Flow, noise and thrust of supersonic plug nozzles

Khairul B.M.Q. Zaman¹, Amy F. Fagan² and John H. Korth³ NASA Glenn Research Center Cleveland, OH 44135

A model-scale experimental study is conducted with a plug nozzle exploring the performance of various plug geometries for supersonic aircraft concepts. All data are acquired with a given outer nozzle that is convergent and has an exit diameter of 2 inches. The shape of the centrally placed plug is varied from conic with various half-angles (lengths), to method of characteristics (MoC) designs, as well as truncated and porous geometries. Noise and schlieren flow visualization data, presented in an earlier paper, are briefly reviewed first. The focus is then on the thrust performance. A newly constructed thrust stand is used to acquire data covering a nozzle pressure ratio (NPR) range from transonic ('landing and takeoff', LTO) to supersonic ('cruise') conditions. Back-to-back measurements allowed assessment of relative performance. A plug with its 'crown' located somewhat inside, rather than near the exit, is found to perform better. A longer 10° plug performs better than a shorter 22° plug. A porous plug, that significantly suppresses broadband shock associated noise, is found to incur a modest thrust loss that might be an acceptable tradeoff near LTO conditions. A companion numerical simulation for some of the plug geometries yields data trends bearing reasonable agreement with the experimental results.

Nomenclature

BBSN	Broad	band	shock	associated	noise
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- CFG Gross thrust coefficient ($=T_{ac}/T_{ideal}$)
- CT Thrust coefficient of ASME nozzles from correlation provided in [8]
- $\triangle x$ Plug crown location relative to nozzle exit (in.)
- D Exit diameter of a nozzle (in.)
- D_{eq} Equivalent diameter of plug nozzles based on exit area (in.)
- mdot Measured mass flow rate (lb/sec)
- M_J Jet Mach number based on NPR had the flow expanded fully
- NPR Nozzle pressure ratio, p_t/p_a
- OASPL Overall sound pressure level (dB)
- p_a Ambient pressure (psi)
- p_0 Total pressure (psig)
- SPL Sound pressure level (dB)
- Tac Actual thrust (lbs)
- Tare No flow 'tare' thrust (lbs)
- Tm Measured thrust with flow (lbs)
- T_{ideal} Calculated ideal thrust (lbs)
- T_{conv} Calculated thrust for a convergent nozzle (lbs)

¹ Inlets & Nozzles Branch, AIAA Associate Fellow.

² Optics & Photonics Branch, AIAA Associate Fellow.

³ Inlets & Nozzles Branch, AIAA member.

Introduction

Nozzles with internal mixers and external plugs are candidates for supersonic aircraft concepts. A fundamental experimental investigation, for static conditions (without an external flow), is being conducted at NASA Glenn Research Center (GRC) with the focus on the performance of the external plug. The objective is to assess various plug geometries for noise reduction potential during landing and takeoff (LTO) of the aircraft while maintaining optimum thrust performance in cruise. Earlier results on flow field and noise were presented at the 2022 AIAA Aeroacoustics Meeting [1]; see also [2] for a review of the plug nozzle literature. For a given nozzle (cowl), results on noise and flow field were presented for plugs of different geometry that included conic plugs of different lengths, plugs designed by the method of characteristics (MoC) as well as porous plugs. Observations included, for example, a remarkable reduction in broadband shock associated noise (BBSN) by porous plugs, relative to corresponding solid plugs, at certain supersonic conditions. Schlieren visualization showed a weakening of the shocks at those conditions. However, the critical question of thrust performance for variations of the plug geometry remained unanswered. Recently, a thrust measurement device has been installed in the jet facility where these experiments are conducted. The device still has large uncertainty specially at low NPR, however, back-toback measurements allowed assessment of comparative performance. These results are summarized in this paper.

Thrust or force is a basic physical quantity, and one may think it's measurement ought to be simple. However, when the flow is somewhat complex, such as with a plug nozzle, thrust is not only difficult to assess experimentally but also numerically. The difficulties and uncertainties in the experiment are explained in the following sections. The experimental data are compared with limited numerical simulation results. There is a relevant numerical simulation study on plug nozzle optimization that is summarized in another paper at this conference [3].

Experimental Facility

The experiments are conducted in an open jet facility described in prior publications [1, 4]. The configuration shown in Fig. 1(a) is used for noise and schlieren data. Overhead microphones are used to measure radiated noise. The test cell is not fully anechoic, however, relative variations in the noise spectrum with variation of parameters are evaluated. All noise data presented in this paper pertain to a microphone location of 90° to the jet axis; it is at a distance of 48" from the jet exit. All dimensions are given in inches.

The plug nozzle is attached to the end of the plenum chamber. In the experiment, the outer nozzle (cowl) remains fixed. A cross-sectional view of the nozzle assembly is shown in Fig.1(b). The 2" diameter nozzle is convergent and has a lip thickness of 0.050". The center plug is held with X-shaped struts. The leading edges of the struts are notched to suppress any organized vortex shedding. The upstream cylindrical part of the plug has a diameter of 0.75". A lead screw fixed to the cylindrical part is used to attach interchangeable end pieces. Various end pieces provide various plug geometries. Spacers placed between the cylindrical and the end piece allow for variation of the axial location of the plug crown.

A few aluminum plugs originally fabricated with the nozzle are shown in Fig. 1(c). Later, other plugs were fabricated using additive manufacturing (3D printing) out of plastic material. Results for only some of the plugs are presented in this paper. The three conic plugs on the left in Fig. 1(c) have half angles of 10°, 16° and 22°, these are denoted as 'P10', 'P16' and 'P22', respectively. The P16 approximately follows the geometry of the plug used in a larger scale experiment [5]. Figure 1(c) also includes two plugs designed by the method of characteristics (MoC) – one pointed (denoted as 'MOC') and another truncated (denoted as 'MCT'). Procedures given in [6] are followed in the design. All plugs have a nominal crown diameter of 1.54". In order to obtain the specified crown diameter with the 2" nozzle, the design Mach numbers for the pointed and truncated plugs had to be 2.036 and 1.978, respectively; an interested reader may look up [1] and [6] for more details. The design Mach numbers for both cases corresponded to an NPR value of about 8. Note that the LTO and cruise NPR values for the supersonic aircraft concept is about 2 and 5.9, respectively. A higher design NPR for the MoC cases was considered acceptable as plug nozzles are expected to perform well over a large range of overexpanded conditions [2].

While the initial aluminum plugs were machined with approximate rounding off near the crown, all 3D printed plugs were fabricated later via computer aided designs (CAD) with close tolerance. The annular gap width between the plug and the nozzle depended on the exact geometry and the axial location of the crown. Small differences had significant impact on the throat area. All plugs, after installation, were also found to have some non-concentricity; the gap width variation in the azimuthal direction was typically 5% and different for different plugs. All porous plugs (Fig. 1d) were intended to have the same geometry as their aluminum counterparts. However, differences existed specially in the roundedness near the crown. Three solid plugs with 10°, 16° and 22° half angles were later 3D printed to have identical outer geometry as the corresponding porous plugs; these are referred to as 'P10P', 'P16P' and 'P22P'. The solid aluminum plugs were used earlier for noise and schlieren experiments. In order for a more accurate assessment of the porosity effect, the 'P' plugs were used in later thrust measurements. The aluminum and the corresponding solid 'P' plugs exhibited small differences in thrust coefficient, enough to mask the effect of porosity, as discussed with the results. The porous plugs have an internal cavity with four quadrants separated by X-shaped struts to support the skin with pores. The 'openness ratio' is defined as the ratio of open area due to the pores to the total surface area of the skin; it is 6% for all data presented in this paper. Pictures of a few porous plugs are shown in Fig. 1(d) while the details of a 10° conic porous plug ('PRS6') is shown by the CAD drawings in Fig. 1(e).

The thrust measurement setup is shown in Fig. 1(f). Flow from a fixed upstream plenum, which is attached to the end of the main plenum of the jet facility, is routed through four U-shaped tubes (1.31" internal diameter). The flow enters radially into a 'floating' plenum chamber that is mounted on a linear bearing which allows it to move freely in the axial direction. Each of the four U-tubes has a flexible component. The flow from the floating plenum passes through two 30-mesh screens, spaced 1" apart, before exiting through the nozzle. The axial force exerted by the nozzle is measured directly by a load cell attached to the face of the fixed plenum chamber. Details of the data reduction procedure is discussed with the results.

A dedicated focused schlieren system exists with the facility (Fig. 1a). The microphone data acquisition is performed using a National Instruments A/D card and LabviewTM software. Sound pressure level (SPL) spectral analysis is carried out over 0-50kHz with a bandwidth of 50 Hz, using a data rate of 100 kHz and a 50 kHz low-pass filter. The 'jet Mach number' M_J is defined based on the plenum pressure, p_0 , and the ambient pressure, p_a , and is given by,

$$M_{J} = (((p_{0} / p_{a})^{(\gamma-1)/\gamma} - 1) \frac{2}{\gamma-1})^{1/2},$$

where γ is the ratio of specific heats for air. The nozzle pressure ratio, NPR = p_0/p_a , as well as M_J are indicated with all data. The data are for unheated flow, i.e., with the total temperature the same everywhere as in the ambient.

Results

Schlieren flow visualization pictures are compared for the MOC and the P16 cases in Fig. 2, for two values of NPR. For ease of comprehension, pictures of the plugs are shown in this and following figures. It can be seen that the flow for the MOC case is marked by larger scale turbulent structures and a faster jet spread. The root cause possibly traces to flow separation and unsteady shock motion over the plug. Recall that the design NPR for the MOC is about 8 and thus the flows are highly overexpanded. The unsteady flow leads to a higher noise. Figure 3 compares SPL spectra for different plug shapes. The MOC and MCT cases clearly have higher noise levels relative to the conic plugs, at the lower NPR (1.69, M_J =0.9). The three conic plugs (P10, P16 and P22) behave similarly. At the higher NPR=3.09 (M_J =1.38) the data are beset with screech tones making the comparisons difficult. As reported in [1], using two tabs the screech tones could be suppressed to assess the comparative noise levels els. With this method the P10 case was found to produce the least noise. The comparative thrust for different plugs as well as thrust penalty incurred by the tabs are assessed in the following.

No significant change in noise was detected with the porous plugs relative to corresponding solid plugs at subsonic conditions. However, clear noise reduction was noted at some supersonic conditions. This was accompanied by an alteration of the shock structure. Schlieren pictures shown in Fig. 4 exhibit such alteration of the shocks for the P16 case (the corresponding porous case being PRS2). The pictures here are time-averaged that displays the shocks more clearly. A fragmentation of the shocks can be seen especially at NPR=3.09 which is

accompanied by a clear decrease in broadband shock associated noise (BBSN) illustrated in Fig. 5. Note the difference between the red curve (solid plug) and the blue curve (porous plug) at NPR=3.09. The best noise attenuation was observed for the P10 case (PRS6 being the corresponding porous case). The comparison of schlieren pictures in Fig. 6 shows an alteration of the shocks at all M_J . The addition of the pores appears to 'splinter' the shocks into multiple cells. Especially at NPR=3.09 (M_J =1.38) the strong shocks with the solid plug are practically eliminated. This caused a remarkable reduction in the broadband noise levels, as shown in Fig. 7. More than 5.5 dB reduction in OASPL occurred. The thrust performance, including limited numerical simulation results, are discussed next.

First, a few characteristics of the thrust rig should be noted. There is a pressure drop between the large upstream plenum of the facility and the floating plenum downstream due to turbulence within the plenums and the U-bends. This meant that the maximum pressure available in the floating plenum is somewhat less, e.g., about 55 psig when the pressure in the upstream plenum is at its limit of 60 psig. The flow quality at the nozzle exit was a concern. From the floating plenum (5" diameter) to the nozzle exit the contraction ratio is about 15; all plug nozzles have an equivalent diameter around 1.3". The large contraction, together with the two 30-mesh screens, positioned before the start of the contraction, are sufficient to yield uniform flow at the nozzle exit. Thus, even though the flow is grossly turbulent in the floating plenum a uniform flow is obtained at the nozzle end, and this has been verified by Pitot probe traverse for a D=1.3" convergent nozzle. Also, due to facility constraints a static pressure tap in the floating plenum could be placed only about 0.25" downstream of the last screen (Fig. 1f). Cross-checks with the total pressure measured at the nozzle exit (using a Pitot probe), however, showed no measurable difference with the tap pressure. Thus, the tap pressure is used as total pressure for all data.

As stated before, finding thrust from the measured axial force was not straightforward. The thrust rig performance was examined using convergent nozzles of different diameters. These nozzles have internal contours similar to standard ASME nozzles; (the geometry can be seen with a set of numerical simulation data later). The measured axial force (Tm) and corresponding mass flow rate (mdot), obtained by an orifice-meter in the supply line, are shown in Fig. 8(a) and (b), respectively. Data for the three nozzles with exit diameters of 1.1", 1.3" and 1.5" are shown, as a function of NPR. The Tm data are compared in Fig. 9(a) with the expected actual axial thrust (Tac). Tac is calculated from the mass flow rate and NPR as follows. The ideal thrust T_{ideal} is calculated first. This is simply a function of NPR and independent of temperature, given, for example, by Eq. 4.33 of Ref. [7],

$$\frac{T_{ideal}}{p_0 A_e} = \gamma \sqrt{\frac{2}{\gamma - 1} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}} \sqrt{1 - \left(\frac{p_a}{p_0}\right)^{\frac{\gamma - 1}{\gamma}}},$$

where A_e is the (convergent) nozzle exit area. It assumes uniform flow with zero boundary layer thickness and in the supersonic regime it represents the thrust had the flow expanded fully. Then a correlation for thrust coefficient (CT) for ASME nozzles, provided in [8], is used to determine Tac=T_{ideal}*CT. The correlation is based on a large set of data from different sources; it is discussed further with numerical simulation results in the following. Thus, the force Tac would be measured had the thrust rig responded correctly without any friction or inertia. As it can be seen in Fig. 9(a) the measured force Tm differs from Tac for each nozzle.

The friction and binding forces due to tautness of the feed tubes under pressure was measured by capping the nozzle (no flow) while varying the plenum pressure. Corresponding 'tare' force data (denoted 'Tare') are also shown by the red curve in Fig. 9(a). The expectation was that a correction with Tare would directly yield the actual thrust, i.e., Tac = Tm+Tare. However, for all nozzles the measured Tare was not adequate to account for the difference between Tm and Tac. Furthermore, there was a noticeable hysteresis in Tare – it depended on the path whether the pressure was increased or decreased during data acquisition. Efforts were made to eliminate the hysteresis, without success. At this point, the idea of measuring thrust directly was abandoned and a method was adopted to determine thrust using the calibration data from the ASME nozzles. Also, all subsequent data were taken while the pressure was increased in order to minimize the hysteresis effect.

The calibration involved recording the difference Tac-Tm as a function of NPR for the three ASME nozzles. A set of such data is shown in Fig. 9(b). Now, for a plug nozzle Tm and mdot were measured as a function of NPR. For a given NPR, the mdot data was used to find an equivalent diameter (D_{eq}) by interpolation of the calibration data of Fig. 8(b). The value of Tac-Tm for that diameter and NPR was then found from Fig. 9(b), yielding the actual thrust Tac. Calculated ideal thrust provided the gross thrust coefficient CFG (=Tac/ T_{ideal}).

The uncertainty in the data was large especially at low values of NPR. Measurements over several weeks with the 1.3" nozzle exhibited a repeatability of Tm within a standard deviation of 0.7% and 1.7% (of the respective mean values) at NPR of 4.2 and 2, respectively. Corresponding standard deviations of mdot data were about 0.8% at both NPRs. The uncertainties of Tm and mdot were main contributors to that of CFG which turned out to be 0.97% and 1.9% at the two values of NPR. These uncertainties are too large to allow differentiating the CFG data for many of the comparative cases, and efforts are under way to improve the thrust stand. However, back-to-back measurements have been made for cases of interest. With the same 1.3" nozzle, sets of data acquired over a day puts the uncertainty in CFG at 0.45% and 0.7% for NPR of 4.2 and 2, respectively. The fidelity in differences for pairs of data sets obtained back-to-back are thought to be within even tighter margins. Such sets of data are discussed in the following.

For a clear understanding of the results, let us start with a set of data taken for the P16 and MOC plugs for which flow and noise data were compared in Figs. 2 and 3. Measured values of Tm and mdot are compared in Fig. 10(a). The scale for mdot is on the left while that for Tm is on the right of the figure. The MOC nozzle is seen to involve larger mass flow rate as well as thrust. Variations in the radius of curvature near the crown and the exact axial location of the crown for these aluminum plugs were sufficient to cause differences in the exit area leading to these differences. This is reflected in the equivalent diameter (D_{eq}) deduced from the calibration data (Fig. 8b), as shown in Fig. 10(b). Values of D_{eq} agreed well with estimates from average gap between the plug crown and the nozzle wall.

CFG data for the P16 and MOC cases are compared in Fig. 11. The differences in CFG are small, however, the overall trends in these data taken back-to-back are deemed representative. The performance of the MOC plug at low NPR is worse apparently due to flow separation but better at higher NPR since it is designed for high NPR.

A similar sequence of comparative data is presented in Figs. 12 and 13 for the effect of porosity with the 16° conic plug. Both of these plugs were fabricated using 3D printing and the outer dimensions were closely matched. Therefore, D_{eq} was found to be nearly the same for the two cases (Fig. 12b). The CFG data (Fig. 13) exhibit a loss (about 1%) due to the porosity at small values of NPR that diminishes at high NPR. Thus, the noise reduction seen in Fig. 5 at NPR=3.09 was achieved with only a slight (<1%) loss of CFG. Here, referring back to the discussion in section 2, one may note that the data for the P16P case in Fig. 13 is slightly different when compared to the data for the corresponding aluminum plug P16 in Fig. 11. This is thought to be not only due to day-to-day uncertainty in measurements but also to small differences in the geometries.

CFG data for three different porous plugs corresponding to the 10° conic case are compared in Fig. 14. The three porous plugs have different pore sizes as stated in the figure caption, however, the openness ratio (defined in section 2) was the same (6%). It is clear that the CFG values for all three porous cases were consistently about 1% smaller than that of the solid case. Similarly, the effect of the two tabs used to suppress screech [1] is illustrated in Fig. 15. The geometric blockage of the annular area by the two tabs was about 1% and it resulted in a CFG loss of similar magnitude. The performances of the two plugs designed by the method of characteristic (MOC and MCT) are compared in Fig. 16. The truncated case (MCT), perhaps as expected, incurs a slight loss relative to the pointed one. We note that the small thrust loss with the porous plugs, illustrated in Figs. 13 and 14, might be encouraging since the noise suppression is large. It could be a viable tradeoff for noise reduction near LTO conditions. This will be explored more in the future.

Next a few other sets of data are discussed that were also investigated through Computational Fluid Dynamics (CFD) analysis. For a detailed understanding of the numerical methodology, the reader is referred to a companion paper presented at this conference [3]. In essence, the method involved Reynolds-averaged Navier Stokes (RANS) simulations conducted via the ANSYS Fluent ® software package. The determination of thrust values was based on the calculation of momentum, pressure, and skin friction forces. Despite the calculations being for no co-flow, the jet entrainment-induced recirculation caused a flow velocity over the outer surfaces of the nozzle. The corresponding forces from this outer flow were also factored in the calculations.

First, let us discuss CFG for the simple D=1.3" convergent nozzle. Numerical, experimental, and analytical results are compared in Fig. 17. The ratio T_{conv}/T_{ideal} is shown by the green line; T_{conv} is the calculated thrust

for a convergent nozzle. It accounts for the unbalanced pressure at the nozzle exit due to underexpansion in supersonic conditions. The ratio is unity in subsonic conditions (NPR < 1.89) and the decreasing value with increasing NPR in the supersonic regime is due to underexpansion. The solid light blue curve is the correlation for thrust coefficient for ASME nozzles (CT) from Ref. [8]. Its difference from the green curve is primarily due to boundary layer losses. The experimental and CFD data are shown by the red and the blue dashed curves, respectively. These are in good agreement with each other, considering the uncertainties in the experimental data and possible deficiencies in the CFD results. Both also follow the overall trends of the CT curve. Some differences are not unexpected since the nozzle internal contour is not exactly the same as ASME contours. The insert on the right of Fig. 17 is a CFD data clip of Mach number distribution (at NPR=3.5) that also shows the geometry of the present D=1.3" nozzle. The results in Fig. 17 provides added confidence in the CFD as well as the experimental results.

Limited simulations were performed for parametric variations with the plug nozzles. The performances of the three conic plugs are compared in Fig. 18. First, from the experimental data (solid curves) it is seen that the CFG for the 10° and 16° plugs are nearly identical (the 10° case being slightly better). Comparatively, the 22° plug performs worse with about 2% lower CFG. The numerical results (dashed curves) also exhibit a similar trend, with the 22° case being the least efficient. There are differences between the experimental and numerical results, the full reasons for which remain unknown. For the experimental data, note again that the differences border on the uncertainty bounds. An inspection reveals differences in the CFG values for a given plug (P10P or P16P) between this figure and earlier data in Figs. 13 and 14. This is because of the larger uncertainty with data taken in different days.

In Fig. 19, the experimental and CFD results are compared for the effect of axial location of the plug crown. Results for the three conic cases and the MOC case are presented. For each nozzle, results for two crown locations, -0.18" and -0.05" relative to the nozzle exit, are shown. Again, the overall trends agree between the experiment and the simulation. In all cases the -0.18" location results in a better nozzle thrust performance. Data presented in Ref. [1] also showed that the upstream crown location resulted in a lower noise. Thus, the crown location should be somewhat inside, rather than close to the nozzle exit, for better performance as well as noise.

Conclusions

A model-scale experimental study is conducted exploring the characteristics of various plug nozzles. All data are acquired with a convergent outer cowl with 2" exit diameter. The plug geometry is varied from conic with different half-angles (lengths), to plugs designed by the method of characteristics (MoC), as well as truncated and porous shapes. Thrust performance of various plugs are measured from near-sonic (LTO) conditions to high supersonic (cruise) conditions. These results are accompanied by results from schlieren flow visualization, radiated noise as well as numerical simulation. The following observations are made:

(1) Relative to the 16° conic plug, the MOC plug has worse thrust and noise at low Mach number (LTO) conditions. Schlieren pictures indicate likely flow separation over the MOC plug due to overexpansion and thus more prominent large-scale turbulent structures and a faster spread of the jet downstream. At higher NPR, as the design condition is approached, the thrust of the MOC case becomes better than that of the conic case.

(2) Among the three conic plugs tested, the thrust performance of the 10° and the 16° cases are found to be comparable with the 10° case being slightly better. In comparison, the shorter 22° case has clearly worse performance. It is not clear but differences in shock structure and flow separation may have led to these differences.

(3) With screech tones suppressed by tabs, the longest conic case (10°) is also found to be the least noisy. The two tabs used for screech suppression incur a loss of about 1% in CFG.

(4) Porous plugs suppress BBSN spectral components at supersonic conditions. The suppression is most prominent for the 10° plug at certain values of NPR; OASPL is reduced by over 5 dB. The reduction is accompanied by a CFG loss of only about 1% that may be an acceptable tradeoff for achieving noise reduction around LTO conditions. However, the noise reduction does not occur at all values of NPR and the effect of porosity needs to be investigated more in the future.

(5) Numerical simulation was performed for some of the parametric variations with the solid plugs. The overall trends in the CFG results, for variation of the half-angles (length) of the conic cases as well as crown

location, agreed with the experimental data. These results provide the confidence in using the CFD tools for further exploration of optimum designs for the problem at hand that has a huge parameter space.

Thus, with the present cowl the 10° conic plug performed best both for thrust and noise. Currently, a different cowl with cylindrical exit, designed to minimize boattail drag, is being considered. A detailed optimization study has been conducted with numerical simulation results that yielded different plug shapes for optimum thrust at different NPR conditions [3]. Experiments are currently under way with the new cowl and the optimized plugs.

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Fig. 1 Experimental Facility. (a) Picture of jet rig, (b) a drawing of the plug nozzle, (c) picture of several solid plugs, (d) picture of several porous plugs, (e) CAD drawings of a porous plug, and (f) picture of thrust measurement apparatus.



Fig. 2 Comparison of schlieren flow visualization pictures (instantaneous shots) between MOC and P16 cases. Nozzle pressure ratio (NPR) and corresponding Jet Mach number (M_J) indicated on left column; plugs shown by inserts on top. Approximate crown location $\Delta x = -0.18$ " for both cases.



Fig. 3 SPL spectra (at 90° polar location) showing effect of plug shape on noise, at two nominal values of NPR. Plug shapes are indicated in legend; second and third columns of legend show jet Mach number M_J and OASPL (dB). Approximate crown location $\Delta x = -0.18$ " for all cases.



Fig. 4 Schlieren flow visualization pictures (time-averaged) for solid and porous cases of 16° conic plug, at three NPR. Left column for solid plug (P16) and right column for porous plug (PRS2, 0.037" diameter pores with a total of 6% openness). Approximate crown location $\Delta x = -0.18$ " for both cases. Plug pictures are shown at top.





Fig. 6 Schlieren flow visualization pictures (time-averaged) for solid and porous cases of 10° conic plug, at three NPR. Left column for solid plug (P10) and right column for porous plug (PRS6, 0.037" diameter pores with total 6% openness). Approximate crown location $\Delta x = -0.18$ " for all cases. Plug pictures are shown at top.



line: porous plug.







Fig. 9 Measured axial force (Tm) and corresponding calculated actual force (Tac) for the three ASME nozzles as a function of NPR. In (a) Tm and Tac are shown by the dashed and solid lines, respectively; also shown are 'tare' forces without flow by the red lines. In (b) corresponding difference (Tac-Tm) are shown for the three nozzles.





Fig. 11 Thrust coefficient CFG (calculated using calibration data of Figs. 8 and 9) vs. NPR for the P16 and MOC cases of Fig. 10.







Fig. 14 Thrust coefficient vs. NPR showing porosity effect for 10° conic plug. The three porous cases have 6% opening but different pore diameters: 0.020" (PRS18, green), 0.037" (PRS6, red) and 0.07" (PRS22, cyan). Plug pictures are shown on the right. Plug crown location, $\Delta x = -0.18$ " for all cases.









The nozzle geometry and typical CFD result showing Mach number contours.

Fig. 17 Thrust coefficient vs. NPR for the D=1.3" ASME nozzle (red curve). Comparison is made with numerical simulation prediction (blue dashed curve), analysis (green) and a correlation (cyan) from Ref. [8].





