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Flow, noise and thrust of supersonic plug nozzles

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Introduction

Nozzles with internal mixers and external plugs are candidates for supersonic aircraft concepts. A fundamental experimental investigation is being conducted at NASA Glenn Research Center (GRC) to assess the optimum performance of external plugs. The focus is on noise reduction potential during landing and takeoff (LTO) operation of the aircraft while maintaining optimum thrust performance. Earlier results on flow field and noise of plug nozzles were presented in the 2022 AIAA Aeroacoustics Meeting [1]; see also [2] for a review of the plug nozzle literature. For a given nozzle cowl, comparative results on noise and flow field were presented in [1] 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. Significant differences in noise were noted between the conic and MOC plugs, the latter being noisier at LTO conditions. With porous plugs, schlieren visualization demonstrated a weakening of the shocks in the flow that was accompanied by a reduction in broadband noise levels compared to corresponding solid plugs. However, the critical question of thrust performance as affected by the variation in plug geometry remained unanswered. Recently, a thrust measurement device has been installed in the jet facility where these experiments are being conducted. The focus of the proposed paper will be on the thrust results for specific plug cases together with details of the flow and radiated noise fields.

The installed thrust measurement device is currently being evaluated and checked for accuracy. Thrust is a basic quantity, and one may think it's measurement ought to be a simple process. However, there are many difficulties. When the flow is somewhat complex, such as with a plug nozzle, thrust is not only difficult to assess experimentally but also numerically. The installed device has shown good promise of providing repeatable data. A preliminary set of results is included in this abstract. The accuracies are yet to be sorted out; this should be completed well before the proposed paper is due. The final paper is to provide comparative thrust results along with corresponding noise and schlieren data for various plug geometries.

Experimental Facility

The experiments are conducted in an open jet facility described in prior publications [1, 3]. 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

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with variation of parameters are evaluated; this should be valid as inferences drawn from such measurements always proved correct upon measurements in anechoic facilities [4]. In this abstract all noise data presented pertain to a microphone location of 90° to the jet axis.

The plug nozzle is attached to the end of the plenum chamber. A cross-sectional view of the nozzle assembly is shown in the drawing in Fig.1(b). In the experiment, the nozzle remains fixed. It is convergent with 2" exit diameter having a lip thickness of 0.050". The center plug is held with X-shaped struts. 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 the plug end pieces. Various end pieces provide various plug geometries. Also, washers placed at the junction between the end piece and the cylindrical part allow for variation of the axial location of the plug crown (Fig. 1b).

A few plugs used in the experiment are shown in Fig. 1(c). Three conic plugs with half angles of 10°, 16° and 22° are used (denoted as 'P10', 'P16' and 'P22'). The set also includes two plugs designed by the method of characteristics – one pointed (denoted as 'MOC') and another truncated (denoted as 'MCT'). These two have a crown diameter of 1.50". In order to obtain the specified crown diameter (1.5"), with the 2" nozzle, the design Mach number for the pointed and truncated plugs had to be 2.036 and 1.978, respectively. The P10, P16 and P22 plugs were designed with a slightly larger crown diameter of 1.54". Note that the annular gap width between the plug and the nozzle depends on the axial location of the crown. The average gap width for most of the cases discussed in the following was roughly the same, however, some differences occurred that could have significant impact on the nozzle exit area. All plugs, after installation, were also found to have some non-concentricity relative to the nozzle exit; the gap width variation in the azimuthal direction was typically 5% and was different for the different plugs. All porous plugs had the same crown diameter as that of the corresponding solid plug. The porous plugs were fabricated by additive manufacturing process (3-D printing).

The thrust measurement setup is shown in Fig. 1(d). Flow from a fixed upstream plenum (attached to the end of the main plenum chamber) is routed through four u-shaped pipes (i.d. = 1.5 in.) The flow enters radially into a 'floating' plenum chamber which is mounted on a linear bearing allowing it to move freely in the axial direction. The four u-shaped feed tubes each has a flexible component. The flow entering the floating plenum passes through two 30-mesh screens and then exhausts through the nozzle. The axial thrust is directly measured by a load cell attached to the face of the fixed plenum chamber. Details of the apparatus and measurement procedures will be provided in the final paper.

A dedicated focused schlieren system exists with the facility (Fig. 1a). The microphone data acquisition is done using National Instruments A/D card and Labview™ software. Sound pressure level spectral analysis is done typically 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 used as an independent variable. It is defined based on the plenum pressure, p_0, and the ambient pressure, p_a, and 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. All data are for unheated flow, i.e., with the total temperature the same everywhere as in the ambient.

Results

As examples of the results, schlieren flow visualization pictures are compared for the MOC and the P16 cases in Fig. 2, for two values of M_J. It can be seen that the flow for the MOC case, at the lower M_J, is marked by larger scale turbulent structures and a faster jet spread. The root cause possibly traces to unsteady shock motions. The flow here is overexpanded. This leads to a higher noise with the MOC cases at the lower Mach number. Figure 3 compares SPL spectra for different plug shapes. At M_J =0.9 one finds that the MOC and MCT cases have higher noise levels relative to the conic plugs. All three conic plugs (P10, P16 and P22) behave similarly. At the higher M_J (=1.38) the data are beset by screech tones making the comparisons difficult. As reported in [1], using two tabs the screech tones could be taken out to assess the comparative noise levels. With this method the P10 case was found to produce the least noise. The comparative thrust for the different plugs as well as thrust penalty incurred by the tabs will be assessed in the final paper.

The best noise reduction with porous plugs was achieved also with the P10 configuration. Schlieren pictures shown in Fig. 4 exhibit a remarkable alteration of the shock structure by the porosity. (These are time-averaged pictures that seemed to show the shocks more clearly). It is apparent that the shocks in the porous case are altered over the plug. At M_J =1.38 the shocks are seen 'splintered' into multiple cells apparently caused by the pores. This caused a remarkable reduction in the broadband noise levels as shown in Fig. 5. The porous plug involved 0.037" diameter holes with 6% openness. More than 5.5 dB reduction in OASPL occurred by the porosity at M_J = 1.38. The reduction in noise is achieved by suppression of BBSN-like components in the spectra.

A set of thrust and corresponding mass flow rate data are shown in Fig. 6. Thrust as a function of jet Mach number is plotted in Fig. 6(a), for the three conic plugs; corresponding noise data can be seen in Fig. 3 (for cross reference, ptnk=50psig corresponds to about M_J=1.63). At high pressures, thrust values are clearly larger for the 10° case while those for the 16° and 22° are relatively comparable. The corresponding mass flow rate data are shown in Fig. 6(b). It is likely that due to small differences in the crown location (relative to the nozzle exit) the exit areas were somewhat different for the different cases. The mass flow rate for the 10° case is more, as is its thrust. Thus, its thrust coefficient, relative to the P16 and P22 cases, remains undetermined at this time. Accuracy of both thrust and mass flow rate are being assessed. However, the data for the P16 and P22 cases reveal that the performance of the former plug is better. The mass flow rates are practically the same, but the thrust is somewhat more for the P16 case. Thus, the thrust coefficient for the P16 plug must be greater than that of the P22 case.

The data presented in Fig. 6 are as measured and without any correction. The thrust data involves a 'tare force'. When the flexible components of the feed tubes are pressurized, they can exert an axial force. This must be accounted for to find the correct thrust. However, measurement of the tare force under flow is not straightforward. The tare force is also found to involve some hysteresis. Mass flow rate, on the other hand, involved an orifice meter that needs to be calibrated properly. These are currently being assessed using a set of ASME nozzles. In the final paper, results for comparative performance of all the plug cases, as well as newer plugs designed by a computational optimization study, will be presented. Those results will be accompanied by corresponding noise and schlieren data.

Acknowledgement

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References

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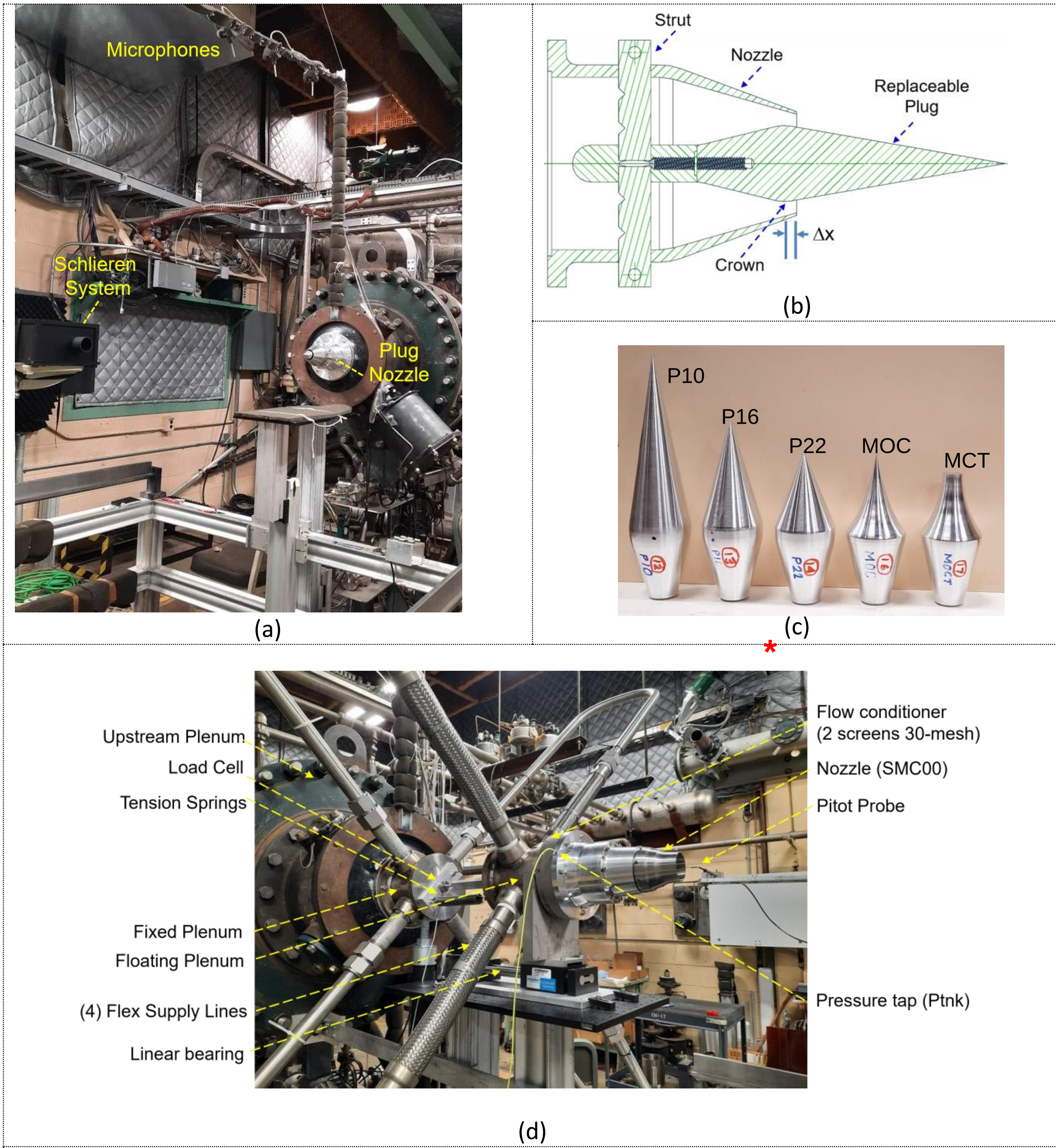


Fig. 1 Experimental Facility. (a) Picture of jet rig, (b) drawing of plug nozzle, (c) picture of several solid plugs, (d) picture of thrust measurement apparatus.

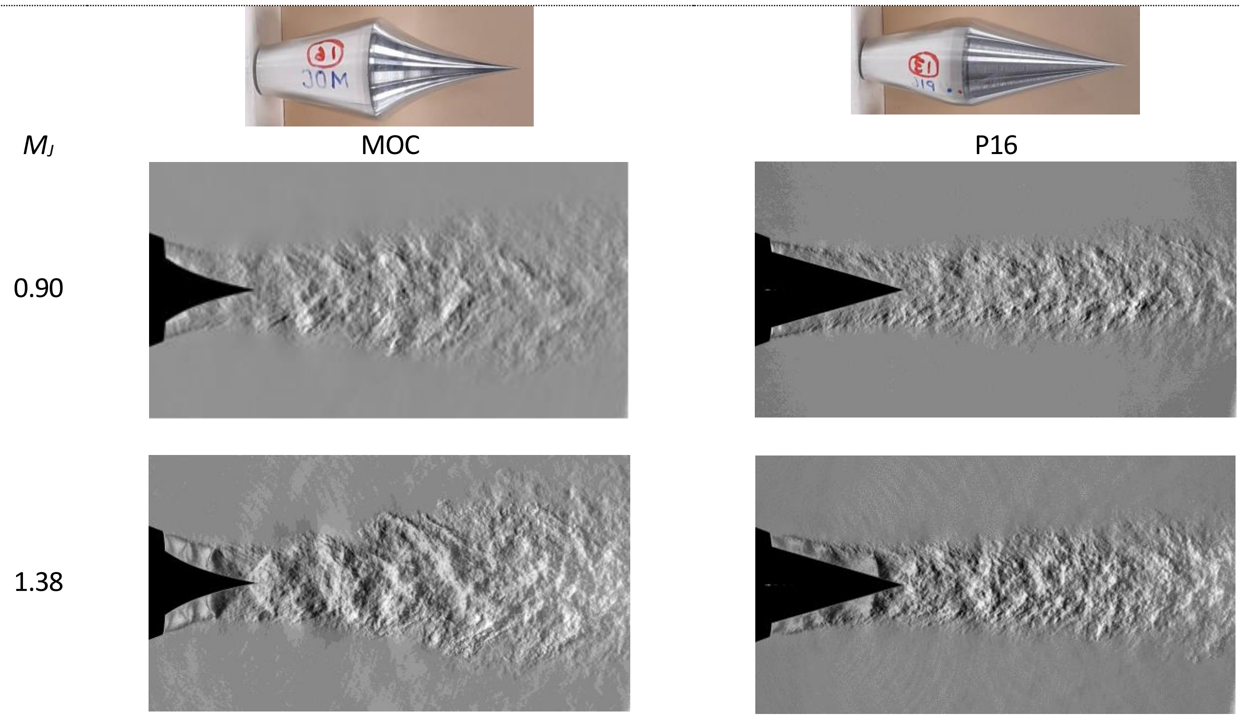


Fig. 2 Comparison of schlieren flow visualization pictures (instantaneous shots) between MOC and P16 cases. Jet Mach number M_J indicated on left column; plugs shown by inserts on top. Crown location Δx =-0.18” for both cases.

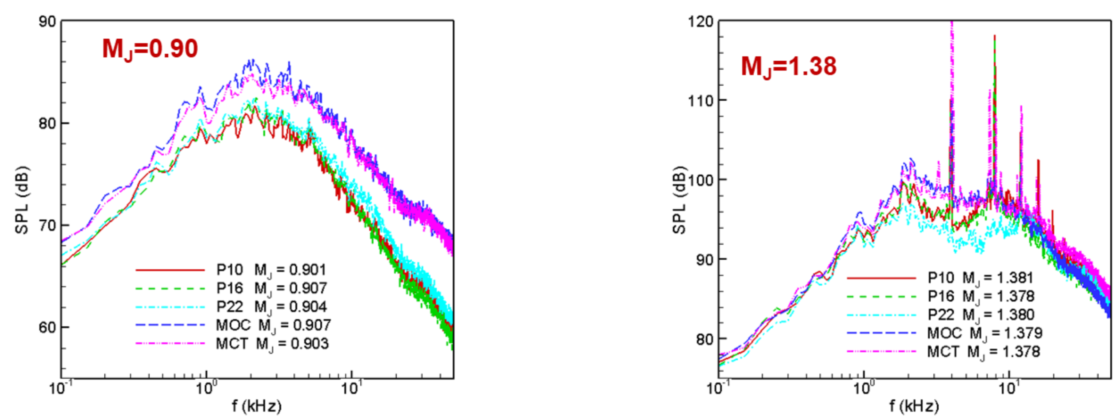


Fig. 3 Effect of plug shape on noise. SPL spectra, at two M_J , for five different plug shapes as indicated in the legend. Crown location Δx =-0.18” for all cases.

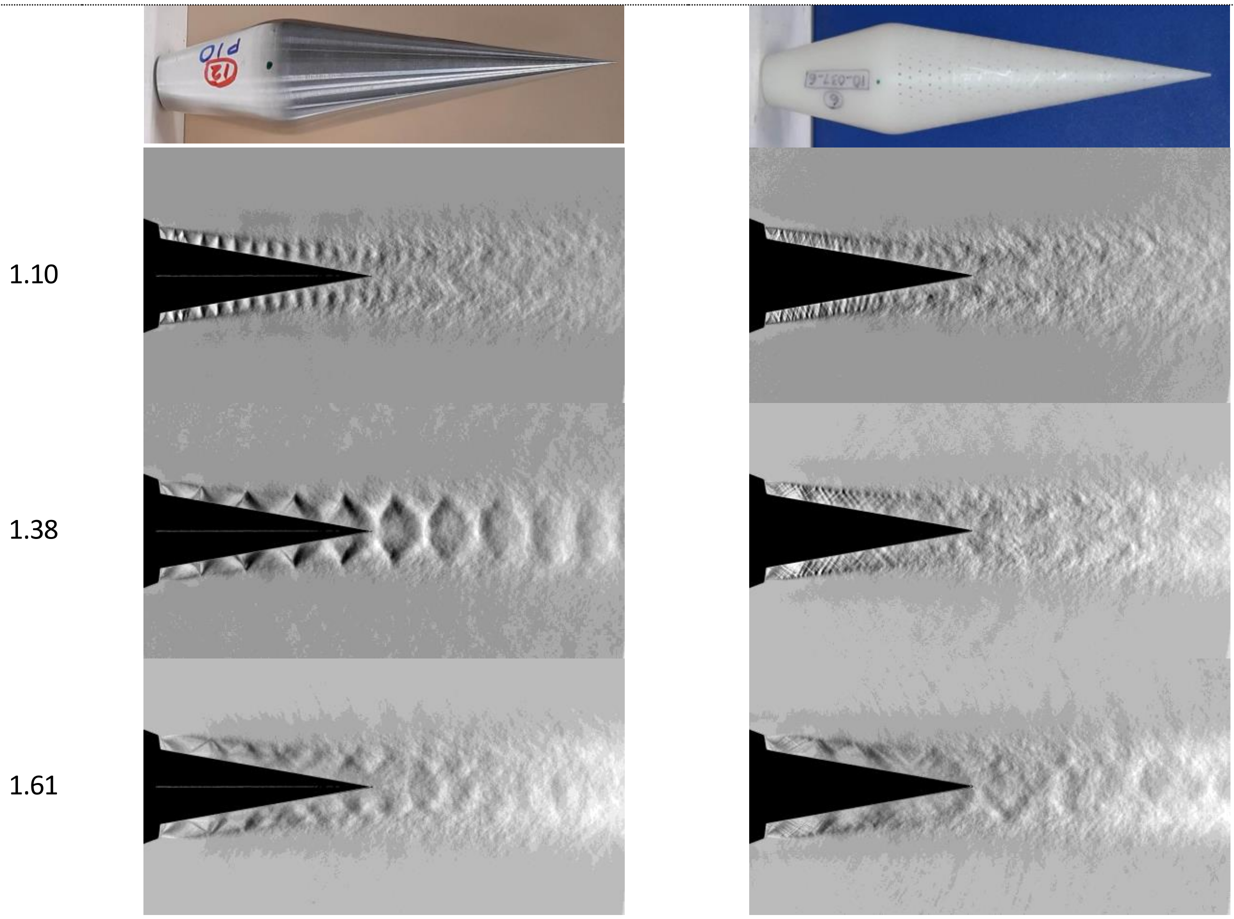


Fig. 4 Effect of porosity on P10 plug. Schlieren flow visualization pictures (time-averaged) for solid and porous cases at three jet Mach numbers.

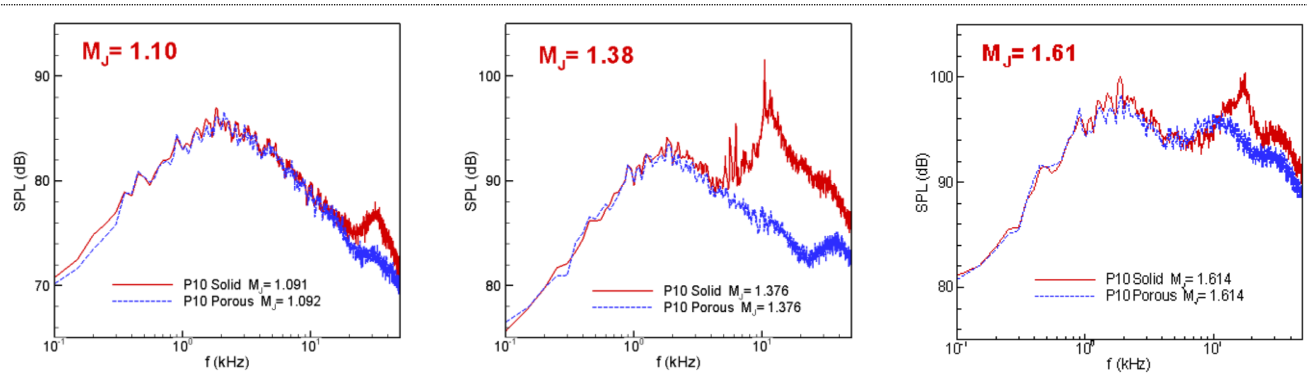
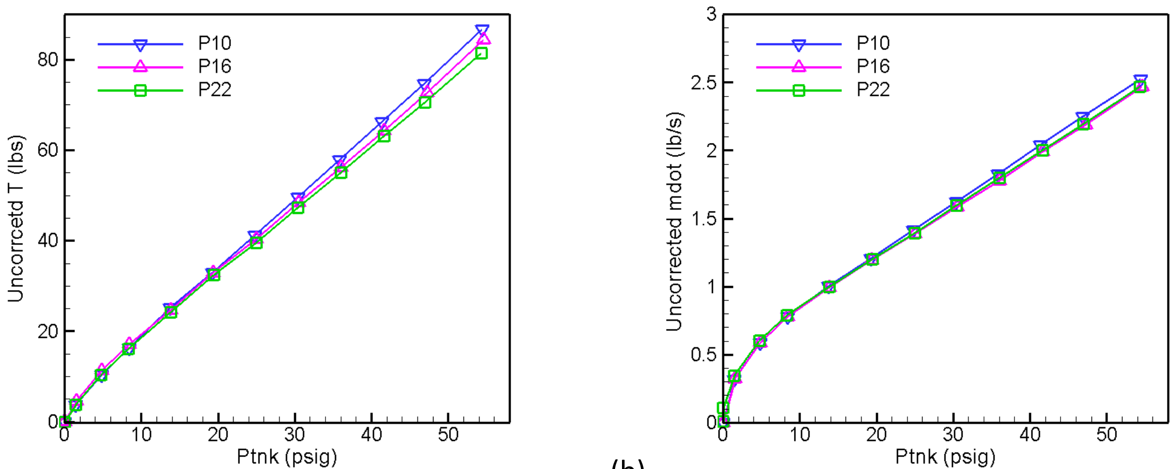


Fig. 5 Effect of porosity on P10 plug at three jet Mach numbers. Red line: solid plug, blue line: porous plug (0.037 in diameter holes, 6% openness); plugs shown by inserts on top row. Crown location Δx =-0.18" for both cases.



(a) (b)

Fig. 6 Effect of plug shape on: (a) thrust and (b) mass flow rate. Data are preliminary and uncorrected. The three plugs are solid (Fig. 1b) and crown location Δx =-0.18” for all cases.