Performance Studies of Pulse Detonation Engine Ejectors

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An experimental study on the performance of pulse detonation engine ejectors was performed. Time-averaged thrust augmentation produced by straight and diverging pulse detonation engine ejectors was measured using a damped thrust stand. The ejector length-to-diameter ratio was varied from 1.25 to 5.62 by changing the length of the ejector and maintaining a nominal ejector diameter ratio of 2.75. In general, the level of thrust augmentation was found to increase with ejector length. Also, the ejector performance was observed to be strongly dependent on the operating fill fraction. A new nondimensional parameter incorporating the fill fraction was proposed. When the pulse detonation engine ejector data were represented as a function of this new parameter, the ejector data were reduced to one representative thrust augmentation curve for ejectors of similar internal geometry. Straight pulse detonation engine ejectors compared well with the available data on straight steady-flow ejectors. Diverging pulse detonation engine ejectors produced nearly twice the thrust augmentation as their straight-ejector counterparts due to the additional thrust surface area the divergence provided. All pulse detonation engine ejectors tested were seen to be sensitive to the axial position of the ejector as well. The optimum ejector axial placement was found to be a function of fill fraction due to a tradeoff between the detonation wave induced drag and increased mass entrainment. Downstream ejector placements performed the best at the low fill-fraction operating conditions.

Nomenclature

D_{EJECT}	=	ejector diameter
D_{PDE}	=	pulse detonation engine detonation tube diameter
DR	=	ejector-to-pulse detonation engine diameter ratio $(DR = D_{\text{EJECT}}/D_{\text{PDE}})$
L_{EJECT}	=	ejector length
F_{PDE}	=	pulse detonation engine thrust force without an ejector
$F_{\text{PDE}_{\text{EJECTOR}}}$	=	pulse detonation engine thrust force with an ejector
F_{ref}	=	reference thrust force
u	=	uncertainty
β	=	pulse detonation engine ejector parameter $(\beta = L_{\text{EJECT}}/D_{\text{EJECT}}/\text{ff})$
Φ	=	ejector thrust augmentation ratio $(\Phi = F_{\text{PDE}_{\text{EJECTOR}}}/F_{\text{PDE}})$

I. Introduction

PULSE detonation engines (PDEs) use controlled periodic detonations of a combustible mixture to generate thrust [1]. One of the primary motivations for PDE development has been based on the potential gain in thermal efficiency that can be achieved with detonation combustion [2]. Experimental and computational researchers have demonstrated some success in obtaining competitive specific impulse values with both simplistic [3] and practical [4,5] PDE cycles. These promising results have led to many PDE applications being proposed. For example, it has been suggested that PDEs can be used as cost-effective replacements for small gas turbine engines, as potential replacements for combustors on existing large-scale gas turbines, or as thrust augmenters. However, even if PDE performance benefits ultimately reveal themselves to be insignificant in practical applications, the PDE cycle will still be an attractive propulsion system because of the reliability benefits of having very few moving parts, the scalability of the engine, and the flexibility in geometry it will provide.

A common approach to increasing the thrust of an engine at subsonic flight conditions is with an ejector. An ejector is a coaxial duct that is placed around the exhaust of an engine to direct the entrainment of the surrounding flow into the engine exhaust stream. The use of steady-flow ejectors and their associated design procedures is well established. The application of ejectors, however, to unsteady primary flows is less common. Several studies [6–11] have examined unsteady ejectors driven by pulsejets or other nondetonation devices where the primary airflow was either unsteady or exhibited strong acoustic coupling with the ejector. Lockwood [6] showed that an unsteady primary flow is more efficient in producing mass entrainment than a comparable steady flow. His pulsejet studies showed ejector thrust augmentation ratios as high as 1.9, much greater than the theoretical isentropic steady-flow ejector. He attributed the unsteady ejector performance to a more efficient energy transfer process between the primary flow and the secondary (entrained) flow through inviscid processes, whereas the steady ejector relies primarily on viscous shear mixing. Because of the unsteady nature of a PDE, these results suggest that an ejector could be highly effective in increasing the PDE performance, specifically for subsonic applications.

Computational studies of single-shot PDE-driven straight ejectors using an Euler code demonstrated the importance of the

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ejector-to-PDE tube diameter ratio in achieving thrust augmentation and its sensitivity to fill fraction [12]. An Euler code with finite-rate chemistry was used to simulate multiple cycles of a specific converging–diverging ejector driven by a PDE at approximately 120 Hz [13]. These simulations demonstrated the potential of thrust augmentation of almost 80%. Further nondetonation computational studies highlighted the importance of the starting vortices, precursor shocks, and direct pressure loads created by the gas dynamic (shock-tube) processes within the ejector to the overall thrust augmentation performance of the system [14]. These computations suggested that high thrust augmentation for PDE-ejector applications is achievable and highlighted the need to understand the gas dynamics, resonance phenomena, and flow interactions of the PDE-ejector system for optimum performance.

A few experimental studies of PDE ejectors have recently been reported. One experimental study by Rasheed et al. [15], using a 5-cm-diam H2–air PDE tube at 10 Hz with 7.62, 10.16, and 15.24-cm-diam ejectors, showed thrust augmentation levels varying from +16 to −5%, depending on the configuration. In all cases, the maximum thrust augmentation was found to occur with the ejector located fully downstream of the PDE tube. Similar experiments using C2H4–air showed maximum thrust augmentation levels of 24%, depending on the configuration [16]. This study presented supporting flow visualizations in the form of shadowgraph images of the ejector inlet throughout one PDE cycle. In both of the preceding studies, the experimentally measured thrust augmentation ratio was significantly lower than the augmentation ratio of 1.9 achieved by Lockwood's pulsejet experiments [6].

One possible reason for the discrepancy in the referenced works on ejector thrust augmentation could be the lack of an appropriately designed ejector inlet. The shape of the ejector inlet is very important in determining the ejector performance because the inlet is an aerodynamic surface that guides the entrainment of the surrounding mass flow. Allgood et al. [17] performed high-speed shadowgraph visualizations of optically accessible PDE ejectors. Their results showed significant losses in mass entrainment and strong flow separation when PDE-ejector inlets were *not* properly rounded or contoured. The importance of an aerodynamic ejector inlet has also been proposed by Lockwood [6], Paxson et al. [7], and Wilson et al. [18].

In addition to ejector inlet geometry, the interior surfaces of the ejector can serve as thrust surfaces on which the pressure forces can act, thereby generating additional thrust. Lockwood [6] showed substantial thrust improvement when using a divergent-type ejector versus a straight cylindrical ejector for pulsejet systems. The experimental work by Paxson et al. [7] also used ejectors with a small diverging section at the end of the ejector for unsteady nondetonating primary flow systems. Wilson et al. [18] have demonstrated experimentally the augmentation benefits of using diverging ejectors for PDEs. However, the mechanisms by which a diverging ejector improves the thrust augmentation of a PDE still needs further investigation.

The relative size of the ejector to the primary flow driver is also known to have a significant influence on ejector performance. An ejector diameter should be sized large enough to allow sufficient area for the primary flow to entrain the secondary flow. However, too large of an ejector diameter could reduce the effect of the accompanying pressure drop on the ejector inlet as well as the pressure rise on a diverging ejector interior surface. An optimum ejector-to-driver diameter ratio corresponding to a peak thrust augmentation level has been observed for a variety of ejector systems [6,7,18]. Typical reported values of optimum diameter ratios range between 2.4 and 3.5.

In a similar manner, the axial placement of the ejector can also affect the ejector flow dynamics. Experimental results by Allgood et al. [17] have shown that the level and efficiency of the PDE-ejector entrainment can be restricted with an upstream axial placement of the ejector. On the other hand, a downstream ejector placement between one to two PDE diameters resulted in a cleaner flowpath for the secondary flow to be entrained into the ejector. This observation is in agreement with the PDE-ejector thrust measurements reported by

Rasheed et al. [15], and similar trends were found by Paxson et al. [7] for pulsejet-ejector systems. Recently, Glaser et al. [19] did an in-depth study on the effects of ejector axial placement and ejector geometry for PDE-ejector systems.

In addition to ejector geometry and placement, there are many operating parameters that have been shown to drastically affect the performance of a PDE, and thus will most likely affect the PDE-ejector performance as well. For example, PDE thrust has been observed to scale linearly with frequency of detonations because it is desirable to minimize the time of each filling event and maximize the frequency of the overall PDE cycle [3]. Thus, adjusting the PDE cycle frequency is one proposed method of throttling the engine. Another way of throttling the engine is to alter the amount of fuel-oxidizer mixture that fills the PDE tube before ignition. The fraction of the PDE tube filled with a detonable mixture relative to the total tube volume is defined as the fill fraction. Although the PDE thrust has been shown to decrease with a reduction in fill fraction, the fuel-based specific impulse values increased at a faster rate [4]. This performance gain observed at lower fill fractions was attributed to the detonation shock wave compressing the nonreactants occupying the remainder of the PDE tube. Allgood et al. [4] demonstrated experimentally the performance benefits of partially filling the detonation tube for a multicycle PDE operation. Their results showed the partial-fill effect being independent of PDE cycle frequency for a constant area detonation tube.

The current work presents an experimental study on the performance benefits of axisymmetric ejectors for multicycle pulse detonation engines. The effect of fill fraction on PDE-ejector performance has been quantified. The performance sensitivity of PDE ejectors to ejector length, internal diverging geometry, and relative axial placement has also been measured. A comparison between PDE ejectors and other ejector systems was given, and a new normalization of PDE-ejector data has been proposed for comparing PDE-ejector data to other ejector systems. In addition to performance measurements, flow visualizations were performed on similar ejector geometries to further explain the trends observed in the performance data.

II. Experimental Facility

A. Pulse Detonation Engine System Description

Thrust augmentation measurements of PDE-driven ejectors were performed. The pulse detonation engine test facility at the U.S. Air Force Research Laboratory at Wright–Patterson Air Force Base was used to obtain the thrust measurements. Premixed hydrogen and air were delivered to a single round detonation tube by way of a mechanical valve system constructed from a modified four-cylinder automotive head. The automotive valve system could be operated at frequencies up to 40 Hz. Because of the nature of automotive valving, the PDE cycle was divided equally between three main processes: 1) filling the PDE with fresh reactants, 2) ignition, detonation, and blowdown of the high-pressure products, and 3) purging the PDE with a buffer of cold air. The hydrogen and air were metered through choked flow orifices. The fill fraction (ff) was varied by controlling the upstream propellant delivery pressures via control valves. By measuring the fuel–air flow rates and controlling the valve timing and frequency, the fill fraction and purge fraction were known. The maximum error in volume flow rate measurements was found to be ±3%. This translated directly into a relative error in fill-fraction measurements of also ±3%. High-speed shadowgraph and chemiluminescence imaging of the exhaust flow, combined with exit pressure transducers, provided a secondary means of verifying the baseline reference condition of ff = 1.

The deflagration-to-detonation transition of the hydrogen–air mixture was enhanced by the use of Shchelkin-type spirals of 0.3 m length. The Shchelkin spiral occupied only 16% of the total PDE tube length. Two pressure transducers (PCB M102A) were mounted 0.1524 m apart to monitor detonation shock speeds and validate that Chapman–Jouguet detonations were produced. The transducer closest to the exit of the PDE was placed a distance of 0.36 m from the PDE exit. The pressure data were collected via a remote 5 MHz

16-channel A/D converter system. The measured wave speed at a fill fraction of 1.0 was on average 1988 m/s (±13 m/s), which is less than 2% deviation from the theoretical Chapman–Jouguet wave speed of 1966 m/s for a stoichiometric–air mixture.

The PDE was mounted on a damped thrust stand rated for a maximum thrust load of 4500 N. The thrust stand was designed to measure the time-averaged thrust of the dynamic PDE. The thrust stand consisted of linear bearings riding along a pair of low-friction rails. The PDE was allowed to move freely on the rails but its motion was weakly damped by springs to prevent any resonance effects. To remove the effects of static friction, the PDE was continuously actuated forward and backward by a linear actuator. Because this was a known force, it could be subtracted from the measurements to get the true average thrust of the engine. The thrust measurements were calibrated by placing static weights and measuring the displacement with a positional sensor. No hysteresis in the system was observed throughout the testing. Calibration curves were obtained before and after each set of tests to monitor changes in the system. A linear relationship between the applied load and measured thrust was observed for the entire range of PDE thrust loading, with a maximum recorded standard deviation of approximately ±1 N. The repeatability of the data was observed to be within this error band and thus indistinguishable from the measurement error. For a more detailed description of the PDE test facility and thrust measurement system, the reader is referred to the recent paper by Allgood et al. [4].

B. Pulse Detonation Engine Ejector Test Conditions

The PDE detonation tube was constructed of a steel pipe of 5.08 cm diameter D_{PDE} and 1.83 m length. The main operating parameters that could be varied were the following: 1) the fuel/air mixture, 2) the fill fraction, 3) the purge fraction (pf), 4) the ignition delay, and 5) the PDE cycle frequency. The fill fraction and purge fraction are defined as the ratio of the detonation tube filled with a fuel/air or air mixtures, respectively. The ignition delay was defined as the delay in time in which the spark was actuated after the valves closed. For all test conditions, the PDE was operated at a 30 Hz cycle frequency with a stoichiometric mixture of hydrogen and air, a purge fraction of 0.5, and an ignition delay of 0.5 ms. Only the operating fill fraction was varied in the current tests.

Thrust augmentation levels of axisymmetric ejectors for pulse detonation engine applications were quantified. All ejectors were mounted coaxially to the PDE exhaust and had a rounded or contoured bell-mouth inlet. As depicted in Fig. 1, two sets of ejectors were tested: straight cylindrical ejectors and straight cylindrical ejectors with a diverging exhaust end piece. The length L_{EJECT} of the straight and diverging ejectors were varied by extending the length of the straight or straight-intermediate sections, respectively. The diverging ejector end piece had a 4 deg half-angle of divergence at a fixed length of 19.3 cm. A similar 4 deg half-angle of divergence was used by Lockwood [6] in his pulsejet-ejector experiments. The diameter D_{EJECT} of the straight/straight-intermediate sections was set at a fixed value of 13.97 cm. Thus, the ejector-to-PDE diameter ratio was kept constant throughout the tests at a value of 2.75. This value was selected because it closely matched the optimum diameter ratios reported in other ejector experiments [6,7,17,18].

A range of ejector length-to-diameter ratios (L_{EJECT}/D_{EJECT}) were also tested and are listed in Table 1. The relative position between the PDE exhaust and the ejector inlet was varied as depicted in Fig. 1. Both upstream ($x/D_{PDE} < 0$) and downstream ($x/D_{PDE} > 0$) ejector axial placements were tested. The range in axial placements tested for both straight and diverging ejectors are given in Table 1. To determine the PDE-ejector thrust augmentation dependence on fill fraction, thrust measurements of both the baseline configuration with
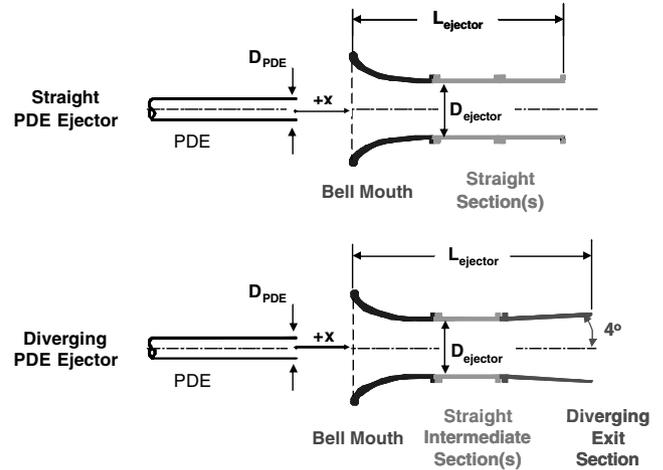

Fig. 1 Schematics of the straight and diverging PDE ejectors.

no ejector and the integrated PDE-ejector system were obtained at the same fill fractions ranging from 0.4 to 1.1. A PDE fill fraction greater than 1.0 means that the PDE combustion chamber was overfilled with a detonable mixture of fuel and oxidizer before ignition.

III. Results and Discussion

A. Baseline Testing of Pulse Detonation Engine

The selected baseline configuration for the ejector tests was the 1.83-m-length PDE detonation tube (5.08-cm-diam) without an exhaust nozzle. The fill fraction for the baseline was varied from 0.4 to 1.1 while maintaining a near stoichiometric fuel–air ratio, an ignition delay of 0.5 ms, a purge fraction of 0.5, and a cycle frequency of 30 Hz. The thrust values for the baseline PDE configuration are given in Fig. 2 as function of experiment run time. The run time is represented in number of PDE cycles, and the thrust is normalized according to a reference thrust value. The reference thrust used in normalizing this data was selected to be the thrust value (77 N) for the baseline configuration at a fill fraction of 1.0. Because the PDE thrust was measured using a damped thrust stand, there was an associated time constant that delayed the average thrust from being recorded, as shown by the slowly rising thrust curves in Fig. 2. This transient delay between the first PDE cycle during each test and the time when a near steady-state thrust level was reached was approximately 33 s, or 1000 PDE cycles, for all fill fractions tested. The observed 33 s time constant was a result of the characteristics of the highly damped thrust stand designed to measure an average thrust of a pulse detonation engine, and was also due to the transient time required for the PDE to reach thermal equilibrium. All thrust data presented in this paper corresponded to the average plateau in thrust recorded after the PDE had been operating continuously for approximately 1000 PDE cycles.

The variation in thrust and fuel-based specific impulse with fill fraction is plotted in Fig. 3. The trends observed were consistent with those found by other researchers. The maximum thrust occurs at maximum fill fraction and decreases nonlinearly with fill fraction. This nonlinear drop in thrust with reduced fill fraction is attributed to the unfilled portion of the detonation tube acting as a straight nozzle. Two sets of expansion waves form during the detonation propagation for a straight nozzle configuration. The first set forms as the detonation shock wave crosses the interface between the filled and unfilled portion of the tube. The second set of expansion waves, which are much stronger than the first, forms as the detonation wave

Table 1 Pulse detonation engine ejector test matrix ($D_{EJECT}/D_{PDE} = 2.75$)

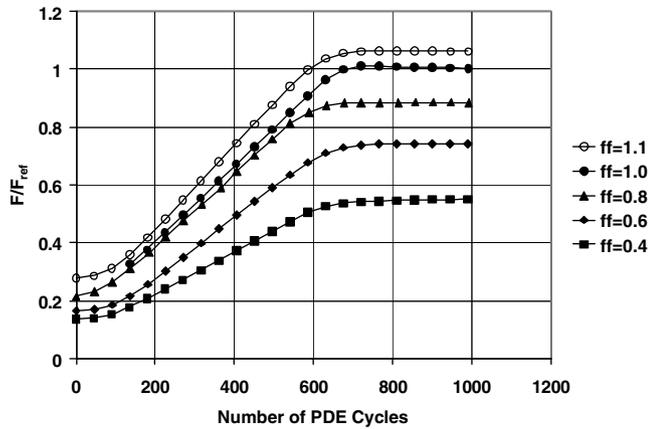|	Fill fraction	Ejector length-to-diameter ratio (L_{EJECT}/D_{EJECT})	Ejector axial position (x/D_{PDE})
Straight ejector	0.4–1.1	1.25–4.25	−1.5–2.0
Diverging ejector	0.4–0.8	2.62–5.62	−2.0–4.0

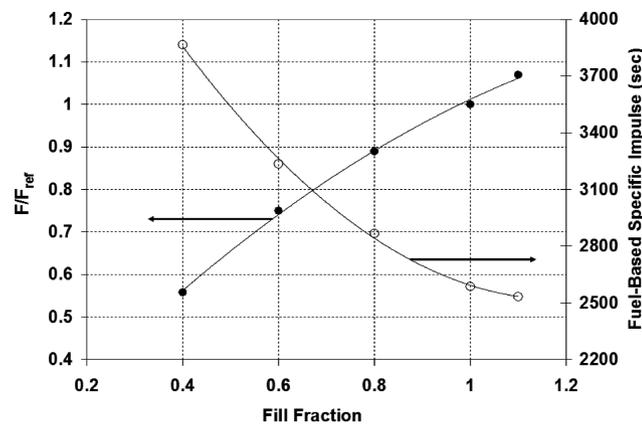**Fig. 2   Baseline PDE average-thrust measurements versus number of PDE cycles ($D_{PDE} = 5.08$ cm, $F_{ref} = 77$ N).**

Fig. 3   Baseline PDE thrust and fuel-based specific impulse variation with fill fraction ($D_{PDE} = 5.08$ cm, $F_{ref} = 77$ N).

and exhaust gases exit the PDE tube. Essentially, the detonation shock wave serves to compress the gases occupying the unfilled portion of the detonation tube, thereby maintaining the pressure inside the detonation tube at a higher pressure. This increased blowdown time with a straight nozzle results in higher thrust. For example, if this straight nozzle or "partial-fill" effect were not present, the thrust at a fill fraction of 0.5 would be approximately 50% of the thrust obtained with a fill fraction of 1.0. The data in Fig. 3 show that the thrust at a fill fraction of 0.5 was instead approximately 65%. Thus, a 15% thrust increase was generated by the partial-fill effect at a fill fraction of 0.5. This effect continued to increase as the fill fraction was reduced. Also, because the PDE thrust levels decreased at a slower rate than the reduction in fuel mass flow rate, the fuel-based specific impulse values increased as shown in Fig. 3. Specific impulse values as high as 3700 s were obtained for the baseline configuration without an ejector.

B.   Effects of Fill-Fraction

In current work, the thrust augmentation of the integrated PDE-ejector system has been represented by an augmentation ratio Φ, where Φ is the total thrust of the PDE-ejector system $F_{PDE_{EJECTOR}}$ normalized by the thrust of the PDE without an ejector F_{PDE} but operating at the same engine conditions. By normalizing the thrust data in this manner, the data will reflect solely the performance of the ejector at those engine conditions. This definition is consistent with the historical approach for representing ejector thrust augmentation. The authors would also like to point out that, although the contributions to thrust by the momentum of the "engine-cold" fuel/air and purge gases were known, as shown in Fig. 2, no correction to the thrust data by subtraction of these thrust values was performed.

The reasoning for this was that the true contribution to the total thrust by the fuel/air and purge gases during engine operation (i.e., ignition on) was unknown during the cycle, due to Rayleigh flow effects of heat addition to these gases by the PDE confining walls and its subsequent effects on the momentum of these gases. However, the selected normalization of the PDE-ejector thrust data attempts to correct for these effects by normalizing the PDE thrust data at the same engine operating condition.

As mentioned earlier, the total uncertainty in the thrust measurements was estimated to be ± 1 N. Using the standard propagation of uncertainty equation established by Kline and McClintock [20], the uncertainty in the thrust augmentation ratio Φ can be computed using the following relation:

$$u_\Phi = \sqrt{\left(\frac{\partial \Phi}{\partial T_{PDE_{EJECTOR}}} \cdot u_{PDE_{EJECTOR}}\right)^2 + \left(\frac{\partial \Phi}{\partial T_{PDE}} \cdot u_{PDE}\right)^2} \quad (1)$$

Substituting the equation for Φ given in the Nomenclature section of this paper gives the following reduced formula for the uncertainty in the thrust augmentation ratio as a function of the thrust of the PDE and the uncertainty in the thrust measurements:

$$u_\Phi = \sqrt{\left(\frac{u_{PDE_{EJECTOR}}}{T_{PDE}}\right)^2 + \Phi^2 \cdot \left(\frac{u_{PDE}}{T_{PDE}}\right)^2} \quad (2)$$

Equation (2) shows that the uncertainty in thrust augmentation measurements will be maximized when the thrust levels of the PDE are at a minimum and augmentation ratios are large. For the current tests, these occurred at the lowest PDE fill fraction tested (ff = 0.4). The maximum uncertainty of the current test data was found to be 0.048, whereas the average uncertainty was 0.033.

The thrust of the PDE ejectors was measured at fill fractions ranging from 0.4 to 1.1. However, due to flow rate restrictions and backfire problems into the delivery manifold, most tests were limited to a maximum fill fraction of 0.8. Figure 4 is a plot of the percent thrust augmentation for a selected set of the straight and diverging ejectors tested as a function of fill fraction. All ejectors showed that the best relative augmentation performance was obtained at the lowest operating fill fraction, and the level of thrust augmentation was seen to have an inverse relation to fill fraction. The maximum recorded thrust augmentation was with the longest diverging ejector ($L_{EJECT}/D_{EJECT} = 5.62$) and was on the order of 65% of the baseline thrust (or $\Phi = 1.65$) at the fill fraction of 0.4. Doubling the fill fraction for this PDE-ejector system resulted in a decrease of the relative thrust augmentation to roughly 51% of the baseline thrust (or $\Phi = 1.51$). The straight ejectors did not perform as well as the diverging ejectors but had roughly the same dependency on fill fraction. For the shortest straight ejector ($L_{EJECT}/D_{EJECT} = 1.25$), negative thrust augmentation (or drag) was measured at the high fill-fraction conditions (ff > 0.8).
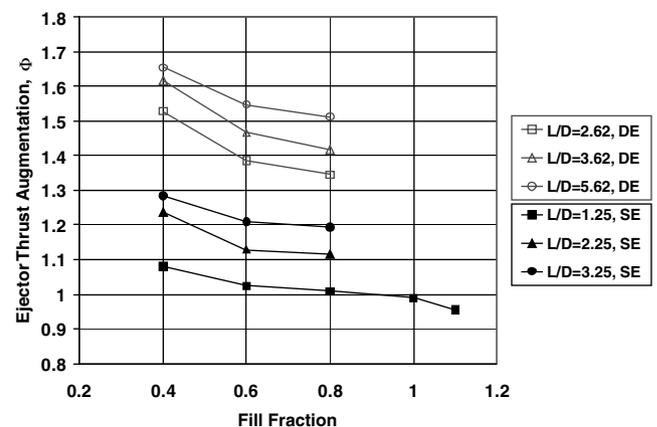

Fig. 4   Straight (SE) and diverging (DE) PDE-ejector thrust augmentation variation with fill fraction for three ejector L/D ratios ($DR = 2.75$, $x/D_{PDE} = +2.0$).

To obtain a better understanding of why the increased fill fraction resulted in reduced ejector performance, flow visualizations were performed on an optically accessible two-dimensional ejector of a similar geometry as those used in the current performance tests. Figures 5 and 6 are instantaneous snapshots of high-speed flame luminosity imaging and particle flow visualizations of the PDE ejector operating at a fill fraction of 1.0. The time corresponding to each image has been specified relative to the exiting of the detonation wave. Although these flow visualizations are qualitative, both visualization techniques clearly show a strong blast wave exiting the PDE and eventually impinging on the inlet surface of the ejector. The impingement of these high-pressure, high-temperature gases on the ejector inlet were believed to be a primary source of ejector drag (or negative thrust augmentation). As the fill fraction of the PDE was decreased, the strength of the blast wave and thus its induced drag contribution should also have decreased. In addition to the induced drag by the PDE blast wave, exhaust gases were observed to have been expelled out of the ejector inlet, with the level and duration of expelled flow decreasing as the fill fraction was reduced. This translated into negative entrainment during the early portion of the PDE cycle. Later in the PDE-ejector cycle, the flame and particle flow visualizations showed a positive direction of entrainment as depicted in Figs. 5 and 6. These observations were similar to those reported by Allgood et al. in a separate study [17].

C.   Effects of Ejector Length-to-Diameter Ratio

In addition to the operating condition of the PDE, the geometry of the ejector was seen to play an important role in the ejector performance. The lengths of the ejector were varied by changing the
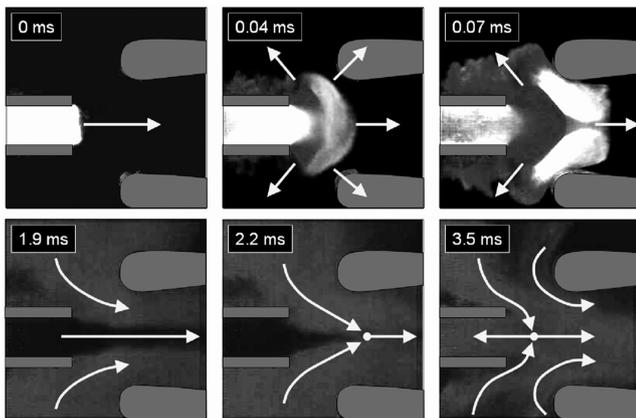

Fig. 5   High-speed flame luminosity imaging of a two-dimensional diverging PDE ejector; vectors indicate direction of visible flame propagation   ($L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}} = 2.9$, $DR = 2.2$, $x/D_{\mathrm{PDE}} = +1.0$, ff = 1.0).
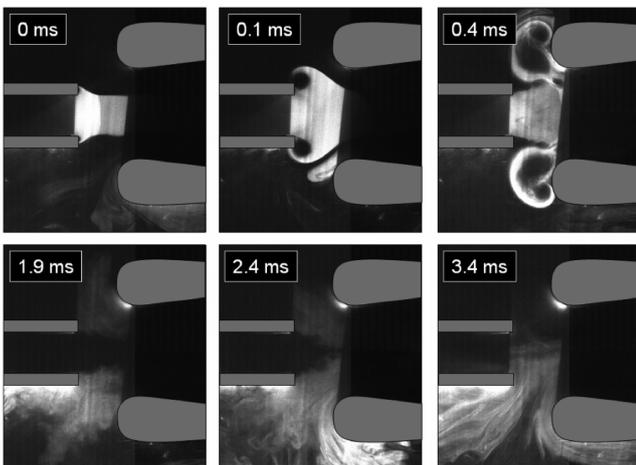

Fig. 6   Particle flow visualizations of a two-dimensional diverging PDE ejector ($L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}} = 2.9$, $DR = 2.2$, $x/D_{\mathrm{PDE}} = +1.0$, ff = 1.0).

length of the straight or straight-intermediate sections, as depicted in Fig. 1, while maintaining a constant diameter of 13.97 cm. Conventionally, ejector augmentation data have been plotted as a function of the ejector length-to-diameter ratio ($L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$). In Fig. 7, the PDE-ejector thrust augmentation of the current work has been plotted as a function of $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ along with other available data from PDE ejectors, pulsejet ejectors, and steady ejectors. Figure 7 shows that, for the straight PDE ejectors, an increase in $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio corresponded to an increase in the relative thrust augmentation. There existed a maximum at an $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio between 3 and 4. The PDE straight-ejector ($DR = 2.75$) thrust augmentation measured in the current study is in good agreement with those reported by Rasheed et al. [15] ($DR = 2.0$) for a fill fraction of 1.0. The largest straight ejector ($DR = 2.9$) tested by Rasheed et al. had a better performance than the current work's straight ejector ($DR = 2.75$), whereas their smallest straight ejector ($DR = 1.5$) showed very poor performance. No data were reported by Rasheed et al. for other fill fractions or ejector geometries.

The data plotted in Fig. 7 also include thrust augmentation values performed by Morrison [21] for straight-walled steady ejectors and diverging pulsejet ejectors. The straight steady-ejector augmentation levels agree very well with the current straight PDE-ejector data when the fill fraction was close to 1.0. A straight PDE ejector operating at a lower fill fraction was observed to outperform the steady ejector at a similar $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio.

The diverging PDE ejectors showed nearly twice as much thrust augmentation as the comparable straight PDE ejectors. This improvement with a diverging ejector was also reported by Lockwood [6]. The pulsejet ejectors tested by Lockwood were of a diverging type with the same 8 deg total angle used in the current work. However, the pulsejet ejectors appeared to outperform the PDE diverging ejectors and have a much smaller optimum $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio of about 1.5. The PDE diverging ejectors showed an increase in performance with increased length. The diverging PDE-ejector performance leveled off at an $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio around a value of 6.0, a value much greater than the optimum $L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}$ ratio of the straight PDE ejectors.

It has been demonstrated both numerically [3] and experimentally [4,22,23] that the fuel-based specific impulse of an air-breathing PDE varies inversely with the PDE fill fraction due to advantageous shock compression of the unfilled volume of the combustor by the detonation waves. This was also shown in Fig. 3 of the current paper. In theory, the partial-fill effect on PDE engine performance should be similar for a PDE-ejector system as well, because similar gas dynamics are occurring. To better understand and isolate the performance gains provided by the ejector, the authors have proposed a new nondimensional parameter ($\beta = L_{\mathrm{EJECT}}/D_{\mathrm{EJECT}}/$ff) to be used in plotting PDE-ejector thrust augmentation. Figure 8 shows that, when the current thrust augmentation data are plotted as a function of the PDE-ejector parameter β, the thrust augmentation collapses onto one performance curve for similar ejector types.
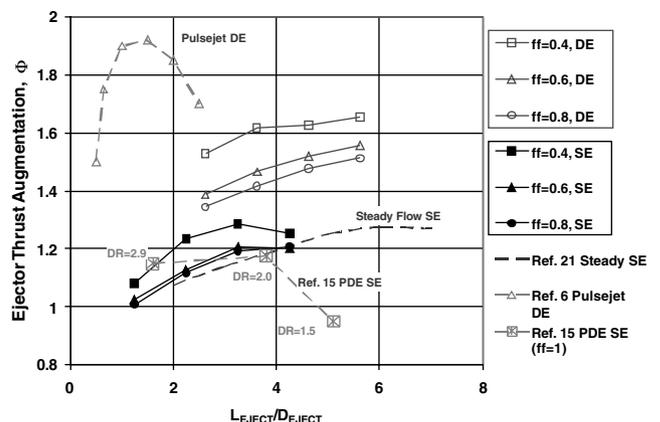

Fig. 7   Normalization of straight (SE) and diverging (DE) ejector performances using the ejector L/D ratio ($DR = 2.75$, $x/D_{\mathrm{PDE}} = +2.0$).
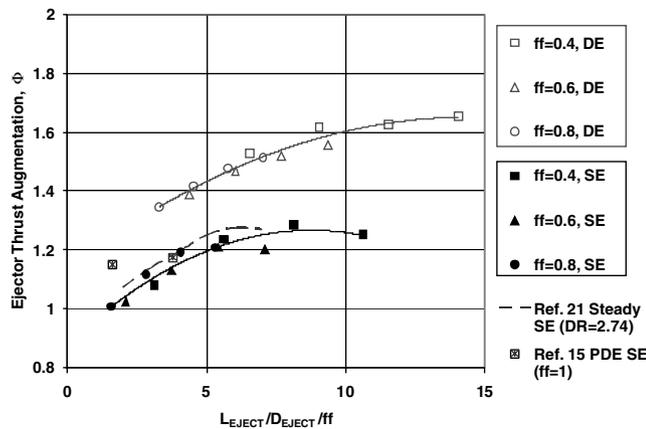
Fig. 8 Proposed normalization of PDE-ejector data for incorporating the PDE fill fraction ($DR = 2.75, x/D_{PDE} = +2.0$).

Fig. 9 Effects of axial position on diverging ejector performance for three operating fill fractions ($L_{EJECT}/D_{EJECT} = 5.62, DR = 2.75$).

However, different thrust augmentation performance curves exist for different ejector geometry types, such as straight or diverging ejectors. For example, Fig. 8 indicates that a better thrust augmentation curve was obtained for a 4 deg diverging PDE ejector than that of a straight PDE ejector. This was attributed to the additional thrust surface area that the divergence of the internal surface of the ejector provided (see Fig. 1). Each ejector performance curve also indicated there was a single optimum β value. This means that PDE-ejector performance is not only highly dependent on its length-to-diameter ratio as typical ejector systems, but also on the operating conditions of the PDE. Other engine operating conditions, such as equivalence ratio and frequency, will obviously affect PDE-ejector performance as well and should be investigated further. However, the preliminary data shown in Fig. 8 indicate that the correlation between straight steady ejectors (ff = 1.0) and straight PDE ejectors was quite reasonable. In addition, the PDE-ejector data provided by Rasheed et al. [15] also agreed reasonably well when plotted in this fashion.

D. Effects of Ejector Axial Position

Another geometrical parameter varied in these tests was the relative position of the ejector inlet to the exhaust of the PDE. All previous results reported in this paper were for an axial position of $x/D_{PDE} = 2.0$, meaning the ejector was placed a distance of two PDE diameters downstream of the PDE exit. However, many previous studies on ejectors showed that the augmentation is very sensitive to its axial location [6–8,16–19]. For this reason, the straight ejector ($L_{EJECT}/D_{EJECT} = 1.25$) and the diverging ejector ($L_{EJECT}/D_{EJECT} = 5.62$) were moved upstream and downstream of the PDE exhaust. In addition, because the results shown previously also indicated a strong dependence on fill fraction, the fill fraction was varied at each ejector axial position.

Figure 9 shows results for the diverging ejector at three operating fill fractions and for x/D_{PDE} locations extending from upstream of −2 to 4 diameters downstream. The sensitivity to axial location was most pronounced with the lower fill fraction of 0.4. For this operating condition, the optimum x/D_{PDE} was a downstream placement of +2 diameters. As the fill fraction was increased, the performance of the downstream ejector placements decreased relative to the upstream placements. At a fill fraction of 0.8, the optimum location was measured to be either inline or slightly upstream of the PDE exhaust. This effect can be attributed to the induced drag generated by the PDE wave, which was discussed earlier in the paper and is shown in Figs. 5 and 6. A downstream placement of the ejector at the lower fill fractions was more optimal because it did not experience as high of an induced wave drag, and it allowed the secondary flow to be more readily entrained without restrictions. This effect was also observed by Allgood et al. [17] in their PDE-ejector visualizations.

Figure 10 shows the relationship between the ejector thrust augmentation and the axial placement of the ejector and the PDE
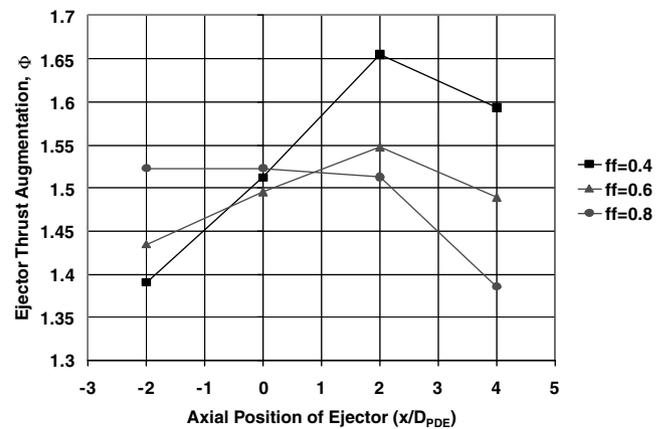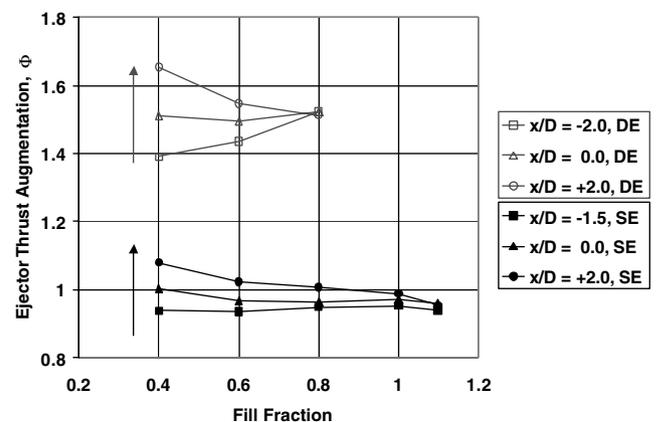

Fig. 10 Performance sensitivity of straight ($L_{EJECT}/D_{EJECT} = 1.25$) and diverging ($L_{EJECT}/D_{EJECT} = 5.62$) ejectors to the operating fill fraction (arrows indicate a positive downstream change in ejector axial position).

fill fraction. The thrust augmentation ratios are plotted as a function of fill fraction for three representative ejector axial placements: upstream, inline, and downstream. Both the straight and diverging ejector configurations showed that, as the fill fraction was increased, the downstream placement performance dropped and the upstream placement performance increased. This indicates again that the optimum axial placement of a PDE ejector is dependent on fill fraction. Furthermore, because both the diverging and straight ejector geometries showed very similar trends, the effect of fill fraction was most likely having a primary impact on the ejector bell mouth and not on the internal thrust surfaces. This conclusion is supported by the visualizations presented in Figs. 5 and 6.

IV. Conclusions

An experimental study of the performance of pulse detonation engine ejectors was performed. Time-averaged thrust augmentation produced by straight and diverging PDE ejectors was measured using a damped thrust stand. The ejector length-to-diameter ratio was varied from 1.25 to 5.62 by changing the length of the ejector while maintaining a nominal ejector-to-PDE diameter ratio of 2.75. The operating fill fraction was varied from 0.4 to 1.1. The PDE-ejector thrust augmentation was found to be strongly dependent on the operating fill fraction. A reduction in fill fraction corresponded to higher levels of ejector thrust augmentation for all L_{EJECT}/D_{EJECT} ratios tested and for both the straight and diverging ejectors. This improvement in ejector performance by operating at low fill-fraction conditions was attributed to a reduction in induced wave drag on the ejector inlet produced by the detonation blast waves. The diverging ejector geometry showed the best

performance due to increased thrust surface area. The diverging ejector produced a maximum of 65% thrust augmentation ($\Phi = 1.65$) compared to a 28% ($\Phi = 1.28$) thrust augmentation with the straight ejector at a fill fraction of 0.4.

In general, longer ejectors outperformed short ejectors. Ejectors with L_{EJECT}/D_{EJECT} ratios greater than 3.0 showed the best performance. For the case of the straight ejectors, maximum augmentation was observed for L_{EJECT}/D_{EJECT} ratios between 3 and 4. The diverging ejectors, however, did not show a maximum for the range of L_{EJECT}/D_{EJECT} ratios tested but began to level off at L_{EJECT}/D_{EJECT} ratios greater than 5.

The current results compared well with a limited set of PDE-ejector data [15,19]. However, the behavior and thrust augmentation of all PDE ejectors were inconsistent with reported deflagration pulsejet-ejector systems. This leads to the conclusion that, although there are some similarities between PDE and pulsejet driven ejectors, there can be a significant difference in the flow dynamics to warrant caution in grouping these two systems into the same classification. However, a new normalization parameter ($\beta = L_{EJECT}/D_{EJECT}/\text{ff}$) based on ejector length-to-diameter ratio and PDE fill fraction was proposed. Using this normalization parameter, the PDE-ejector performances for all fill fractions compared well with available steady ejector performances for the specific ejector geometries evaluated.

The axial placement of the ejector also greatly affected the performance of the PDE-ejector system. Unlike other ejector systems, a single optimum ejector placement for PDE applications was not found but rather a function of the operating fill fraction. The sensitivity of ejector augmentation to the axial placement was believed to be a result of a tradeoff between reduced detonation wave induced drag with upstream placement and increased mass entrainment with downstream placement. For most test conditions, a *downstream* ejector placement provided the best performance. However, as the operating fill fraction was increased (i.e., stronger blast waves), the relative performance of an upstream placement increased, whereas the performance of a downstream placement decreased. In contrast, the inline ejector placement performance was nearly independent of fill fraction.

Although these observations on the sensitivity of the ejector performance to axial placement are in qualitative agreement with the behavior reported by Glaser et al. [19], the optimum PDE-ejector placement has not been consistent in the reported literature, as was commented on in the recent work by Wilson et al. [18]. Despite this fact, what is consistent in all the reported studies performed on this subject, including the current paper, is that the optimum ejector axial placement is a strong function of the engine configuration and operating conditions (fill fraction [19], detonation frequency [18], etc.) and the ejector inlet and diffuser geometry [15,16,19]. This is a result of the augmentation being a strong function of the dynamics of the engine exhaust flow and its complex interactions with the ejector geometry.

Acknowledgments

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