The hot films were placed at approximately three cylinder diameters downstream and one cylinder diameter above its centerline in a horizontal plane. The position of the first hot film [stationary probe (SP)] was near the midsection of the cylinders and remained stationary, whereas the second sensor [moving probe (MP)] was moved in the spanwise direction toward the wind-tunnel wall in increments of 0.51 cm.

The signals from the hot films were digitized by a Metra-Byte DAS-20 analog-to-digital converter, connected to a Pentium-based microcomputer. At each location, 50 records per channel of data, where each record consists of 2048 samples, are digitized at a sample rate of 6000 samples/s and then analyzed using standard software.

Results and Discussion

Figure 2 shows spanwise variation of the normalized shedding frequency. The shedding frequencies are obtained from the spectra of axial turbulent velocity. The normalized shedding frequency is obtained by dividing the shedding frequency from the MP at each position by the shedding frequency of the SP.

For the smooth cylinder, the shedding frequency of MP drops to 90% of the shedding frequency of SP at $Z/D = 2.4$ and stays constant until at $Z/D = 0.2$, where it reduces to a near zero value near the wall. The decrease in the shedding frequency is due to the end wall effect.

For the wire-wrapped cylinder with $p/D = 0.25$, the drop in shedding frequency from the MP is the same as the corresponding drop for the smooth cylinder, except that it starts at $Z/D = 5$ and approaches zero near the end wall. When it is considered that the wire wrapping starts at $Z/D = 4.5$, the effect of wire wrapping is seen as increased oblique angle as compared to the smooth middle portion of the cylinder, and in this case, the oblique angle seems to be the same as the one caused by the end wall on the smooth cylinder.

For the wire-wrapped cylinders with $p/D = 0.5$ and 1.0, the shedding frequency from MP initially decreases to 80% of the shedding frequency from SP, at $Z/D = 3$ and 4, respectively. This is followed by a zigzag behavior, fluctuating between 80 and 90% values, until they approach zero near the wall. Here it seems that the wire wrapping divides the flow along the span of the cylinders into cells of different frequencies. Those affected by the wire wrapping have a higher oblique angle and, thus, a lower frequency, and those in between, which are not affected, have a lower oblique angle, and thus, a higher frequency.

Figures 3 and 4 show spanwise variations of coherence and phase angle between the two probes. For all cases, coherency is low at almost all of the spanwise locations, except for a few locations where there are slight increases in the coherency.

The phase angle changes along the span for all cylinders and the maximum shifts in the phase angles are from −180 to 150 deg.

Conclusions

The present limited experimental studies indicate that, for a finite aspect ratio cylinder, similar to the observation of Szepessy and Bearman,[9] there is phase angle variation along the span of the cylinder, and in our case, the end wall effect is observed at $Z/D \leq 2.4$. The effects of wire wrapping is seen as controlling the shedding angle, reducing the shedding frequency with increasing oblique angle. The oblique angle can be changed with changes in the pitch spacing. Different pitch spacings have different helix angles; thus, it can be concluded that an imposed helix angle maybe a viable option in controlling the flow angle along a cylinder.

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Oscillating Flows in a Model Pulse Detonation Engine Inlet

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Introduction

MULTITUBE detonation devices connected to a common inlet provide a promising configuration for a pulse detonation engines (PDE) as a design that allows for the generation of continuous thrust by initiating the detonation and recharging of the detonation ducts at controlled frequencies.[1–4] However, such configurations raise the issues of inlet-combustion chamber interactions resulting in unsteady inlet flowfields. The exit plane of the inlet experiences nonuniform pressure fields arising from the operation of the intake valves on the PDE detonation tubes. Backpressure induced by cyclic operation of the detonation tubes might affect the inlet operation including the potential of hammershock and inlet-unstart. A single inlet acting as a plenum for multiple detonation tubes reduces the effect of backpressure on the inlet flowfield allowing for flow transfer from the blocked channels to the open ones.

The unsteady interactions between the combustion chamber and supercritical inlets have been studied mainly on ramjets' inlets, and, in most cases, the exit plane pressure has been simulated by spatially uniform pressures oscillating only in time.[5] Previous theoretical studies[6] indicated that during the transient flow at the inlet exit produced by the valving system of a stack of detonation tubes the time available for the transfer of air between adjacent tubes is $\mathcal{O}(10\ \mu s)$, which is significantly shorter than the time required to form the hammershock, $\mathcal{O}(10\ ms)$. Thus, the concept of a plenum inlet supplying air to multiple tubes has the potential to become a practical solution for the inlet of a PDE. Analyses of diffuser flows displaying self-excited fluctuations have shown that the bulk of the

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fluctuation energy is contained in the frequency range below approximately 300 Hz (Ref. 7), a regime in excess of the unticipated PDE frequency domain.

Studies on forcibly excited transonic and low supersonic inlets[5,8] indicated that the shock displacement amplitudes were inversely dependent on the backpressure excitation frequency. These results coincide with the findings of the present work. Previous studies also indicate that large-amplitude and/or low-frequency oscillations tend to move the mean shock position upstream of the diffuser eventually leading to an inlet unstart. At higher excitation frequencies the shock train was predicted to be stable.

The current experiment simulates the operation of a PDE inlet, wherein the exit is temporally and spatially, that is, in a spanwise direction, excited in a sinusoidal manner. This was achieved by blocking the exit with four plunging pistons mounted on a camshaft having a 90-deg phase offset between two adjacent cams. Emphasis was placed on the 15-Hz excitation frequency tests because the lower frequencies were found to have a stronger impact on the flowfield, therefore rendering them to greater interest. The blockage ratio, defined as $A_{\text{piston}}/A_{\text{exit}}$, was varied to simulate different pressure amplitudes within 32–85%. Despite the large blockage in the present work, the inlet started and remained started for all of the test conditions. The amplitude of pressure oscillations increased with increasing blockage and decreased with increasing excitation frequency. Flow visualization using schlieren indicated that the shock motion was limited to the diffuser part in accordance with the measured pressure fluctuations. Tests using pressure-sensitive paint[9] (PSP) clearly showed the extent of the two-dimensionality of the pressure fluctuations.

Experimental Setup

Figure 1 shows the two-dimensional model inlet viewed in the direction of the flow. It has a 10-deg, 3.75-cm-long ramp designed for Mach 2.5 operation, and a throat height $h = 1.2$ cm with a short throat length, $0.5h$, followed by a $7.5h$ diffuser with 2-deg expansion on the lower wall and 1-deg expansion on the upper wall. The inlet's exit plane was a 1.54×5 cm^2 rectangle. The opening and closing of the detonation tubes' intake valves were modeled by a set of four plunging pistons distributed uniformly across the inlet's span as just described.

The measurements accuracy, including repeatability, was below 3%. The pressure ports were connected to the scanner and transducers by 0.75-m long tubes. On separate bench tests the response of the 0.75-m tubes/transducers was calibrated, and it was found that the system behaved roughly like a first-order system with time constant of about 8 ms, giving a cutoff frequency around 50 Hz.

Five different sets of piston faces affecting the blockage ratio at the exit were used to get different excitation pressure amplitudes. These corresponded to a blockage ratio of 32, 40, 63, 75, and 83%. Both low (15 and 20 Hz) and high frequency, up to 50 Hz and limited by the motor torque capability, excitations were attempted.

Flow visualization using PSP[9] was carried out with the excitation frequency set at 15 Hz. The PSP had a ruthenium-based compound as the active luminophore with a frequency response, at the pressure range experienced in these experiments, of 1000 Hz (Ref. 10).

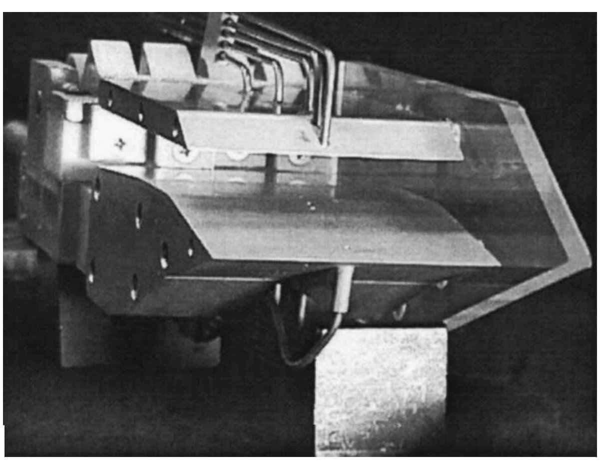

Fig. 1 Ten-deg, 3.75-cm-long ramp designed for operation at Mach 2.5, has a throat height *h* of 1.2 cm with a short throat length and a 7.5*h* diffuser with divergence of 2- and 1-deg on the lower and upper sides, respectively.

Results and Discussion

Figure 2 shows time traces of selected centerline wall pressures with open duct (unblocked) and with maximum blockage at an excitation frequency of 15 Hz. All of the streamwise distances are measured from the throat. Figure 2a shows the time trace of pressures along the centerline at different axial locations with the open duct. The wall pressures are shown normalized by the stagnation chamber pressure. This test serves as a baseline to compare the results from all other experiments, and it indicates stable flow throughout the inlet. With maximum blockage the effect of oscillations moved upstream to the throat. This is reflected in the higher mean pressure levels and in the oscillations that are shown in Fig. 2b. The inlet remained started in all of the tests at all blockage ratios. The pressures at the location $x/h = -2.1$ show negligible variation with change in blockage or frequency.

Figure 3 shows the axial mean pressures with increasing blockage and at two different frequencies. Figure 3a corresponds to the excitation of the backpressure at 15 Hz and at the maximum attainable frequency in Fig. 3b. The maximum attainable frequency was limited by the motor torque capability and ranged between 47 Hz at 32% blockage to 39 Hz at 85% blockage, as indicated in the figure. The mean pressure increased with blockage but did not vary significantly with frequency. The flowfield between the leading edge and up to $x/h = 1.2$ was stable and insensitive to both the blockage ratios and the frequency. Figure 4 shows the pressure perturbation as a percentage of the mean pressure at different axial locations. The

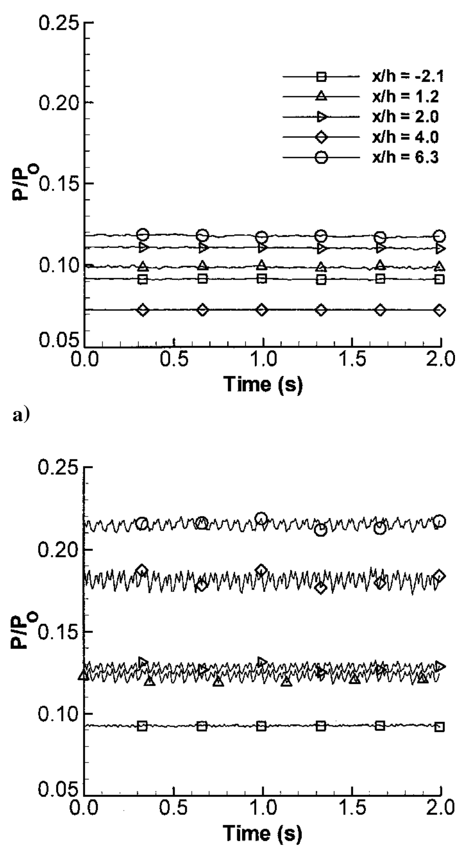

Fig. 2 Pressure time trace with backpressure excitation at 15 Hz for a) unblocked inlet and b) blockage of 83%.

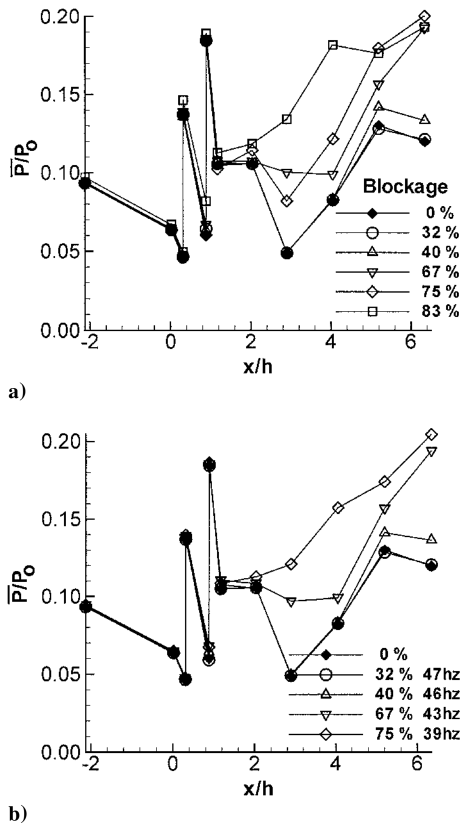

Fig. 3 Effect of blockage ratio on the mean pressure distribution at a) 15 Hz and b) maximum frequency.

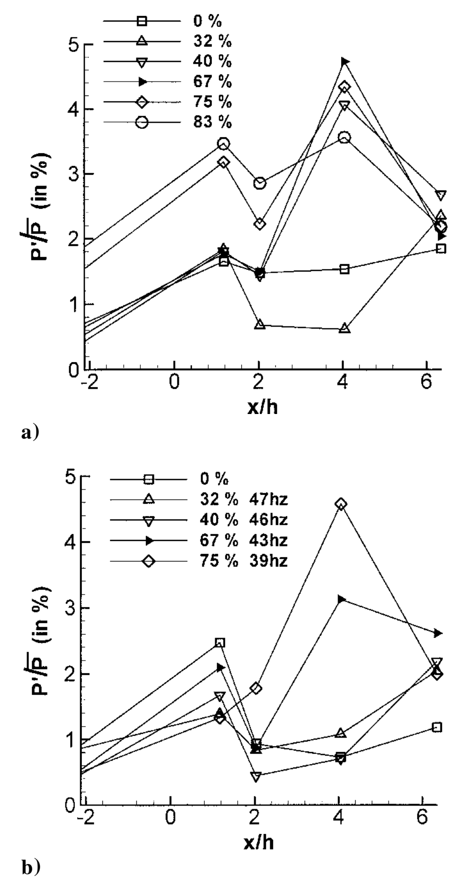

Fig. 4 Effect of blockage ratio on the pressure oscillation amplitude for a) 15 Hz and b) maximum attainable frequency.

pressure perturbation decreased at the higher frequency compared to the data from the lower frequency.

Flow visualization using schlieren indicated that the shock train is almost unaffected along the entire diffuser when the blockage was 32%. Increasing the blockage to 67% affected the shock structure in the latter $\frac{2}{3}$ of the diffuser region. Increasing the blockage to 75% affected the flow almost all of the way up to the throat. PSP confirmed in a two-dimensional visualization the extent of the upstream pressure rise and the transverse pressure field perturbation as a result of blocking pistons periodic position at their individual top dead end, indicating that the two-dimensional effects occupy a small region close to the inlet exit, whereas most of the perturbation upstream is sensed as a one-dimensional effect.

Summary

A supersonic inlet with backpressure excitation to simulate the flowfield experienced by the inlet of a PDE has been tested at Mach 2.5. The excitation was varied from 15 to 50 Hz, and increasing the blockage at the exit plane varied the amplitude. Flow visualization using schlieren and PSP was used to obtain lower wall surface-pressure distribution. The results indicated the following:

1) The pressure oscillations were confined to the downstream of the throat, and no adverse effects were observed on the flowfield upstream of the throat, that is, the inlet remained started for all conditions.

2) The effect of increasing the excitation frequency was a decrease in the amplitude of the pressure perturbations.

3) The effect of increasing the excitation amplitude was an increase in the upstream distance over which the perturbation was sensed.

4) Schlieren photographs and flow visualization using PSP indicated the shock motion within the last $\frac{2}{3}$ of the inlet and showed that the two-dimensional wall pressure variation was restricted to a small region in front of the periodic blockage.

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