EXPERIMENTAL INVESTIGATION OF THRUST AUGMENTATION BY EJECTORS ON A PULSE DETONATION ENGINE

by

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Utilizing gasoline as the fuel, air as oxidizer, a series of multi-cycle detonation experiments was conducted to study thrust augmentation by pulse detonation engine driven ejectors. The straight cylindrical ejectors with different inner diameter, length, and inlet geometry were designed. The effects of the axial location of the ejectors relative to the end of the detonation tube, ejector length to diameter ratio on thrust augmentation were investigated, with the operating frequency of 25 Hz. A peak thrust augmentation level of 80.5% was achieved by adding an ejector to the exit of the detonation tube. Performance measurements of the pulse detonation engine ejector system showed that thrust augmentation is a strong function of the ejector axial position. The result indicated that there exists a maximum thrust augmentation with ejector upstream of the detonation tube exit at least. The exact location at which the maximum thrust augmentation was obtained varies with the ejector to the pulse detonation engine diameter ratio and the ejector inlet geometry. With the increase of the length-to-diameter ratio, thrust augmentation was noticeably enhanced and finally tended to a constant. There exists an optimum ejector length. In the present study, the optimum length to diameter ratio of ejector was 4.58. Furthermore, the effect of operating frequency on ejector thrust augmentation also investigated. The operating frequency was varied from 15 Hz to 35 Hz.

Key words: *pulse detonation engine, thrust augmentation, ejectors*

Introduction

A pulse detonation engine (PDE) [1-4] is a propulsion system utilizing repetitive detonations to produce thrust or power. It differs from conventional systems in two major ways: unsteady operation and detonation combustion. Over the last decade, PDE has attracted considerable attention because of its potential advantages in thermodynamic cycle efficiency, hardware simplicity, operation stability, and reliability. Despite extensive research in PDE over the past several decades, it is not yet to be used in practical volume-limited propulsion applications. When the detonation products are directly exhausted from the detonation tube to the ambient environment, a great part of the available internal energy is still not converted into the kinetic energy to produce the propulsive thrust. To develop a practical PDE with high performance, many methods are proposed to increase the thrust, including by adding an ejector [5].

An ejector is a coaxial duct that is placed around the exhaust of an engine to direct the entrainment of the surrounding air flow into the engine exhaust stream. The engine exhaust is re-

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ferred to as the primary flow, while the entrained air inflow is the secondary flow. The theory and application of steady-flow ejectors are well established [6, 7]. For a conventional jet engine, adding an ejector can enhance thrust at low speeds by adding momentum to the entrained air flow [8]. In this situation, the mechanism of energy transfer is due to viscous shear mixing. However, the application of ejectors to unsteady primary flows is less common. Several studies [9-14] have examined unsteady-flow ejectors driven by pulse jets or other non-detonation devices by which the primary airflow was interrupted. The results indicate that unsteady-flow ejectors are dominated by flow mechanisms different from those seen in steady-flow ejectors and unsteady-flow ejectors tend to produce more thrust augmentation than steady-flow ejectors. Lockwood [9] attributed the unsteady-flow ejector performance to a more efficient energy transfer process between the primary flow and the secondary (entrained) flow through inviscid processes. Because of the unsteady nature of PDE, a PDE-driven ejector could have the potential to be highly effective at providing thrust augmentation.

A few experimental studies of PDE ejectors [15-24] have recently been reported. Experimental results [19-24] have confirmed that PDE-driven ejectors are extremely effective in thrust augmentation. Wilson *et al.* [19] had achieved thrust augmentation as high as 150% with a tapered ejector, using stoichiometric air-hydrogen mixture and operating at 20 Hz. Previous studies investigated the effects of ejector geometry and placement on ejector performance. Allgood *et al.* [20] made a good summary of those relevant literatures. Because the inlet is an aerodynamic surface that guides the entrainment of the surrounding mass flow, the shape of the ejector inlet is very important in determining the ejector performance. Allgood *et al.* [15] 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. Hence, the ejectors with a bell-shaped contour inlet or a rounded inlet were adopted in the current study. Both the relative size of the ejector to the primary flow driver and the ejector length-to-diameter ratio are also known to have influences on ejector performance. An optimum ejector-to-driver diameter ratio corresponding to a peak thrust augmentation level has been observed for a variety of ejector systems [9, 10, 19]. Typical reported values of optimum diameter ratios range between 2.4 and 3.5 [20]. In the present study, one set of ejectors with the ejector-to-PDE diameter ratio of 2.0, 2.5, and 2.8 were tested. Some results [9, 14, 19, 20] indicated that there existed an optimum ejector length corresponding to a peak thrust augmentation level, and the values of optimum ejector length-to-diameter ratio vary from 1.5 to 9, while some results showed that the thrust augmentation increased with ejector length [18]. Therefore, the effect of ejector length on thrust augmentation is still worth to being investigated. Experimental results have shown that ejector performance is extremely sensitive to the axial position of the ejector inlet relative to the detonation tube exit. As for thrust augmentation as a function of ejector entrance to detonation tube exit distance, however, there exist conflicting results. Thus it seemed useful to investigate this phenomenon. Some researchers [20-22] have found a maximum with ejector downstream of the detonation tube exit, other with it upstream [23]. A study by Wilson *et al.* [19] showed that there exist two maxima, one with ejector entrance upstream, and one downstream, of the detonation tube exit. It should be noticed that the maximum thrust augmentation was still located at the upstream of the detonation exit in the whole range of the ejector axial position tested by Wilson *et al.* [19]. Furthermore, previous experiments indicated that many operating parameters such as the PDE cycle frequency [19, 24] and fill fraction [20] affect the PDE-ejector performance as well. However, the fuels used in these previous experiments [15-24] were gaseous, despite liquid hydrocarbon being the preferable fuel for a practical propulsion system. Therefore, in the current study, liquid

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gasoline was chosen as the fuel and the effect of operating frequency on thrust of PDE with an ejector and without an ejector.

A preliminary experimental investigation of the ejector performance on a multi-cycle gasoline/air pulse detonation engine is performed, which include the axial location of the ejectors relative to the end of the detonation tube, ejector length-to-diameter ratio and the operation frequency. The ejector performance is quantified by thrust measurements.

Experimental set-up

Pulse detonation engine system description

A schematic of the apparatus is illustrated in fig. 1. The experimental system consisted of an oxidizer and fuel supply subsystem, a control and ignition subsystem, a detonation tube, an ejector subsystem, a measurement subsystem, and a data acquisition and processing subsystem, *etc*.

The detonation tube was 1.6 m long, with an inner diameter of 60 mm (D_{PDE}). The detonation tube was closed at one end and opened at the

Figure 1. Schematic of the experimental arrangement

other, which was composed of a thrust wall, a mixing chamber of 150 mm, an ignition section of 150 mm and a detonation chamber of 1300 mm. A Shchelkin spiral was inserted into the front of the detonation chamber to reduce the deflagration-to-detonation transition (DDT) run-up distance. The inlet ports of fuel and oxidizer were located at the thrust wall.

Liquid gasoline was chosen as the fuel and air as the oxidizer in the current study. The air and gasoline entered the detonation tube through respective pipelines in which an axial mode of air injection and an air atomizing spray nozzle were adopted to enhance the atomization and vaporization of liquid fuel, as well as the mixing of fuel and oxidizer. The sauter mean diameter of fuel droplet varied from 50 µm to 100 µm as fuel mass flow rate changes. The proportional regulating solenoid valve were used to adjust the flow rates of fuel and air to give the desired equivalence ratio and fill faction, which is the fraction of the tube that is filled with a fuel/air mixture. In all the experiments, the equivalence ratio of gasoline/air mixture and the fill fraction were 1.2 and 1.0, respectively, which were estimated through the flow rate of mixture supplied by the valves. After being injected into the detonation tube, the gasoline and air rapidly mixed in the mixing section, and then were ignited in the ignition section.

The spark plug employed in this system is Champion N12YC, and the energy of the spark plug discharge was around 50 mJ in one pulse. The experiment apparatus allowed the operating parameters such as air and fuel flow rates and the frequency of spark generator to be independently varied. The operation frequency of PDE was controlled by the ignition frequency driven by a signal generator.

A dynamic piezoelectric pressure transducer was mounted at the thrust wall (position 0) to record the pressure history at the thrust wall. Two dynamic piezoelectric pressure transducers (position 1 and 2) were used to survey the pressure history along the detonation chamber and velocities of the detonation waves. The pressure transducers used in the experiments were SINOCERA pressure transducers (CY-YD-205). The velocities of detonation wave could be computed through the distance and time difference when the same full-developed detonation wave propagated over the two pressure transducers which were 300 mm apart. The response
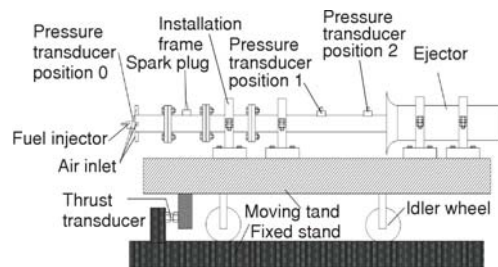
time of the pressure transducers was 2 seconds. A 16-channel data acquisition device (DEWE-3020) was used in the present study, and the single-channel sampling rate was 200 kHz. So the typical time-of-arrival measurement error is ±5 seconds. The velocity measurement uncertainty was approximately ±5%.

Ejector hardware

To investigate the effect of ejector axial position on thrust augmentation, three straight cylindrical ejectors with a bell-shaped contour inlet were designed. The inner diameters of these ejectors with a bell-shaped contour inlet were 120 mm, 150 mm, and 170 mm, respectively, *i. e.*, the ejector-to-PDE diameter ratios ($D_{ejector}/D_{PDE}$) were 2.0, 2.5, and 2.8. The lip radius of bell-shaped contour ejector inlet was 50 mm. Moreover, a straight cylindrical ejector with a rounded inlet and the inner diameter of 150 mm was test. The lip radius of rounded inlet was 10 mm. The two types of ejector were selected in order to compare the effect of ejector with or without bell-shaped contour inlet on the flow. It could be seen that flow resistance loss would be large if the ejector inlet had no any contour. So the rounded inlet was added to the ejector.

All ejectors were mounted coaxially to the detonation tube at various positions relative to the PDE exit plane, with the length ($L_{ejector}$) of 950 mm. Various axial positions of the ejector with respect to the detonation tube were tested to characterize engine performance. To normalize the parameter, it referred to the overlap position as x/D_{PDE}, with x being the axial distance from the detonation tube exit to the ejector inlet and D_{PDE} being the inner diameter of the detonation tube. As a convention, it selected a negative x/D_{PDE} factor to represent overlapping of the engine and the ejector in the experiments and positive x/D_{PDE} factor to represent separation. The dimensionless axial position of the ejector inlet (x/D_{PDE}) was varied from –8 to +2.

To investigate the effect of the ejector length-to-diameter ratio on thrust augmentation, five ejectors with different length were tested. The inner diameter of these ejectors with a rounded bell-shaped inlet was 120 mm. These ejectors were 350 mm, 450 mm, 550 mm, 750 mm, and 950 mm long, respectively, *i. e.*, the ejector length-to-diameter ratios (L/D) were 2.9, 3.75, 4.58, 6.25, and 7.92.

All the experiments about the effects of the ejector configuration were based on a constant operating frequency of 25 Hz. To investigate the effect of operating frequency on ejector thrust augmentation, PDE with or without ejector operated at 15 Hz, 20 Hz, 25 Hz, 30 Hz, and 35 Hz. The ejector with a bell-shaped contour located the 0 position. The inner diameter and length of the ejector were 150 mm and 950 mm, respectively.

Thrust measurements

As shown in fig. 1, the PDE thrust test stand consisted of a moving frame, a fixed frame, and a thrust transducer. The fixed frame was a cast iron base, and supported the movable frame by idler wheel. The detonation tube was mounted on the movable frame. A dynamic piezoelectric thrust transducer (KISTLER 9331B) was installed between the fixed frame and the movable frame to record instantaneous thrust produced by PDE. The time-averaged thrust produced by PDE was calculated by integrating instantaneous thrust per unit time. In order to make sure that the thrust measured was true and net one of PDE, the thrust system had to be calibrated to compensate the zero drift after PDE being installed.

To make sure the reliability of experimental results, under the same operating conditions, the thrust was measured by at least four experiments of PDE. The average thrust deviations for any two experiments were in the range of ±5 N. The arithmetic average values were computed as the best estimator of the measurement. The average thrust of the PDE without ejec-

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tor was taken as the baseline value, and thrust augmentation (θ) of the ejector under the same operating conditions could be calculated. Here, θ is defined:

$$\theta = \frac{F'_{aver} - F_{aver}}{F_{aver}} \tag{1}$$

where F'_{aver} is the average thrust of PDE with ejector and F_{aver} – the average thrust of PDE without ejector.

Results and discussion

Effect of ejector axial position

In the current study, PDE with or without an ejector operated at 25 Hz. Pressure profiles obtained at three pressure transducer locations are shown in fig. 2, for PDE without an ejector. At the position p_1 location, all the pressure spikes were around 2.0 MPa. During the same detonation cycle, the pressure peak propagated over 300 mm between the two pressure transducers (position 1 and position 2) in $1.95 \cdot 10^{-4} \sim 2.1 \cdot 10^{-4}$ s. Therefore, the wave speed was between 1425 m/s and 1538 m/s. The waved speed obtained was 15%~21% less than the value calculated from CEA code. In consideration of the effects of liquid-gas two-phase flow, the response time of pressure transducer and the limitation of sample rate, the result was acceptable. So the experi-
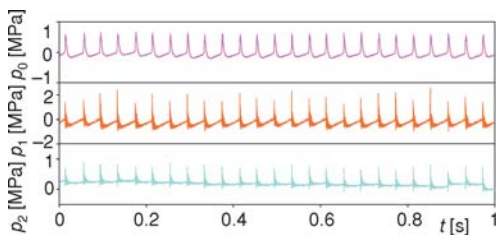

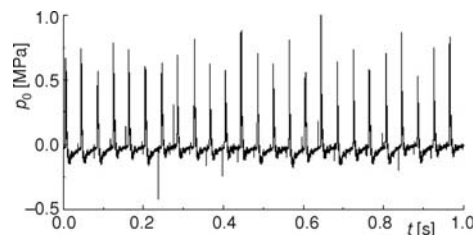**Figure 2. Pressure profiles for PDE without an ejector**

Figure 3. Pressure profile at the thrust wall for PDE with an ejector

mental results indicated that a near C-J detonation wave can be achieved in the current experiment rig and the detonation frequency was 25 Hz. For PDE with an ejector, only the pressure profile at the thrust wall was obtained, as shown in fig. 3. The experimental result demonstrated that the actual operating frequency of PDRE was consistent with the assigned frequency.

At different ejector positions, time averaged PDE-ejector thrust measurements were made for a selected set of the ejectors with a bell-shaped inlet, and the variations of thrust augmentation (θ) with dimensionless ejector axial position (x/D_{PDE}) were plotted in fig. 4.

As show in fig. 4, thrust augmentations obtained at the −1 location were smaller than those
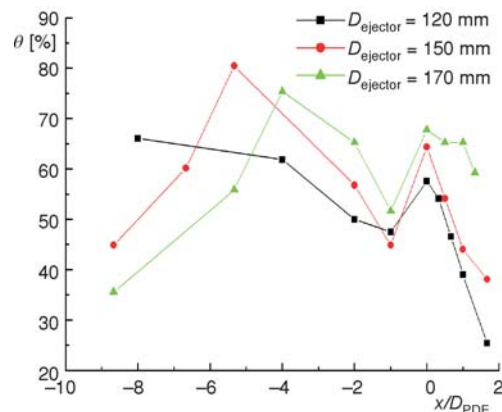

Figure 4. Variations of thrust augmentation with ejector axial position for the ejectors with a bell-shaped contour inlet

at the 0 location. When the detonation products were exhausted from the detonation tube, a great part of the available internal energy is still not converted into the kinetic energy. After propagating from the exit of detonation tube, the detonation wave decayed to a quasi-spherical expanding shock wave. The detonation products exhausted from the detonation tube were bounded by the quasi-spherical shock wave. As the propagation of the quasi-spherical shock wave, it expanded in all directions, its size continuously increased, and its strength gradually decayed. When the ejector located at upstream of the PDE exit, a left-running shock wave and a right-running shock wave would occur in the ejector, after the quasi-spherical expanding shock wave collided with the interior wall of the ejector [25]. The left-running shock wave propagated to the ejector inlet and an initial upstream flow existed at the ejector inlet. After the left-running shock wave emerged outside of the ejector, it diffracted and then air entered the ejector and established a secondary flow. When the ejector located at the –1 position, the expansion of the combustion produces in the downstream of the PDE exit was restricted by the ejector interior wall. When the left-running shock wave emerged outside of the ejector, the distance between the PDE exit and the right-running shock wave was still small. When the ejectors located at the –1 position, the right-running shock wave acted as a plug to prevent the secondary flow being entrained into the ejector. Due to the diminishment of the secondary flow, thrust augmentation obtained at the –1 position was lower than that obtained at the zero overlap location.

When the ejector was continually moved upstream from the –1 position, thrust augmentation was gradually increased due to the enhancement of the secondary flow being entrained into the ejector. Additionally, the ejector provided partial confinement of the detonation products escaping from the detonation chamber; and consequently the pressure relaxation time at the thrust wall was prolonged. The maintenance of the high pressure level in the detonation tube also brought thrust enhancement. With the ejector inner diameters of 150 mm and 170 mm, the maximum thrust augmentations reached 80.5% and 75.4%, and the corresponding critical ejector locations occurred at the –5.33 and –4 location, respectively. As the ejector was continually moved upstream from the critical location, the distance between the ejector exit and the PDE exit was deceased. The shortening of the distance between the ejector exit and the PDE exit affected the mixing of the primary and secondary flows. They had been exhausted from the ejector before the primary and secondary flow fully mixed with each other. Therefore, thrust augmentation gradually reduced as the ejector was continually moved upstream from the critical location. With a larger ejector inner diameter, the expansion of combustion products was more rapidly in the ejector. Hence, with the increase of ejector inner diameter, the critical location of ejector inlet was closer to the PDE exit. Based on the current results, it is inferred that the critical location of ejector inlet still existed for the ejector with the inner diameter of 120 mm. With the ejector inner diameters of 120 mm, 150 mm, and 170 mm, thrust augmentations obtained at the zero overlap location ($x/D_{\text{PDE}} = 0$) were 57.6 %, 64.4 %, 67.8%, respectively. In the range of 0 to +2, thrust augmentation was enhanced with the increase of the inner diameter of ejector. Due to the increase of the ejector cross-section area, more combustion products exhausted from the PDE exit entered into the ejector, instead of being directly exhausted into the atmosphere. When the ejectors located at downstream of the PDE exit ($x/D_{\text{PDE}} > 0$), thrust augmentation declined as the increase of x/D_{PDE}. Due to the restriction of the ejector installation position, the values of x/D_{PDE} tested were in the range of 0 to +2. Currently, the variation of thrust augmentation with the ejector axial position was not temporarily investigated for a greater x/D_{PDE}. In the tested range of 0 to +2, the distance between the PDE exit and the ejector inlet was relatively small. Hence, with the increase of x/D_{PDE}, the pressure relaxation time at the thrust wall was shortened

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and the amount of combustion products entered into the ejector was deceased, both of which would result in the decline of thrust enhancement.

As mentioned, the peak thrust augmentation obtained in this paper was lower than the one of Wilson *et al.* [19]. The shape of the ejector and the difference of fuel maybe contribute to the result. In Wilson's *et al.* [19] experiment, the air-hydrogen mixture and the taper ejector were used. However, this paper used cylindrical ejector and liquid gasoline as fuel. Due to the effects of liquid-gas two-phase flow, DDT would be longer, and strength and speed of detonation wave would be worse than that of single-phase flow.

Figure 5. Variation of thrust augmentation with ejector axial position for the ejector with a rounded inlet

For the ejector with a rounded ejector inlet, the variation of thrust augmentation (θ) with dimensionless ejector axial position (x/D_{PDE}) was plotted in fig. 5. At the zero overlap location ($x/D_{PDE} = 0$), thrust augmentation reached 50.0 %. When the ejector located at downstream of the PDE exit ($x/D_{PDE} > 0$), thrust augmentation firstly rose and then dropped as the increase of x/D_{PDE}, and the maximum thrust enhancement of 53.4. % was obtained at the + 0.5 location. In the negative overlap domain ($x/D_{PDE} < 0$), thrust augmentation firstly increased, then decreased as the decrease of x/D_{PDE}. The maximum thrust augmentation of 66.9 % was obtained at the –5.33 and –4 locations. In this case, the maximum thrust augmentation was still achieved with ejector upstream of the detonation tube exit.

Ejector length-to-diameter ratio

The second parameter investigated was the ejector length-to-diameter ratio ($L_{ejecor}/D_{ejector}$). The PDE with or without ejector operated at 25 Hz. The ejector located at the 0 position. Figure 6 plots thrust augmentations of the ejectors with different $L_{ejector}/D_{ejector}$. As shown in fig. 6, with the increase of $L_{ejector}/D_{ejector}$, thrust augmentation was noticeably enhanced and finally tended to a constant of 57% when $L_{ejector}/D_{ejector} \geq 4.58$. The result demonstrates that with a fixed ejector inner diameter, an optimum ejector length exists. When the ejector length is less than the optimum ejector length, the maximum thrust augmentation can not be obtained, due to the lack of the sufficient mixing between primary flow and the secondary flow. When the ejector length is greater than the optimum ejector length, thrust augmentation can not be dramatically enhanced by further increasing the ejector length, while the ejector weight will significantly rise. In the current study, the optimum length-to-diameter ratio was 4.58. In the section *Effect of ejector axial position*, the maximum thrust augmentation achieved was 80.5% with the length-to-diameter ratio of 5.59. The
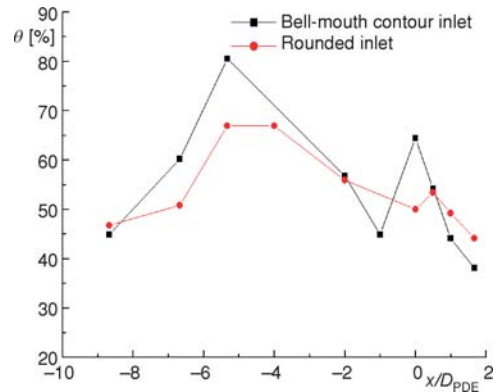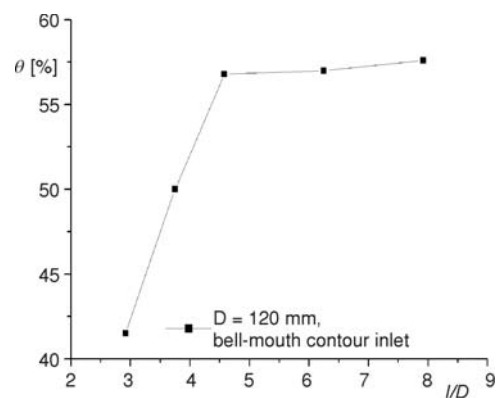

Figure 6. Thrust augmentations of the ejectors with different $L_{ejector}/D_{ejector}$

Figure 7. Thrust augmentation *vs.* operation frequency

results indicated that the PDE-driven ejector could be expected to be shortened under the premise of guaranteeing high performance, and thrust augmentation has potential to be further enhanced.

Effect of operating frequency

Figure 7 plots the variations of average thrust of the PDE with ejector and without ejector with operation frequency. As shown in fig. 7, whether or not to install an ejector, average thrust almost lineally increased with the rise of operating frequency. Figure 7 also plots thrust augmentation at different operation frequency. Under all th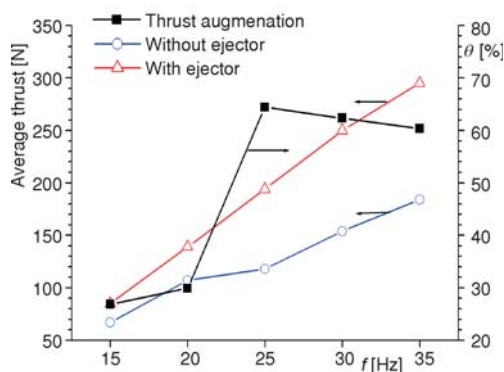e tested operating frequencies, installing an ejector could bring thrust augmentation. At the operating frequencies of 15 Hz and 20 Hz, thrust augmentations brought by the ejector were 26.9% and 29.9%. When the operating frequency was relatively low, the increment of thrust augmentation with the increase of operating frequency was not noticeably. When the operating frequency increased to 25 Hz, thrust augmentation was up to 64.4%, due to the increase of the secondary flow being entrained into the ejector. In the range of 20 Hz to 25 Hz, thrust augmentation was significantly enhanced with the increase of operating frequency. When the operating frequency was in the range of 25 Hz to 30 Hz, thrust augmentations were in the range of 65% to 60%. When PDE run at a high operating frequency, thrust augmentations slightly deceased with the increase of operating frequency, and seemed to tend to a constant, which was attributed to the operating of PDE tending to quasi-steady-state.

Conclusions

A series of multi-cycle experiments was conducted to investigate thrust augmentation by ejectors on a gasoline/air PDE. Based on the experimental results, it is concluded following.
- Adding an ejector to the exit of the detonation tube can significantly enhance thrust produced by PDE. A peak thrust augmentation level of 80.5% was achieved.
- Thrust augmentation is a strong function of the ejector axial position. The result indicated that there exists a maximum thrust augmentation with ejector being at upstream of the detonation tube exit. The exact location at which the maximum thrust augmentation was obtained varies with the ejector-to-PDE diameter ratio and the ejector inlet geometry.
- With the increase of $L_{ejector}/D_{ejector}$, thrust augmentation was noticeably enhanced and finally tended to a constant of 57% when $L_{ejector}/D_{ejector} \geq 4.58$. In the current study, the optimum length-to-diameter ratio was 4.58. When the ejector length is less than the optimum ejector length, the maximum thrust augmentation can not be obtained. When the ejector length is greater than the optimum ejector length, thrust augmentation can not be dramatically enhanced by further increasing the ejector length, while the ejector weight will significantly rise.
- The operating frequency has an important effect on ejector thrust performance. When the operating frequency was relatively low, the increment of thrust augmentation with the increase of operating frequency was not noticeably. In the range of 20 Hz to 25 Hz, thrust augmentation was significantly enhanced with the increase of operating frequency. When

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PDE run at a high operating frequency, thrust augmentations slightly deceased with the increase of operating frequency, and seemed to tend to a constant.

Acknowledgments

Nomenclature

D_{PDE}	– inner diameter of detonation tube	$L_{ejector}/D_{ejector}$	– ejector length-to-diameter ratio
$D_{ejector}$	– inner diameter of ejector	$L_{ejector}$	– ejector length
$D_{ejector}/D_{PDE}$	– ejector-to-PDE diameter ratio	x	– axial distance from the
F_{aver}	– average thrust produced by PDE		detonation tube exit to the
	with no ejector installed		ejector inlet
F'_{aver}	– average thrust produced by PDE	x/D_{PDE}	– dimensionless axial position of
	with ejector installed		ejector inlet
f	– frequency	θ	– thrust augmentation,
			$(F'_{aver} - F_{aver})/F_{aver}$

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