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Performance Measurements of Multicycle Pulse-Detonation-Engine Exhaust Nozzles

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Performance measurements of multicycle pulse-detonation-engine (PDE) exhaust nozzles were obtained using a damped thrust stand. A pulse detonation engine of 1.88 m length was operated on a cycle frequency of 30 Hz at stoichiometric conditions. Both converging and diverging bell-shaped exhaust nozzles were tested for PDE fill-fractions ranging from 0.4 to 1.1. The area ratios of the nozzles were varied from 0.25 converging to 4.00 diverging. The nozzle length was negligible compared to the overall length of the PDE. The feasibility of normalizing the PDE nozzle thrust data was investigated by testing two different PDE combustion chamber diameters (2.54 and 5.08 cm) with the same nozzle area ratios. The optimum nozzle area ratio was found to be a function of the PDE fill-fraction. For fill-fractions at or below 0.5, the optimum configuration was a PDE without an exhaust nozzle. However, as the operating fill-fraction was increased to values close to or above one, thrust enhancement was obtained with a converging nozzle. The diverging nozzles also showed a relative increase in their performance with increased fill-fraction. Unlike the converging nozzles, the diverging nozzles and baseline configuration were observed to be sensitive to the ignition delay.

Nomenclature

AR	=	area ratio of nozzle (D_{nozz}^2/D_{comb}^2)
D_{comb}	=	PDE combustion chamber diameter
D_{nozz}	=	exhaust nozzle-exit diameter
ff	=	fill-fraction
Isp	=	fuel-based specific impulse
Isp_{ref}	=	reference fuel-based specific impulse
L_{comb}	=	PDE combustion chamber length
L_{nozz}	=	length of nozzle
M_{exit}	=	exit Mach number
T	=	thrust
T_{ref}	=	reference thrust
t	=	time
t_{cycle}	=	PDE cycle time
β	=	nozzle length ratio (L_{nozz}/L_{comb})

Introduction

PULSE detonation engines (PDE) use controlled periodic detonations of a combustible mixture to generate thrust.[1] Detonation combustion differs from the more commonly used deflagration combustion in that the fuel/oxidizer mixture is consumed much more rapidly because of the detonation flame front being closely coupled to a leading shock wave. The shock/flame front coupling is caused by a feedback mechanism between the temperature rise caused by the shock wave and the chemical energy release and gas expansion caused by the reaction. Originally, one of the primary motivations for PDE development was the theory that higher thermal efficiency could be achieved using detonation combustion.[1,2] However, the application of this theory assumes that a conventional steady-state thermodynamic analysis is appropriate for modeling a PDE.[3] Although recent experimental studies have reported competitive performance values for laboratory-scale PDEs compared to constant-pressure combustion-cycle engines,[4] the appropriateness of using a conventional thermodynamic analysis for the inherently unsteady PDE cycle is still in question.[5] Thus, one of the key technological challenges still facing researchers and engineers is to quantify the range of propulsive efficiencies for a practical PDE system.

Experimental and computational researchers have demonstrated some success in obtaining competitive specific impulse values with a simplistic PDE cycle.[4,6,7] 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.

Many operating parameters have been shown to drastically affect the performance of a PDE. For example, at a constant fill Mach number, PDE thrust has been observed to scale linearly with engine cycle frequency.[7] The linear behavior in net thrust was a result of a linear increase in the percentage of time at which the combustion chamber was at the detonation-induced elevated pressure. 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 combustion chamber before ignition. The ratio of the PDE combustion chamber filled with a detonable mixture relative to the total combustion chamber

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length 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. This performance gain observed at lower fill-fractions was attributed to the leading shock wave of the detonation front compressing the nonreactants occupying the remainder of the PDE combustion chamber.[7,8] Schauer et al.[7] demonstrated experimentally the performance benefits of partially filling the combustion chamber for a multicycle PDE operation. Their results showed the partial-fill effect being independent of PDE cycle frequency for a constant-area combustion chamber.

An alternative viewpoint of the partial-fill effect is that the thrust of a PDE can be increased by maintaining a constant amount of fuel-oxidizer mixture and simply adding additional length to the combustion chamber. The additional combustion chamber length can be viewed as a constant-area straight nozzle that alters the pressure relaxation process at the head wall of the PDE. When the detonation wave interacts with the interface separating reactive and nonreactive gases, a shock wave is transmitted into the nonreactive gas while a reflected wave propagates back toward the thrust surface. In most cases of interest to PDE applications, the reflected wave is an expansion wave. A second expansion wave is generated at the end of the combustion chamber when the shock wave reaches the sudden area change. This expansion also propagates back toward the thrust wall. Thus, by extending the length of the straight nozzle, the stronger exit-flow rarefaction waves can be delayed in time, thereby allowing a slower rate of pressure relaxation at the head wall of the PDE. Li and Kailasanath[8] have predicted that significant increases in peak impulse values can be obtained by increasing the length of a straight nozzle. However, although straight nozzles provide impressive performance benefits, they also limit the maximum cycle frequency of the PDE because of longer associated blowdown times.

More conventional nozzle geometries have also been shown to provide performance benefits for PDE applications. A very detailed review on the current level of PDE nozzle technology was given by Kailasanath.[4] The outcome of this review revealed some significant disagreements on the reported behavior of PDE nozzles. The source of the disagreements was attributed to the highly dynamic nature of the PDE and its sensitivity to the operating conditions. For example, most of the previous PDE nozzle research investigated the effects of nozzles that had relatively large lengths compared to the combustion chamber ($\beta = L_{\text{nozz}}/L_{\text{comb}} > 0.1$). Thus, for these nozzles of nonnegligible length, partial-fill effects will have a significant impact on the PDE performance and should be taken into consideration when interpreting the results. Another common difference observed between the various PDE nozzle studies was that most studies modeled single-cycle detonations, whereas very few looked at the behavior of a more practical multicycle operation.[4] These differences in PDE nozzle operating conditions lead to differing conclusions on an optimum nozzle geometry. Some highlights of these studies are discussed next.

Eidelman and Yang[9] modeled a series of straight, converging, and diverging nozzles for a PDE operating in a single-shot detonation mode. The fill and purging processes and multicycle effects were not modeled. In their study, the nozzles represented a significant portion of the PDE ($\beta = 0.167$–0.4) All nozzles showed an improvement over the baseline configuration without a nozzle, as a result of the partial-fill effect. Although the converging and straight nozzles increased the peak thrust (impulse), the peak thrust did not occur until much later during the cycle because of the increase in blowdown time. The diverging nozzles, on the other hand, increased the thrust of the PDE by converting the thermal energy of the underexpanded gases into kinetic energy, but produced the higher peak thrust levels at a faster rate as a result of an increased rate of expansion. The one drawback observed with diverging nozzles was that because of overexpansion inside the PDE the increased thrust surface area resulted in negative thrust later in the cycle. Despite this drawback, the bell-shaped diverging nozzle showed the best performance overall for this single-shot detonation operation.

Yungster[10] confirmed the results by Eidelman and Yang[9] in that a bell-shaped diverging nozzle performed the best and converging nozzles limit the operating frequency of the PDE. Yungster attributed the performance benefits of the bell-shaped nozzle over conical diverging nozzles to a slight minimization in overexpansion and therefore a reduction in negative thrust during the later stages of the blowdown process. The computations by Cambier and Tegner[11] also are in agreement that a bell-shaped diverging nozzle, with its associated negative curvature in the change in internal surface-area, performs better than a diverging nozzle with straight or positive surface-area curvature. However, one distinct difference in the PDE operation modeled by Cambier and Tegner[11] compared to the works already mentioned was that the relatively large nozzles were filled with a detonable mixture. Thus, unlike the previous studies Cambier and Tegner[11] predicted a decrease in specific impulse with diverging nozzles. This was because the thrust gain provided by the diverging nozzle did not overcome the cost of providing additional fuel mass to fill the diverging nozzle. This negligible benefit of using a diverging conical nozzle with a filled mixture was also predicted by Mohanraj and Merkle[12] and by Cooper et al.[13]

These and other PDE nozzle simulations have focused primarily on predicting simplistic single-shot PDE operations in which the subsonic fill and purge portions of a practical PDE cycle were not considered. In reality, the filling and purging processes of a multicycle operation are not insignificant portions of the cycle. Thus, although a diverging nozzle has been shown to expand the high-pressure detonation gases and provide additional thrust surface on which this pressure can act, the diverging nozzle will act as a diffuser during the remainder and perhaps majority of the cycle. Yungster[10] modeled the multicycle operation of PDE diverging nozzles and found that the first cycle showed nozzle thrust augmentation, but no augmentation was observed during the following second and third PDE cycles. The loss in thrust augmentation was attributed to the cold air that occupied the nozzle during the first cycle being replaced with low-density combustion products. Wu et al.[14] have also modeled such multicycle operations and have shown that the performance enhancements of diverging nozzles during the detonation phase of the PDE cycle did not have a significant impact on the overall system. Rather, they found that a converging nozzle is helpful in maintaining significant backpressure at altitude conditions. From these and other studies, it can be concluded that the subsonic filling and purge portions of the cycle can significantly contribute to the thrust of the PDE during multicycle operations and thus should be considered in the nozzle design.

Other benefits of using exhaust nozzles for PDE applications have been recently proposed by Kaemming and Dyer.[15] First, a converging exhaust nozzle for a PDE provided control over the pressurization inside the combustion chamber as in the case of a ramjet engine. By choking the exhaust flow, the Mach number and pressure inside the detonation chamber were independent of the flight speed and atmospheric conditions. If the pressure was not controlled, an increase in flight speed corresponded to an increase in the combustion chamber Mach number and a decrease in pressure inside the chamber. Kaemming and Dyer[15] performed a thermodynamic analysis showing that the efficiency of a PDE diminished without the converging exhaust nozzle controlling the chamber pressure. In addition to the thermodynamic effects of backpressurization, the converging section of an exhaust nozzle provided a means of controlling the frequency of the engine. For example, Kaemming and Dyer[15] have shown that a reduction in chamber pressure (increase in chamber Mach number) translated into an increase in the required operating frequency of the PDE engine. Because the PDE frequency has usually been controlled through valves, this lack of chamber pressure control might place an impossible requirement on the valve system. For these two reasons, an exhaust nozzle with a converging throat section appeared to be beneficial for PDE applications.

The current work is a unique experimental study of a multicycle PDE operation, in which gross thrust augmentation levels provided by various converging and diverging bell-shaped exhaust nozzles were quantified. The nozzle-area ratio was varied from 0.25 converging to 4.0 diverging. The nozzle length represented a negligible portion of the overall PDE length ($\beta < 0.042$). The PDE operated on a stoichiometric mixture of hydrogen air at a cycle frequency of 30 Hz.

The PDE cycle time was divided evenly between three stages: a fill stage, an ignition/detonation/blowdown stage, and a purge stage. For each nozzle configuration, the operating fill-fraction was varied to quantify their corresponding partial-fill effects. The PDE frequency and backpressure were held constant during testing, but because of their potential significant impact on an engine's performance should be investigated in future studies in order to fully understand the performance benefits of using exhaust nozzles for PDE applications.

Experimental Setup

Gross thrust measurements of a PDE were performed to quantify the effects of exhaust nozzle geometry on PDE performance. 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 cylindrical combustion chamber by way of a mechanical valve system constructed from a modified four-cylinder automotive head. In the standard automotive cycle, each cylinder has four ports, two for intake and two for exhaust. However, for the PDE operation, the two intake ports served to deliver the premixed hydrogen-air, while the two exhaust ports operated in reverse to deliver purge-air to purge the combustion chamber of hot gases after each detonation and before injecting a fresh mixture of reactants. The combustion gases exited from the exhaust end of the combustion chamber. The automotive valve system could be operated at frequencies up to 40 Hz. Because of the nature of automotive valving, the division of the cycle timing for various events such as fill time and purge time and detonation time were fixed to be each $\frac{1}{3}$ of the cycle. Only one of the four automotive valve sets was used to deliver mass flow to a single cylindrical combustion chamber. The hydrogen and air were metered through choked flow orifices, and the flow rate and pressure data were collected via a remote 5-MHz 16-channel analog-to-digital-converter system. For a more detailed description of the PDE test facility, the reader is referred to the recent paper by Schauer et al.[7]

For the current PDE nozzle performance tests, the pulse detonation engine was operated with a stoichiometric mixture of hydrogen and air. To determine the feasibility of normalizing PDE exhaust nozzle data based on the nozzle inlet-to-exit area ratio, two combustion chambers of 2.54 and 5.08 cm diameter (D_{comb}) were tested. Both PDE combustion chambers had a length of 1.88 m, and the PDE cycle frequency was kept constant at 30 Hz. Bell-shaped exhaust nozzles of area ratios ($AR = D_{\mathrm{nozz}}^2/D_{\mathrm{comb}}^2$) ranging from 0.25 converging to 4.0 diverging were tested. In all test cases, the nozzle length represented only 2–4% of the total length of the PDE. Nozzles of this length were chosen so as to limit the partial-fill effects introduced by adding the additional length to the PDE.

The two operating parameters varied during these tests were the fill-fraction (ff) and ignition delay. The fill-fraction was defined as the ratio of the combustion chamber volume initially filled with a detonable mixture compared to the total combustion chamber volume. The fill-fraction was varied from 0.4 to 1.1 for all nozzle configurations. The fill-fraction was determined by measuring the volume flow rates of the reactants using upstream choked flow nozzles. Because the maximum error in volume flow rate measurements was found to be $\pm 3\%$, the relative error in fill-fraction measurement was also $\pm 3\%$.

A purge-air cycle was added to cool the combustion chamber and provide a buffer between the hot combustion products and the fresh reactants being injected for the next cycle. Because of the automotive valve system that was used, $\frac{1}{3}$ of the cycle was allocated for purging. Similar to fill-fraction, the purge-fraction can be defined as the ratio of the combustion chamber filled with purge-air relative to the total combustion chamber volume. The purge-fraction was kept constant at 0.5 during all tests.

The ignition delay was defined as the time delay for the spark plug to ignite relative to the closing of the valves. Because of the response of the valve system, the ignition delay could not be set below a value of 0.5 ms without the risk of a backfire upstream into the injection manifold. The maximum delay time was set by the 30-Hz cycle frequency of the PDE. For the ignition delay studies, the delay time was varied from 0.5 to 7.5 ms for the baseline configuration of a PDE without an exhaust nozzle and for two representative converging ($AR = 0.25$) and diverging ($AR = 4.0$) nozzles. A maximum ignition delay of 7.5 ms allowed a sufficient amount of time (3.5 ms) for the deflagration-to-detonation transition (DDT) and blowdown to occur before the purge-air entered the combustion chamber. All other nozzle tests were performed at a baseline ignition delay of 0.5 ms.

The DDT of the hydrogen-air mixture was enhanced by the use of Shchelkin-type spirals of 0.3 m length for both the 2.54-cm- and 5.08-cm-diam combustion chambers. The Shchelkin spiral occupied only 16% of the total combustion chamber length. Two pressure transducers (PCB M102A) were mounted 0.15 m apart to monitor detonation wave speeds and validate that Chapman–Jouguet (CJ) 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 detonation wave speed measured for both combustion chambers 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 CJ wave speed of 1966 m/s for a stoichiometric hydrogen-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 pillow-block bearings (Thompson Industries M/N SPB-16-0PN) riding along a pair of 25.4-mm-diam linear bearing rails (Thompson Industries P/N SR-16). 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 pneumatic actuator (Bimba M/N 096-DXDEH) at an oscillation rate of 0.3 Hz. The linear actuator was a double acting balanced actuator that applied the same force in both directions for a set flow rate of air. The air pressure was generally set to deliver a ± 25.4-mm travel distance. Because the actuator produced a net zero average force, the average position of the thrust stand was solely a function of the engine average thrust. A displacement sensor (Data Instruments P/N DCFS4) with a 101.6-mm stroke was used to measure the position of the thrust stand as a function of time. The frequency response of the displacement sensor was from dc to 10,000 Hz. The output of the displacement sensor was electrically filtered to remove spurious noise and isolate only the dc component of the signal that corresponded to the average position (or thrust) of the engine. Because of the time constant inherent in the filtering process and the time required to obtain an accurate measure of the average displacement of the 0.3 Hz oscillating thrust stand, a run time of at least 10 s would theoretically be needed. In practice however, run times on the order of 20 to 30 s were required to reach a steady-state average thrust measurement.

Calibration of the thrust stand position as function of applied load was obtained by placing static weights on a pulley/cable system and recording the time-averaged output of the displacement sensor. The procedure used in the calibration was to load the thrust stand from a zero applied load to a value above the maximum expected thrust level of the PDE. The applied loads were then removed sequentially to determine if any hysteresis effects were present. 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.

Results and Discussion

Baseline Configuration

The selected baseline configuration for the nozzle tests was the 1.88-m-length combustion chamber (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 gross thrust values for the baseline PDE configuration

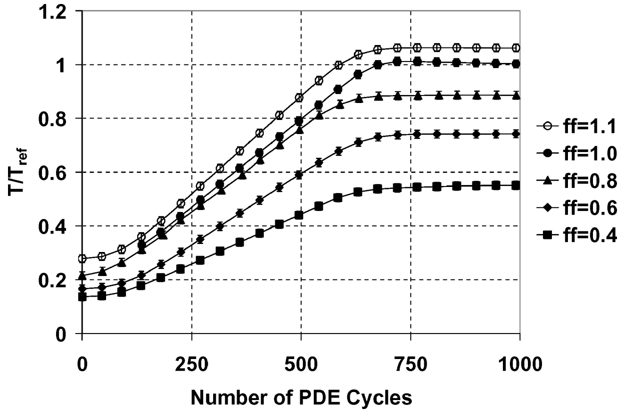

Fig. 1 Normalized PDE average-thrust measurements as a function of number of PDE cycles ($AR = 1.0$, $D_{comb} = 5.08$ cm, $T_{ref} = 77$ N).

are given in Fig. 1 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. All reported thrust values in the current work correspond to the gross thrust of the engine, and no correction of the data for changes in the fill/purge stream thrust has been performed.

A transient delay between the first PDE cycle during each test and the time when a near steady-state thrust level was observed. Figure 1 shows this time delay to be approximately 30 s, or 1000 PDE cycles, for all fill-fractions tested. The transient delay was a direct result of the 0.3-Hz oscillating thrust stand, the signal filtering process, and the averaging used to obtain the thrust measurements. Although the wall temperature was not recorded, the extended run time required to obtain a steady-state average thrust also allowed time for the PDE to come to thermal equilibrium. All thrust data presented in this paper correspond to the average plateau in thrust recorded after the PDE had been operating continuously for approximately 1000 PDE cycles.

The variation in thrust with fill-fraction can be inferred from Fig. 1. An increase in fill-fraction resulted in higher average thrust values. The thrust increased nonlinearly with fill-fraction as a result of the shock compression of the nonreactant gases occupying the remainder of the PDE combustion chamber as has been reported previously in literature. However, the thrust continued to increase at fill-fractions above 1.0 because of the increase in mass flow rates and the fact that the reactants were not of a uniform stoichiometric mixture inside the PDE. Previous studies have suggested that the fuel-air mixture becomes leaner near the exit of the PDE because of a dynamic effect of entrainment of ambient air back into the PDE combustion chamber during the unsteady filling process.[7] Overfilling the PDE can also have a dramatic impact on the performance when an excessively large exhaust nozzle ($\beta > 0.1$) is present as a result of the nozzle being occupied by reactant gases vs nonreactant or product gases.[4]

The current baseline data have been compared to previously reported PDE data by plotting the variation in fuel-based specific impulse with fill-fraction as shown in Fig. 2. The general trend of a nonlinear increase in fuel-based specific impulse with decreased fill-fraction was consistent with those found by other researchers. This behavior has been directly attributed to shock compression of the gases occupying the unfilled portion of the combustion chamber as discussed earlier in this paper. Essentially, the leading shock wave of the detonation served to compress the gases occupying the unfilled portion of the combustion chamber (straight nozzle) thereby maintaining the pressure inside the combustion chamber for a longer duration. This increased blowdown time with a straight nozzle resulted in higher thrust than would have been observed without the straight nozzle present. As a result of the PDE thrust levels decreasing at a slower rate than the reduction in fuel mass flow rate associated with reduced fill-fraction, the fuel-based specific impulse

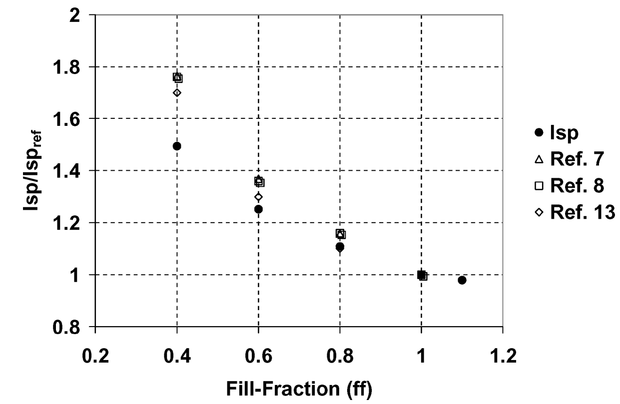

Fig. 2 Normalized fuel-based specific impulse as a function of fill-fraction for the baseline configuration ($AR = 1.0$, $D_{comb} = 5.08$ cm) (Isp_{ref} corresponds to Isp @ ff = 1.0).

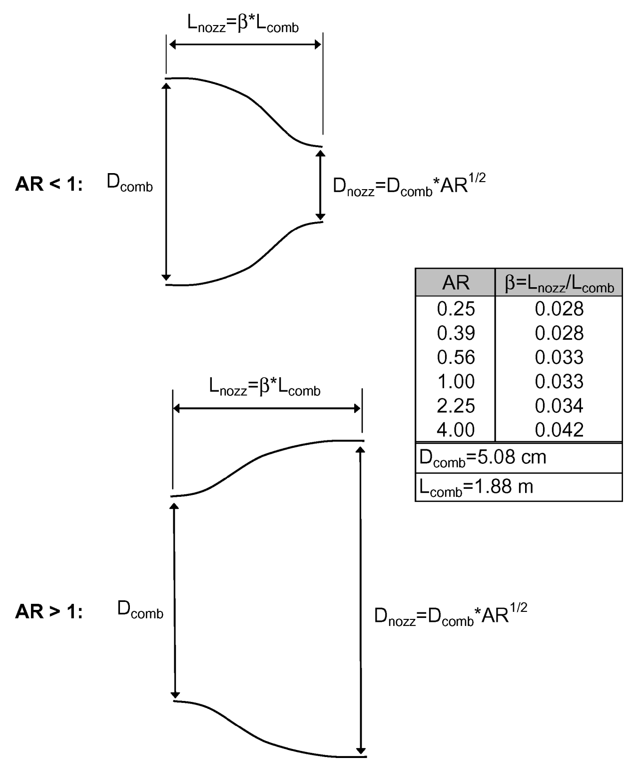

Fig. 3 Converging and diverging nozzle cross-sectional schematics and dimensions.

values increased as shown in Fig. 2. Although the current results ($Isp_{ref} = 2600$ s) were lower than other reported relative specific impulse values, specifically at the lowest fill-fraction, the important performance variation with partial fill-fraction was captured in the current work.

Effects of Nozzle-Area Ratio

The effects of converging and diverging bell-shaped exhaust nozzles on PDE thrust were measured. Figure 3 shows representative schematic drawings for the exhaust nozzles and their respective dimensions. The area ratios of the nozzles tested were 0.25, 0.39, 0.56, 1.0, 2.25, and 4.0, where ratios less than one are converging nozzles and greater than one are diverging nozzles. The nozzle lengths ranged from 5.2 to 7.8 cm in length, and therefore only extended the total length of the PDE by a maximum of 4% (or $\beta = 0.04$). Because $\beta < 0.1$ and the uncertainty in fill-fractions has been reported to be $\pm 3\%$, the partial-fill effect of adding these exhaust nozzles was negligible. The PDE was operated at the baseline operating conditions of a stoichiometric fuel-air mixture and cycle frequency of 30 Hz.

Table 1 Total reactant mass flow rates and Mach numbers during fill portion of cycle

Fill-fraction	Total reactant mass flow rate, kg/s	M_{exit}					
		$AR = 0.25$	$AR = 0.39$	$AR = 0.56$	$AR = 1.0$	$AR = 2.25$	$AR = 4.0$
0.4	0.042	0.201	0.129	0.090	0.050	0.022	0.013
0.6	0.064	0.307	0.197	0.137	0.077	0.034	0.019
0.8	0.085	0.411	0.263	0.183	0.103	0.046	0.026
1.0	0.107	0.513	0.329	0.229	0.128	0.057	0.032
1.1	0.116	0.560	0.359	0.250	0.140	0.062	0.035

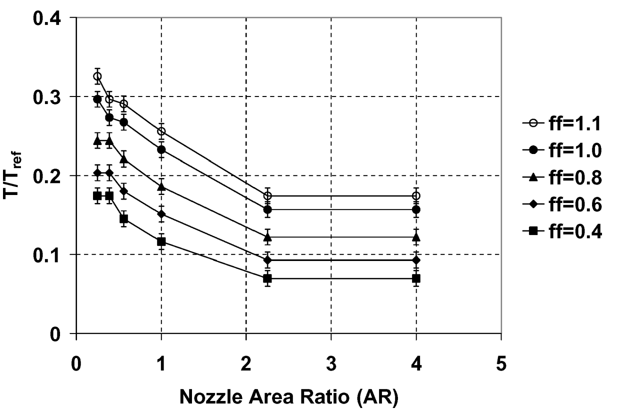

Fig. 4 Normalized PDE cold-flow thrust as a function of nozzle area ratio ($D_{comb} = 5.08$ cm, $T_{ref} = 77$ N).

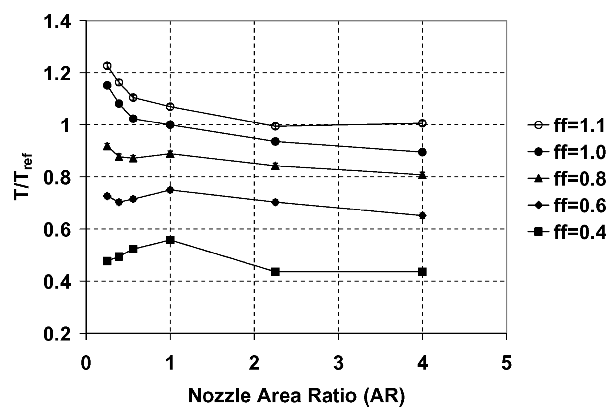

Fig. 5 Normalized PDE thrust as a function of nozzle area ratio ($D_{comb} = 5.08$ cm, $T_{ref} = 77$ N).

Two-thirds (22 ms) of the PDE cycle involved filling the combustion chamber with reactants and purge gases at subsonic speeds. Initial cold-flow tests were performed to determine the effect of exhaust nozzles on these subsonic portions of the cycle. The cold-flow thrust measurements were performed at the same operating conditions and configurations as in the "hot" detonation cases but without igniting the mixture. The mass flow rates of the fill gases for each fill-fraction are given in Table 1 along with the exit Mach numbers for the baseline ($AR = 1.0$), most convergent nozzle ($AR = 0.25$), and most divergent nozzle ($AR = 4.0$). These data were provided to show the span from maximum ($AR = 0.25$) to minimum ($AR = 4.0$) exit Mach numbers during the filling process for the current test conditions. Table 1 shows that all exit Mach numbers associated with the fill portion of the cycle corresponded to subsonic Mach numbers. Although the majority of the Mach numbers were below a value of 0.3, the convergent nozzle did accelerate the fill gases to Mach numbers as high as 0.56. Thus, compressibility effects were present for these test conditions, but no exhaust nozzles produced choked conditions during the filling and purging portions of the cycle. In addition to the filling process, a constant purge fraction of 0.5 was used during purging producing a constant purge gas (air) mass flow rate of 0.073 kg/s for all test conditions.

The cold-flow thrust measurements are shown in Fig. 4. For all tested fill-fractions, a decrease in nozzle area ratio resulted in an increase in thrust. Because it has been established that the cold-flow exhaust was subsonic through the nozzles for all test conditions, convergent nozzles ($AR < 1.0$) were accelerating the exhaust flow during the filling and purging portions of the cycle while divergent nozzles ($AR > 1.0$) decelerated these gases. A linear rate of increase in thrust with contracting area ratio is shown in Fig. 4 for the intermediate nozzle-area ratios of 0.56, 1.0, and 2.25. However, this linear variation deviated for the smallest convergent nozzle of $AR = 0.25$ and the largest divergent nozzle of $AR = 4.0$. The large divergent nozzle most likely did not continue to cause a linear decrease in thrust because of increased flow separation from the walls, which is commonly observed from such a larger bell-shaped nozzle. Thus, interpretation of this large area-ratio nozzle data is questionable. Compressibility effects and increased profile drag were believed to cause the deviation from linear behavior for the smallest area ratio converging nozzle.

In addition to the importance of documenting the variation of cold-flow thrust with nozzle-area ratio, it was also important to quantify the contribution of the filling and purging cycles to the overall thrust of the engine. Figure 4 shows that the cold-flow air thrust for the baseline configuration represented between 10 to 30% of the total hot thrust (reference thrust). This signifies that the subsonic gas flows occurring during the PDE cycle were substantially affecting the overall PDE performance. Thus, for PDE applications all portions of the cycle should be considered when selecting the appropriate nozzle design.

Once the cold-flow PDE thrust measurements were completed, the reacting-flow PDE thrust measurements were obtained for each nozzle/fill-fraction combination. The results of these tests are plotted in Fig. 5. For both the cold-flow and reacting-flow conditions, all nozzles tested exhibited an increase in thrust with a decrease in nozzle area ratio when the operating fill-fractions were above 0.8. This was the same trend observed in the cold-flow tests. However, at fill-fractions below 0.8, the converging nozzles were observed to decrease the thrust of the PDE. This shift in converging nozzle performance with reduced fill-fraction was believed to be caused by the converging nozzle having less effect on the blowdown process because of the reduced combustion chamber pressures and the negative effect of its profile drag playing a dominant role in the overall nozzle performance. On the other hand, the sensitivity of the diverging nozzles to area ratio did not appear to change with fill-fraction. All diverging nozzles at all fill-fractions were observed to have performance degradations with increased nozzle-area ratio. The maximum diverging nozzle performance loss was approximately 20% and occurred at a fill-fraction 0.4.

The fill-fraction condition of 1.1 generated more thrust than the $ff = 1.0$ despite the fact the PDE was overfilled. This was a result of two factors. First, an increase in the fill gas flow rates caused an increase in thrust as was shown in the cold-flow tests. Second, because the filling process involved a very dynamic process, the PDE had a tendency to have a lower equivalence ratio near the end of the PDE as a result of oscillating entrainment of ambient air into the PDE combustion chamber. By slightly overfilling the PDE, the mixture equivalence ratio near the open end of the PDE chamber was more likely to be close to the desired stoichiometric conditions.

The similarity between the cold flow (Fig. 4) and the reacting flow (Fig. 5) thrust profiles further suggests that the nozzle

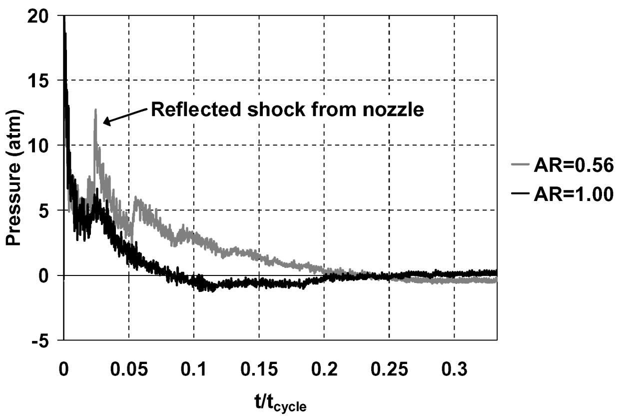

Fig. 6 Pressure-time traces for the baseline and $AR = 0.56$ converging nozzle (ff = 1.0, tcycle = 0.033 s).

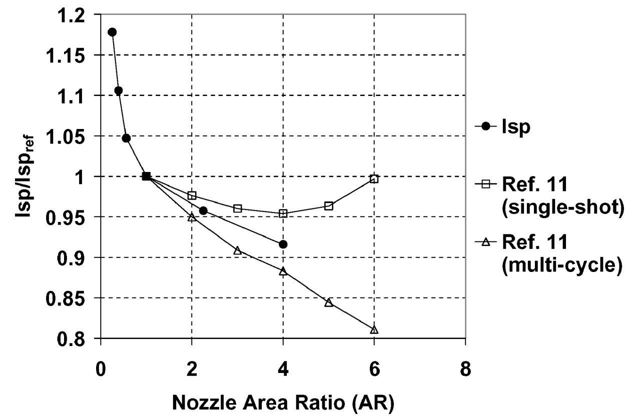

Fig. 7 Normalized fuel-based specific impulse as a function of nozzle area ratio (ff = 1.0, $D_{comb} = 5.08$ cm).

performances were being influenced substantially by the subsonic portions of the PDE. However, the filling and purge portions of the PDE cycle were not the only important factors that governed the PDE-nozzle performance. To demonstrate the effect of a nozzle on the entire PDE cycle, example combustion chamber pressure-time traces for two nozzle configurations ($AR = 1.0$ and 0.56) have been plotted in Fig. 6 for a fill-fraction of 1.0. These two configurations represent a comparison between the baseline configuration and a converging nozzle case that produced an increase in blowdown duration. The pressure data in Fig. 6 have been plotted as a function of normalized time (time divided by the cycle time of 33.3 ms). A comparison between the two pressure traces shows that additional thrust was provided by the converging nozzle because of the pressure rise inside the PDE combustion chamber and the associated increase in blowdown time. The additional compression inside the combustion chamber was a result of the leading shock wave of the detonation front reflecting from the converging walls of the nozzle back to the headwall of the PDE. Figure 6 shows that the pressure inside the PDE was near or below atmospheric pressure for more than 80% of the PDE cycle, or 26.4 ms. In comparison, it can be inferred from the baseline pressure trace that the exhaust flow was subsonic for more than 92% of the total PDE cycle, or 30.36 ms. In either case, the exhaust flow was only choked during a small portion of the entire cycle. This pressure data along with the hot- and cold-flow thrust measurements demonstrate that a convergent nozzle can outperform a diverging nozzle by increasing the headwall pressure during combustion and thereby increase the blowdown time during expansion. In addition to this thrust contribution of a convergent nozzle, the exhaust velocity during the purge and fill portions of the PDE cycle was also increased.

To demonstrate the performance effects of PDE exhaust nozzles for multicycle PDE operations, the current nozzle data were compared to data available in the literature by plotting the variation in fuel-based specific impulse as a function of nozzle area ratio for a fill-fraction of 1.0. Figure 7 shows that in the current study a significant enhancement in the PDE performance with a convergent nozzle was observed, whereas the divergent nozzles produced a loss in the overall engine performance for the range of tested nozzle-area ratios. This behavior was consistent with computational simulations performed by Cambier and Tegner.[11] Their studies showed that a loss in engine performance was associated with increasingly divergent nozzles for multicycle PDE operations. In addition to changes in the combustion chamber pressure-time behavior, this loss in thrust with the excessively large diverging nozzles could be a result of increased flow separation from the nozzle walls in both the current study and the referenced work. In addition, Cambier and Tegner[11] further demonstrated that a single-shot PDE operation can have different behavior because of the cycle-to-cycle variations of the gaseous mixtures inside the PDE combustion chamber and nozzles. This is also in agreement with the observations and conclusions reported in the current study.

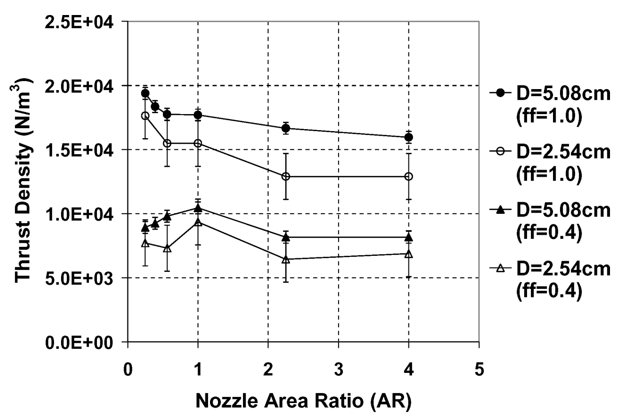

Fig. 8 PDE thrust density for two PDE combustion chambers ($D_{comb} = 2.54$ cm: $L_{comb} = 1.88$ m, $T_{ref} = 16$ N) and ($D_{comb} = 5.08$ cm: $L_{comb} = 1.88$ m, $T_{ref} = 77$ N).

Scalability and Normalization of PDE Nozzle Thrust Data

It was desired to determine whether the PDE exhaust nozzle thrust scales with the initial PDE combustion chamber diameter. To be more precise, the question to be answered was whether the nozzle area ratio was the appropriate normalization for the thrust data. Figure 8 is a plot of nozzle thrust measurements that were made on both a 2.54-cm-diam combustion chamber and a 5.08-cm-diam combustion chamber, which is associated with the data that have been discussed in the paper as of this point. Both combustion chambers had lengths of 1.88 m. Both sets of converging and diverging nozzles were similar in shape and length. To compare the thrust profiles obtained for these two configurations, the thrust values in Fig. 8 were converted to a thrust density, where thrust density has been defined as the ratio of the thrust to the volume of the combustion chamber. The error bars associated with each data point have been included in Fig. 8. Larger uncertainty was associated with the low thrust level measurements of the 2.54-cm-diam combustion chamber. Despite this uncertainty in the measurements, the comparison in thrust densities for these two combustion chamber diameters shows qualitatively that the nozzle performance was independent of the PDE combustion chamber diameter. Specifically, the relative variation in thrust density with nozzle area ratio was consistent for both combustion chamber diameters operating at a representative underfilled PDE condition (ff = 0.4) and a completely filled PDE. There was an absolute offset in thrust density between the two combustion chamber diameters demonstrating that the absolute variation in thrust density was not scalable in these tests. However, the relative variation in thrust density with nozzle area ratio was consistent and is therefore believed to be an appropriate normalization for comparing the relative changes in PDE nozzle data.

Effects of Ignition Delay

Ignition delay has been shown by researchers to play an important role in the performance of a pulse detonation engine when there are strong pressure oscillations occurring inside the combustion chamber prior to ignition.[7] The sensitivity of thrust to the initial pressure has been contributed by Schauer et al.[7] to the pressure effects on the DDT process. Igniting the mixture when the local gases are at a state of higher pressure can result in reduced DDT times[16–22] and higher thrust. However, igniting when the local pressure is at a minimum can increase DDT times and reduce the thrust. Pressure oscillations can occur inside the PDE because of excitation of a fundamental acoustic mode or by forced excitation of the fuel-air valve system, which can commonly occur in multicycle PDE operations. Thus, the relative timing of ignition to the local pressure can have a significant impact on the PDE performance.

Another possible cause for the sensitivity of a PDE thrust to the acoustic pressure dynamics is that an increase in overall combustion chamber pressure corresponds to an increase in propellant density. Thus, because thrust scales with the propellant density, timing the ignition relative to the chamber pressure fluctuations can affect the PDE thrust in addition to the DDT effects. Furthermore, the convergent exhaust nozzles create a backpressurization (propellant density increase) that can significantly impact the thrust of the engine. The purpose of the current work was to quantify the overall effect of the ignition delay for various exhaust nozzles on the gross thrust of the engine. The specific relative contribution of the DDT effects, propellant density modifications, and backpressurization will be examined in future studies.

To determine the effects of ignition delay on the current PDE nozzle configurations, the ignition timing relative to the closing of the valves was varied from 0.5 to 7.5 ms for nozzles with area ratios of 0.25, 1.0, and 4.0. The fill-fraction was held constant at 1.0. These configurations and test conditions were selected to be representative of a typical converging, baseline, and diverging PDE nozzle system's response to changes ignition delay. The minimum ignition delay time was set by the response of the current valve system and could not be set below this value without resulting in a backfire upstream of the valves into the fuel-air premixed injection chamber. The maximum ignition delay time was chosen to be 7.5 ms so as to not allow the blowdown to extend into the PDE purge cycle.

The normalized thrust as a function of ignition delay is plotted in Fig. 9. The baseline PDE thrust has a sinusoidal-type behavior with changes in ignition delay resulting in a maximum of +8% deviation from the average thrust at the best delay and a −5% thrust deviation at the worst ignition delay. The large amplification in PDE thrust was presumably from igniting at a time in the cycle when there was a local compression wave near the ignition region, whereas the attenuation in thrust was a result of the ignition occurring while there was a local expansion wave present.[7] The sinusoidal-type behavior was caused by the acoustic properties of the closed/open-ended combustion chamber. The diverging nozzle configuration also had a sinusoidal-type variation in thrust with ignition delay. The diverging nozzle ($AR = 4.0$) thrust appeared to vary nearly in phase and with similar amplitude of deviation from its mean thrust as that of the baseline configuration. On the other hand, the converging nozzle with $AR = 0.25$ appeared to vary out of phase with respect to the baseline and diverging nozzle cases.

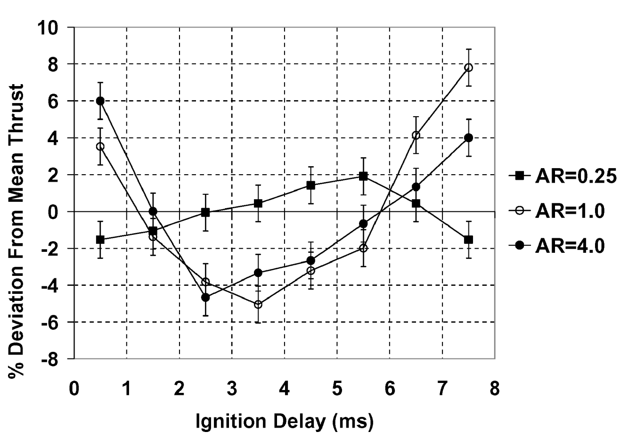

Fig. 9 Variation in PDE thrust with ignition delay (D_{comb} = 5.08 cm, ff = 1.0).

The sensitivity of thrust to ignition delay was believed to be a direct result of the propagation of expansion/compression waves inside the PDE. Expansion waves reflect as compression waves near the open end of the PDE for the baseline configuration and the diverging nozzles. This explains the similarities between the baseline and diverging nozzle sensitivity to ignition delay. However, the convergent nozzles have an opposite boundary condition in which expansion waves reflect as expansion waves. Thus, the convergent nozzles were observed to be less sensitive to ignition delay and out of phase with respect to the baseline and divergent nozzles. Also, the level of deviations from its average thrust was much less (approximately ±2%) for the convergent nozzles presumably because of the constriction in the PDE exit area dampening the pressure oscillations inside the combustion chamber.

Conclusions

Performance measurements of pulse-detonation-engine (PDE) exhaust nozzles were obtained using a damped thrust stand. A pulse detonation engine of 1.88 m length was operated on a cycle frequency of 30 Hz at stoichiometric conditions. Both converging and diverging bell-shaped exhaust nozzles were tested for fill-fractions ranging from 0.4 to 1.1. The length of the nozzles represented only about 2–3% of the total length of the PDE. The area ratio of the nozzle was varied from 0.25 converging to 4.00 diverging. Qualitatively, the variation in PDE thrust density with nozzle area ratio was consistent for the two PDE combustion chamber diameters (2.54 and 5.08 cm) tested. The optimum nozzle area ratio was found to be a function of the fill-fraction. For fill-fractions at or below 0.5, the optimum configuration was a PDE without an exhaust nozzle. However, as the operating fill-fraction was increased to values close to or above one, thrust enhancement was obtained with a converging nozzle. The diverging nozzles showed a relative increase in their performance with increased fill-fraction as well. The baseline and diverging nozzle configurations tested were observed to be sensitive to the ignition delay, but the converging nozzle geometry was observed to dampen out any pressure wave dynamics that would alter the ignition/DDT process.

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