules have a circular module exit; module represents a conventional bell nozzle; flow at the module exit is parallel; a closure plate exists between the module exits and the plug; ratio of specific heats is constant; the module tilt angle is obtained according to the Prandtl–Meyer condition; the conical plug has a half-angle equal to the module tilt angle; isentropic expansion exists around the module exists, at the impingement point on the plug, the flow is redirected toward the tip of the full-length plug; and calculation is one dimensional.

The conditions at the module exit are taken as homogeneous because of the assumption of an ideal parallel flow and can be obtained by a simple one-dimensional calculation. The effects of the boundary layer have been neglected but are required for a detailed modeling of the pressure distribution in the recirculation zone between the module jets, the plug, and the closure plate.

For touching modules and sufficiently low ambient pressures, the recirculation zone is completely secluded from the ambient environment. If, however, the modules are separated by a small gap, there is an open area between the module exit plane and the impingement point of two neighboring jets. This establishment of a connection between the recirculation zone and the ambient environment leads to a potential outflow of gases that are usually entrained in the recirculating flow. Because performance decreases drastically with an increasing gap distance between modules, only configurations with modules touching each other are considered. A configuration with spaced modules can be dealt with later by modifying the conditions of the recirculating flowfield.

Downstream of the module exit, the flow is no longer confined by walls, but rather adapts to the local ambient pressure. This behavior can be modeled by assuming a Prandtl–Meyer expansion around the module exit to ambient pressure on the nozzle external side, and to the pressure level of the recirculation zone on the side lying within the touching points of the modules. Although the expansion to ambient pressure is of importance only to determine the propagation of expansion waves into the flowfield, the problem lies in a reliable prediction of the pressure level within the recirculation zone. The expansion angle depends on the local ambient pressure, but, because the recirculation region is closed, this pressure results directly from the core-flow conditions. The problem is similar to the base-pressure determination and has not been addressed yet. The assumption, however, is that the pressure in this recirculation zone will remain constant in a first approximation. Also, no definite conclusion on the best way for determining the plug wall pressure distribution within the expanding core flow has been reached yet, but a higher-dimension modeling seems to be unavoidable. The influence of the recirculation zone can be reduced by installing fences along the plug between the module exits. Clustering losses thus may be reduced because of a smoother transition of the flowfield.

The boundary where the core flow impinges on the plug is strongly dependent on the pressure in the recirculation zone. Figure 5 shows this boundary as a projection into the plug base area for different assumptions of the recirculation pressure. For this reference configuration with 16 modules and a geometric area ratio of $\varepsilon_E = 100$, the neighboring jets impinge on each other on the plug surface only for chamber-to-recirculation pressure ratios above $p_c/p_{\text{rec}} = 986$. In the diagram, the curvature of the jet plumes has been neglected. The redirection of the flow toward the tip of the full-size plug can be modeled either by application of the shock condition or by assuming a Prandtl–Meyer compression in the boundary layer. Unfortunately, reliable measurements of the plug pressure distribution are lacking, so a prediction of which method is more applicable cannot be made. Only a few pressure measurements are available in the module center plane and in the plane between modules.[8–11] Additional test data

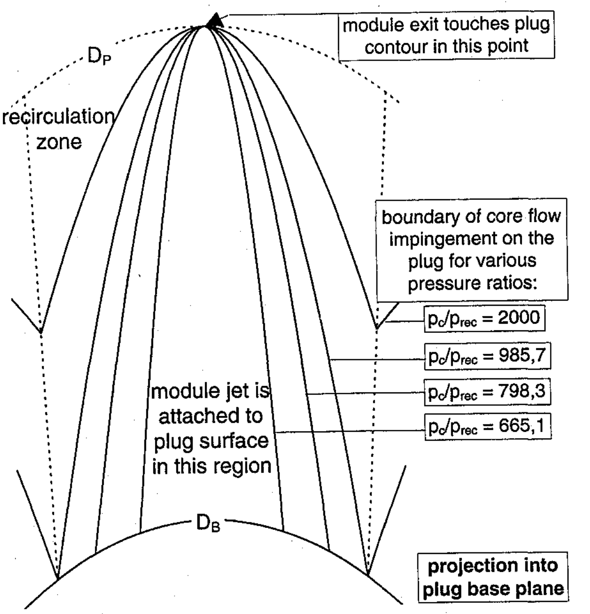

Fig. 5 Boundary of impinging module jets on plug surface.

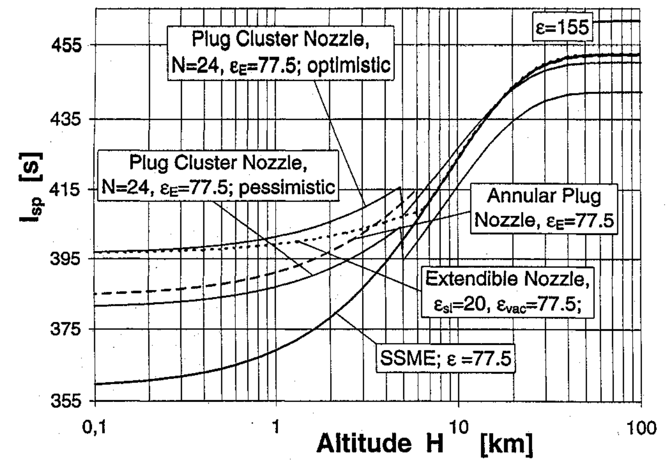

Fig. 6 Performance of different nozzle types.

with known geometries and pressure measurements also in intermediate planes are required to verify any assumptions regarding the flowfield properties along the plug surface.

Construction of the performance model is still incomplete with major questions yet to be addressed. The primary issues to be resolved herein are the impact of the recirculation zone and the modeling of the pressure level, as well as the grade of the continued expansion of the core flow with the resulting pressure distribution along the plug surface. Also, the base pressure problem has to be modeled in more detail, especially to include the influence of base bleed. To allow a simple calculation of nozzle performance, e.g., for a preliminary engine design, reliable empirical or semi-empirical models are being sought. After a definition of all contributing factors, the performance model for plug cluster nozzles can be put together. It must separately account for the thrust contributions of the modules, the plug base area, and the plug contour resulting from the pressure distribution over the plug surface. The restrictions such as parallel flow at the module exit, touching modules, and circular module exit shapes must be gradually alleviated to allow the application of the model to an arbitrary plug-cluster configuration. This could eventually lead to the definition of the range of optimum plug-cluster-nozzle design parameters. The exact modeling of all thrust contributions as a function of the nozzle design parameters could provide an input for a future optimization tool for plug cluster engines.

Because of higher intrinsic losses of a plug cluster engine, at the nozzle design point an equivalent conventional nozzle will usually be superior. Figure 6 compares the performance as a function of altitude for a plug cluster, an annular plug, and an extendible nozzle with that of the Space Shuttle main engine (SSME) at identical geometric area ratios. Engine cycle, total throat area, chamber pressure, and so forth are assumed to be the same for the different configurations. The curves for the plug nozzles were obtained by scaling available data from cold-flow tests and including some reasonable assumptions with respect to combustion and kinetic efficiencies. The range of performance for plug cluster engines results from optimistic (close to the annular case) and pessimistic (stronger influence of the module tilt angle and inefficient merging of the flowfield) assumptions for the external expansion along the plug. Two curves are shown for a plug cluster nozzle with 24 modules of an area ratio of about $\varepsilon_M = 25$. The modules are ideally adapted at a 3-km altitude. No attempt has been made to optimize the number of modules, since the primary objective of Fig. 6 is to roughly show the performance range that can be expected for a plug cluster nozzle.

At extremely low altitudes, the extendible nozzle with an initial area ratio of $\varepsilon = 20$ and possibly the plug cluster with $\varepsilon_M = 25$ show slightly better performance than the ideal annular nozzle. In this range, the annular nozzle expands the gases slightly beyond ambient pressure, as the flow still remains attached to the plug contour. The performance improvement of the annular plug and the plug cluster nozzles as compared to the SSME at sea-level conditions results primarily from the fact that the plug base pressure essentially equals ambient pressure up to an altitude of about 5 or 6 km, where the wake begins to close.

The extendible nozzle is indicated by the dotted line, which assumes a transition from the initial area ratio of $\varepsilon_{sl} = 20$ to $\varepsilon_{vac} = 77.5$ at a 7-km altitude. Because of the truncation of the contour at an area ratio of $\varepsilon_{sl} = 20$, the extendible nozzle shows high divergence losses at sea-level conditions. The vacuum specific impulse for an area ratio of $\varepsilon = 155$ has been included to show the effect of a higher expansion level: if a plug cluster were designed with a geometric area ratio of $\varepsilon_E = 155$ and an optimum number of modules, then both its vacuum and its sea-level performance would be above that of the SSME, without having to consider the danger of flow separation. The comparison in Fig. 6 shows that plug, or plug cluster, nozzles make sense especially for certain applications, such as realizing high or very high area ratios at short nozzle lengths, or for booster propulsion over wide ranges of altitude.

Conclusions

To be able to find the optimum configuration for a model describing performance as a function of the nozzle design parameters and geometry is required. The performance elements to be considered in the construction of a thorough performance model have been described. Several of these elements have been discussed in detail. The performance of the tilted modules, which have been assumed to consist of conventional bell nozzles, can be readily determined in the same way as for any conventional nozzle. The external expansion of the flow thereafter and the merging of the discrete stream tubes into a quasiannular flowfield define the pressure distribution over the plug surface from which, eventually, thrust and performance can be obtained. The analytical model to predict this pressure distribution, and especially the influence of and the pressure level in the recirculation zone between the module jets and the plug, remains to be elaborated. An empirical model that relies on a validated base-pressure theory for cylinders has been adapted to predict the base pressure of plug nozzles. However, further work is required to provide a general theory that also includes the effects of base bleed.

Only nozzle performance aspects have been described, since this is the most sensitive aspect of the applicability of plug nozzle concepts to future space launch vehicles. Other issues, such as the cooling of the huge surfaces, and overall engine mass have not been treated. Keep in mind, however, that, especially for mass aspects, but also for the slipstream problem, the complete vehicle with the integrated engine has to be considered.

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