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Inlet/Engine Interactions in an Axisymmetric Pulse Detonation Engine System

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The effects of oscillatory backpressure on the air induction system for pulse detonation engines were examined for an axisymmetric, external compression configuration at a freestream Mach number of 2.1. The pressure perturbations at the diffuser exit were produced by a rotating mechanism simulating a valve, which periodically opened and closed the detonation tubes. The oscillation frequency was varied from 30 to 100 Hz for each individual tube. Through varying the downstream blockage, the spillage was altered, and different mass flows were obtained. In all cases the results indicated that fluctuations in the static and stagnation pressures in the inlet were within 3%, without flow instability noted near the inlet capture.

Nomenclature

f	=	excitation frequency, Hz
h	=	diffuser length, that is, the axial distance between cowl lip and inlet exit, mm
k	=	trip height, mm
l	=	inlet length, tip of cone disk, mm
P	=	static pressure, atm
P_n	=	Fourier transform of local pressure normalized by P_{01}
P_{rms}	=	rms of static pressure, atm
P_0	=	stagnation pressure, atm
P_{01}	=	tunnel freestream stagnation pressure, atm
$\tilde{R} = (r - r_i)/(r_o - r_i)$	=	nondimensional radial coordinate
r	=	radius, mm
r_i	=	radius of centerbody, mm
r_o	=	inner radius of outer cowling, mm
x	=	downstream axial coordinate measured from the cone vertex, mm
x'	=	downstream axial coordinate measured from the cowl lip, mm
$\tilde{x} = x'/l$	=	nondimensional axial coordinate measured from the cowl lip

Introduction

THE pulse detonation engine (PDE) might prove to be an attractive alternative to gas-turbine and rocket engines if the predicted high efficiency, simple design, and low weight materialize. Based on ideal-cycle analysis, up to 33% higher cycle efficiency can be achieved when compared to a Brayton cycle.[1–4] To achieve high specific impulse, high operational frequencies of the PDE are required; a cycle frequency in the 50–200 Hz range appears feasible within current technology limits. With a suitable air intake system a PDE is expected to operate over a wide velocity range from zero to supersonic speeds. The thrust can be controlled through changing the firing frequency or the detonation tube filling.[5]

There are several challenges in the design of a viable PDE, particularly in the area of detonation initiation. Deflagration-to-detonation transition in detonation tubes with practical propellants would require significant tube length, whereas direct initiation requires substantial initiation energies.[5–8] A recent review of relevant PDE related theoretical and practical issues is presented by Kailasanath.[9]

Efficient combustion imposes two requirements on the air induction system: 1) the external airflow needs to be decelerated from supersonic freestream conditions to a low Mach number, typically about 0.2 in the detonation tube, without significant losses in the stagnation pressure; and 2) the opening and closing of the detonation tube valves at the back of the inlet produces flow oscillations that must be prevented from separating the boundary layers in the inlet and cause an inlet unstart.[10–12]

PDE tubes combined into batteries with a common inlet firing out of phase with each another have two advantages compared to single-tube inlets: smoother thrust and weaker excitations of the inlet's flow as the blocked mass flow in front of one tube might spill into the adjacent detonation tube. An earlier theoretical study[5] indicated that during transient flow at the inlet exit produced by the valving system of a stack of detonation tubes the time available for the air transfer between adjacent tubes is $\mathcal{O}(10\ \mu\text{s})$, which is significantly shorter than the time required to form a hammershock, $\mathcal{O}(10\ \text{ms})$. 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.

Studies on forcibly excited transonic and low supersonic inlets[10–12] indicated that the shock displacement amplitudes are inversely dependent on the backpressure excitation frequency. 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. In previous experiments[13,14] using a supersonic two-dimensional inlet, where pistons were used to generate a blockage similar to the PDE valves, the amplitude of the oscillations upstream of the pistons was found to be too small to cause an inlet unstart with oscillations limited to the second half of the inlet channel.

The present investigation is a continuation of these studies with a refined inlet exhibiting high pressure recovery and a new excitation mechanism in the form of a rotating disk. Both features more closely approximate a realistic inlet and valving mechanism of a PDE. Additionally, the inlet mass flow was controlled during these studies, and the oscillations' effects at different mass flows have been evaluated.

The purpose of the experiment described in the present paper was to investigate the fluctuations produced in an inlet common to several detonation tubes that operated out of phase with one another and study the impacts of 1) valving frequency and 2) mass-flow variation on the inlet performance and flow stability. Described next

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is the extent of these effects and the upstream interactions in the inlet duct in terms of amplitude, rms, and spatial extent of the flow perturbations.

Experimental Setup

Configuration Geometry

The experiments were carried out using an inlet assembly depicted in Fig. 1. The inlet was designed for $M = 2.1$ with a single central cone with a 20-deg half-angle, to provide external compression from the freestream Mach number down to Mach 0.8 at the capture. The theoretical pressure recovery of this shock system was 85% at nominal mass flow and without backpressure oscillations. The diffuser reduces the Mach number to 0.2 at the inlet exit as required for PDE operation. To ensure that the boundary layers were turbulent in the diffusor, 0.13-mm-thick trip tape strips were applied 5 mm downstream of the tip of the centerbody ($Re_k = 15 \times 10^3$) and 4 mm inside the capture on the cowl ($Re_k = 9 \times 10^3$). All experiments presented here took place at zero angle of attack.

Downstream of the inlet were six 13-mm-long cylindrical ducts representing detonation tubes distributed evenly along a 15-mm radius circle circumference, as shown in Fig. 1. Each cylindrical duct, which represented a PDE detonation tube, had a diameter of 13 mm.

The PDE intake valve operation was simulated with a flywheel located between the inlet and the PDE channels with two contoured cutouts such that, at any given time, a maximum of four PDE channels were exposed to the flow and the remaining two were completely covered by the disk. The disk was driven by a rod passing through the model, as shown in Fig. 1, and connected to an external motor via a flexible shaft, which controlled the frequency of operation. Figure 2 shows the inlet internal area distribution normalized by the throat area. It can be seen in the figure that the inlet exit was blocked both by the disk and by the area around the PDE tubes to an area that ranged between 33 and 43% of the total exit area, depending on the flywheel position. The minimum blockage occurs when two pairs of tubes are open, and the maximum blockage occurs when the rotating valve transitions from one set of valves to another. Thus, a significant area blockage exists at all times in addition to the oscillation induced by the valving mechanism. The blockage oscillation induced at the inlet exit results in either 1) unsteady spillage at the inlet's capture or 2) increased mass flow through the open tubes at the inlet exit. Downstream of the PDE channels, a cylindrical plenum exhausts the air downstream into the wind tunnel. To fix the mass-flow, varying portions of the exhaust channels were blocked inside the plenum, as discussed next.

Each of the three 3-mm-wide radial supporting struts placed near the diffuser exit shown in Fig. 1 contained three stagnation pressure ports with staggered radial locations for pressure recovery

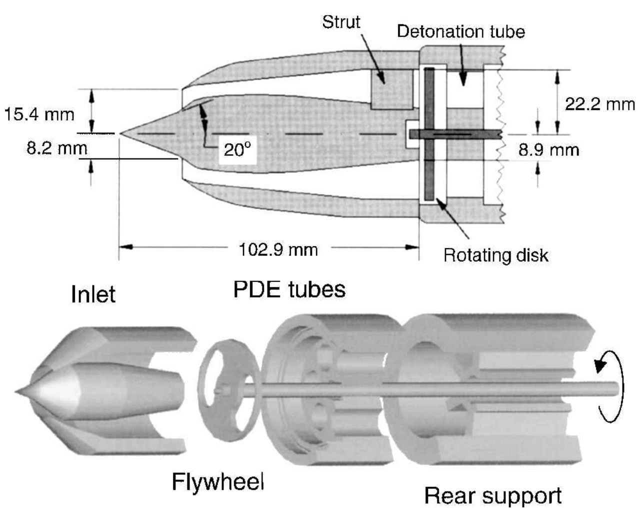

Fig. 1 Cross section of the axisymmetric inlet with rotating disk and detonation tubes.

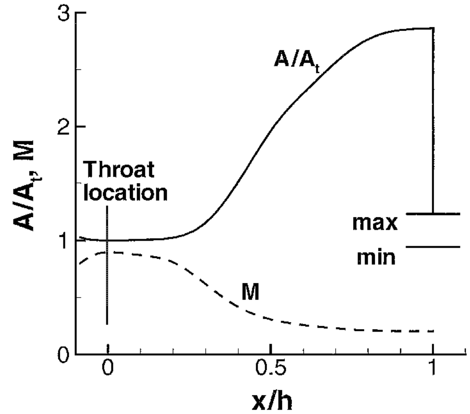

Fig. 2 Inlet area distribution normalized by the throat area and the corresponding Mach number. The exit area variation is caused by the flywheel rotation and the simulated PDE tubes. The inlet length from the cowl to exit is $h = 81$ mm.

measurement. Expressed in the nondimensional radial coordinate $\tilde{R}$, the nine stagnation tap locations ranged between 0.16 and 0.94 at the axial location $\tilde{x} = 0.85$. The cowl had six static pressure ports at the axial locations $\tilde{x} = 0.27$ (throat), 0.33, 0.46 0.58, 0.70, and 0.87. All static ports had the same circumferential position, centered between two of the struts to minimize interferences. Static and stagnation pressures were also measured in one of the PDE channels.

Mean pressures were measured using a PSI® 9010 scanner, and pressure fluctuations were measured by connecting five Omega® transducers to the ports. These were read along with the tunnel stagnation and static pressures at 1-kHz sampling frequency using a NI® AT-MIO-16E-2 DAQ board on a PC, while the pressure scanner was read at 30 Hz.

Test Conditions

The wind tunnel is a continuously adjustable throat blowdown Mach 1.5-4 tunnel with a 150 × 150 mm test-section cross section. In these experiments the wind tunnel operated at $M = 2.1$. Examination of the flow quality in the wind tunnel indicated a near-Gaussian pressure distribution with 1% P_{01} rms. Fourier transform analysis revealed no significant peaks in the frequency spectrum. During the 30-s runs, dry air at 300 K was provided while the tunnel stagnation pressure dropped from 13 to 2 atm. Despite the large drop in stagnation pressure during the course of a run, the variation of all steady-state inlet stagnation and static pressures remained stable within ±1.5% of P_{01} throughout a run when normalized by the tunnel stagnation pressure. This also meant that the local Mach numbers were constant, and hence there was no fluctuation in speed of sound, flow speeds, or Reynolds number during the runs as long as heat-conduction effects near the model surface are neglected. Furthermore, the data presented here were recorded during the approximately 15 s of quasi-steady pressure plateau following the wind-tunnel start. Using a schlieren system, the model's capture was observed throughout the test to ensure that no unstart or major shift in the external flowfield occurred during the experiment.

Through varying the blockage behind the detonation tubes, thereby affecting the spillage at the capture, two different mass-flow cases were attained. The flow rates were determined using the mean stagnation pressures on the struts and the static pressure at the same axial position and were found to be 388 and 284 g/s, respectively, when the tunnel stagnation pressure was 3.06 atm. Normalizing with the capture nominal flow, defined at "shock-on-lip" conditions, which was 434 g/s, capture ratios of 89 and 65%, respectively, were obtained. The uncertainty in the mass flows is estimated at ±10%.

The Omega and PSI 9010 transducers used in this model had highly stable calibrations giving slope differences of <0.5% between calibrations carried out at different times. The uncertainty at $P_{01} = 2.3$ atm, where most data were acquired, was 0.3% of P_{01} for the Omega measurements. This implied that the systematic error was significantly smaller than the experimental scatter as illustrated by the rms bars in the results plots to be discussed next.

Results and Discussion

Wall Static Pressure

The static pressures in the inlet's duct for the two different mass flows are presented in Fig. 3 for three excitation frequencies. The static pressure is found to rise monotonically throughout the inlet. At $M = 2.1$ the conical shock system results in a capture Mach number of 0.8 with an increase in static pressure from 0.10 P_{01} to 0.57 P_{01}. The overall static pressure increase in the diffuser is, thus, small compared with the external compression. The rms fluctuation amplitude remains 1% of P_{01} throughout the inlet, clearly demonstrating that no large-amplitude oscillations are induced by the rotating disk at any of the frequencies indicated in the figure.

Stagnation Pressure

Figure 4 shows the stagnation pressures measured by the inlet exit rake with Figs. 4a–4f separated for the three frequencies, that is, 30, 60, and 100 Hz and the two mass flows employed, 89 and 67%. The figures indicate the presence of a slight deviation from symmetry more pronounced at high mass flow. The asymmetry is maintained at all frequencies and indicates the presence of separated flow in front of strut 1 and 3. The local mean pressure recoveries were used to calculate area-weighted mean recoveries for the two cases of 89 and 67%, with peak recoveries of 82 and 71%, respectively, at 60 Hz. The rms fluctuation amplitude was less than 2% of the tunnel stagnation pressure in all cases, slightly lower for the 67% mass flow case.

Effect of Excitation

Through varying the rotational speed of the disk between 900 and 3000 rpm, excitation frequencies in the 30–100 Hz range were studied. Figure 5 presents the filtered rms fluctuations of the duct static pressures at different excitation frequencies when the mass-flow capture ratio was 89%. A bandpass filter centered at the excitation frequency with a bandwidth of 1 Hz was applied. The figure shows that the amplitude of the static-pressure oscillations decreased upstream from the excitation source. The error bars in this figure show ± 1 standard deviation and indicate that the signal level is low compared to the statistical variation in the 100-Hz case.

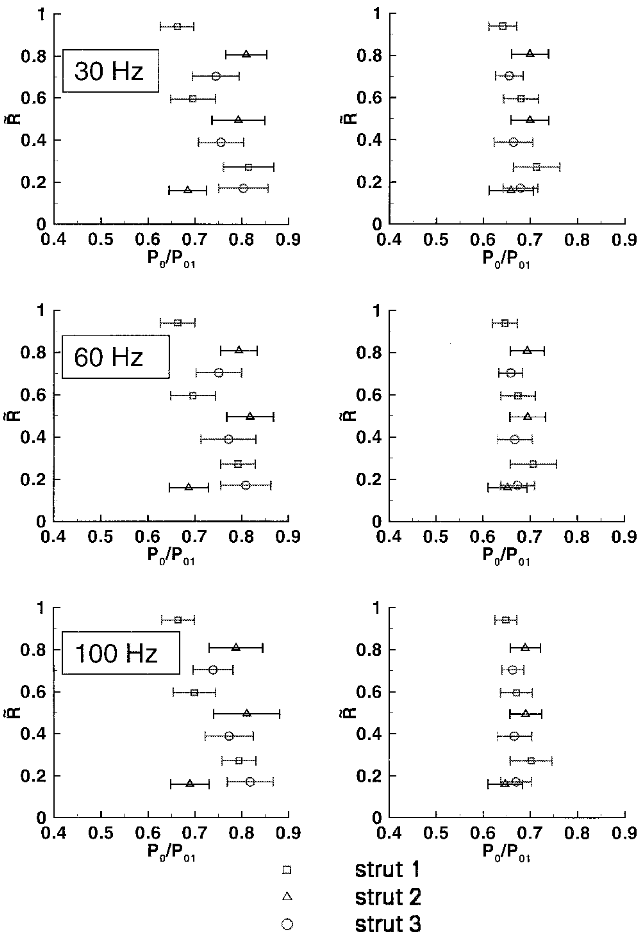

Fig. 4 Stagnation pressures for two different flow rates corresponding to 89 and 65% of the nominal capture mass flow, respectively, at three selected frequencies. The error bars show the $\pm 3 \times$ rms fluctuation amplitude.

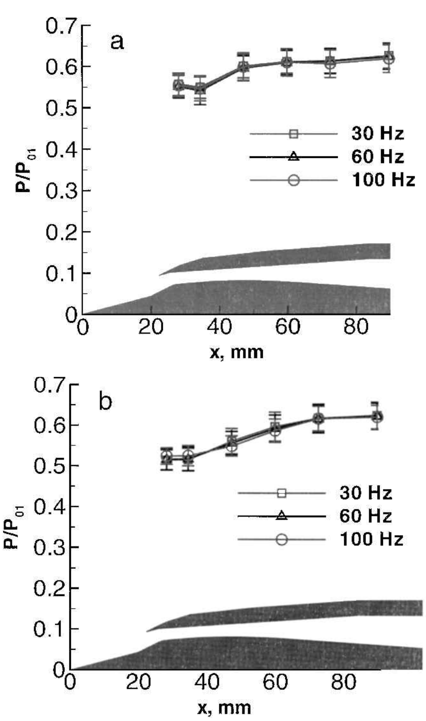

Fig. 3 Static pressures at two different mass flows corresponding to a) 89% and b) 65% of the capture mass flow, respectively. The error bars show the $\pm 3 \times$ rms fluctuation amplitude.

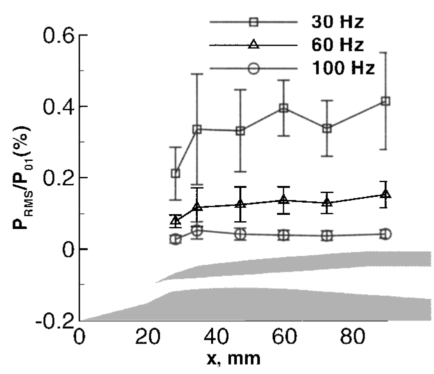

Fig. 5 Filtered fluctuation rms amplitude of the static pressure normalized by the wind-tunnel stagnation pressure at 89% capture mass-flow ratio. Error bars show ± 1 standard deviation of the rms amplitude.

Figure 5 also suggests a general trend towards increasing the amplitude as the disk is approached. The signal measured in the duct is an order of magnitude stronger than the similarly filtered signal from the transducers connected to the wind tunnel. A comparison with the unfiltered rms amplitudes shown as error bars in Fig. 3 clearly demonstrates that the excitation frequency peak contributes only a minor part of the total rms amplitude because these fluctuations do not diminish appreciable with increasing frequency.

The frequency spectra in Fig. 6 show the damping in the inlet and the dominance of the excitation frequency over the wind-tunnel

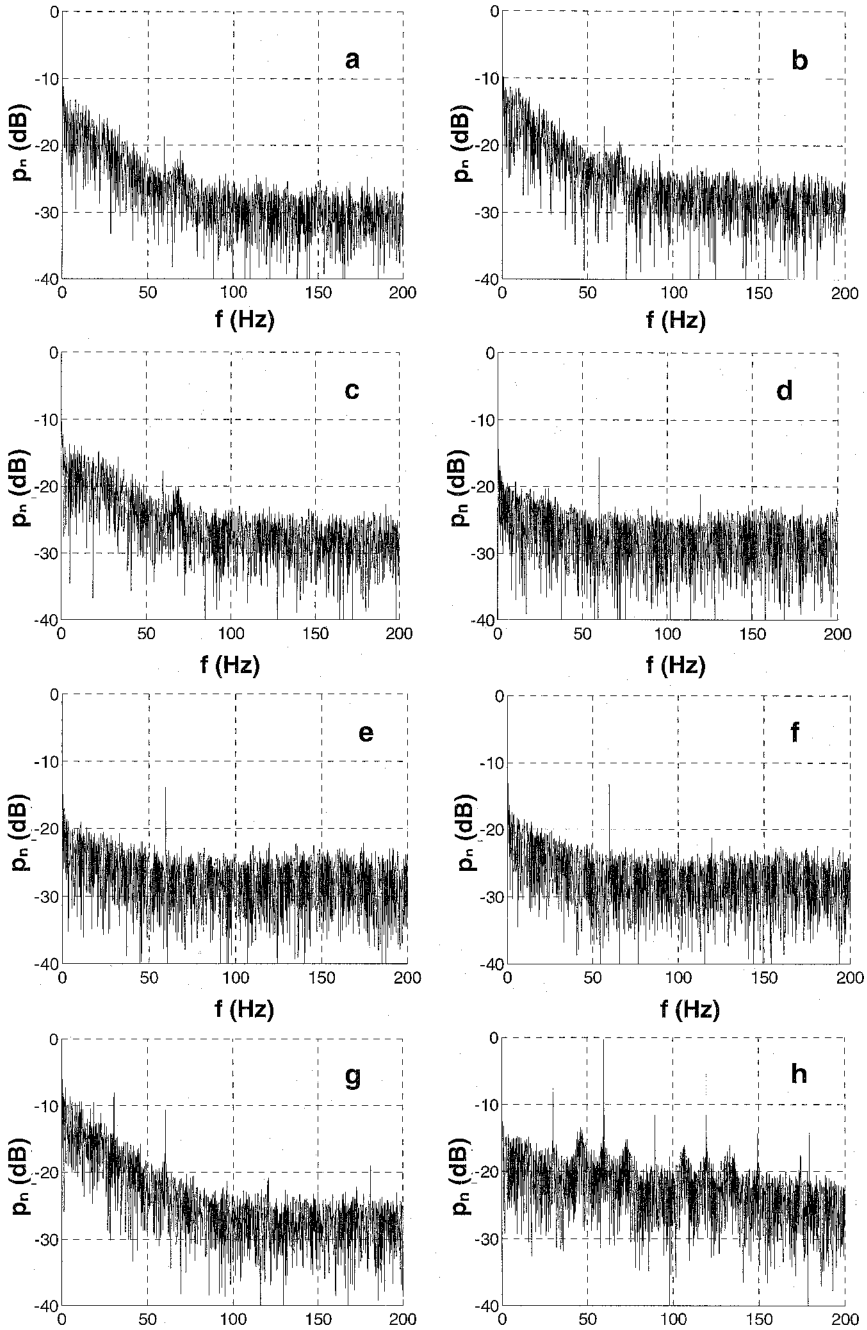

Fig. 6 Pressure spectra at 60-Hz excitation frequency and 89% capture mass-flow ratio. Static pressures at a) $\tilde{x} = 0.27$, b) 0.33, c) 0.46, d) 0.58, e) 0.70, and f) 0.87. Also shown are stagnation pressures at g) $\tilde{R} = 0.495$ and h) in the detonation tube center.

noise. Although the static-pressure spectra only indicate the excitation frequency, the stagnation taps also show harmonics of half of the excitation frequency. Comparing the stagnation pressures in the detonation tube with those at the inlet exit, it is clear that low frequencies are transmitted upstream with less damping than the high frequencies. The peak value reduction was found to be 0.5 dB at 30 Hz, 11 dB at 60 Hz, and 16 dB at 120 Hz, as shown in Figs. 6g and 6h. Using the integrated energy in a 0.5-Hz band about the peak, the damping was found to be 3, 6, and 12 dB, respectively. Taken together, the observations in Figs. 5 and 6 suggest that there is a strong damping of the fluctuations at high frequency and that the low-amplitude oscillations are still stronger than the background noise level.

Two different explanations for the absence of large oscillations in the present study compared to that found in an earlier study[13] are suggested:

1) Use of a rotating valve redirects the flow into adjacent open tubes in a common inlet resulting in near-constant total mass flow;

2) The low excitation frequencies allow a subsonic inlet duct to adjust completely to the imposed exit conditions during a cycle. The time it takes for an acoustic wave to travel from the disk to the capture is of the order of 0.5–0.7 ms ($St < 0.1$); therefore, frequencies of kilohertz magnitude would be required to reach acoustic resonance for an inlet of this size.

Summary

An axisymmetric PDE inlet has been tested in Mach 2.1 airflow with oscillation produced by a rotating valve opening and closing simulated PDE detonation tubes. The upstream effect of the backpressure oscillation on the inlet flow and on the inlet pressure recovery was measured. The results indicated the following:

1) The spatial peak mean stagnation pressure recovery ranged between 71 and 82% for mass-flow ratios based on the nominal capture flow of 65 and 89%.

2) In none of the studied cases, with frequencies from 30 to 100 Hz the oscillations were strong enough to unstart the inlet.

3) The recorded rms variations in the wall pressures were $<3\%$ of the corresponding mean pressures at all locations.

4) The stagnation pressure fluctuation amplitude at all excitation frequencies remained $<2\%$ of P_{01} in all cases.

5) The amplitude of the oscillations decayed upstream of the simulated rotating valve. At the throat the static-pressure oscillations at the excitation frequency exhibited an amplitude half of that found at the static tap just upstream of the valve. These results indicate that the common-inlet configuration suppresses flow oscillations in a PDE inlet, providing stable capture flow.

6) The pressure recovery was measured in the range of 64–83%, despite measured noncircumferential symmetry, which indicates that high performance can be achieved in a carefully designed full-scale PDE inlet.

7) With simple valving systems as used in this study, a nonnegligible blockage is present at all operational conditions resulting in pressure recovery losses and an effective increase in frontal area drag.

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