Gui-yang Xu, Chun-sheng Weng*, Ning Li and Xiao-long Huang

Investigation of Thrust Augmentation and Acoustic Performance by Ejectors on PDE

Abstract: Thrust augmentation and acoustic performance of a Pulse Detonation Engine (PDE) with ejector system is experimentally investigated. For these tests the $L_{\text{Ejector}}/D_{\text{Ejector}}$ is varied from 1.18 to 4 and the axial placement of the ejector relative to the PDE exhaust is varied from an x/D_{PDE} of −3 to 3. Results from the tests show that the optimum $L_{\text{Ejector}}/D_{\text{Ejector}}$ based on thrust augmentation and Overall Sound Pressure Level (*OASPL*) is found to be 2.61. The divergent ejector performed the best based on thrust augmentation, while the reduction effect for *OASPL* and Peak Sound Pressure Level (*PSPL*) at 60° is most prominent for the convergent ejector. The optimum axial position based on thrust augmentation is determined to be $x/D_{\text{PDE}} = 2$, while, $x/D_{\text{PDE}} = 0$ based on *OASPL* and *PSPL*.

Keywords: aerospace propulsion system, pulse detonation engine, ejector, thrust augmentation, noise radiation

PACS®(2010). 47.40.Rs

DOI 10.1515/tjj-2015-0002
Received January 17, 2015; accepted February 8, 2015

Introduction

The pulse detonation engine (PDE) is an innovative propulsion technology that could potentially provide significant advantages such as hardware simplicity, high thermodynamic cycle efficiency and wide working scope. It has been suggested that the use of ejector, which is a coaxial duct placed around the exhaust of an engine performing as a fluidic pump on PDE, may be an effective way to increase the thrust being generated.

Many previous experimental studies of PDE with ejector have been conducted and presented in the literature [1–4]. It has been observed that ejector performance is sensitive to the ejector geometric parameters, such as ejector-to-PDE diameter ratio, ejector length and ejector shape. In most cases, an optimum ejector-to-PDE diameter ratio ranges between 2.4 and 3.5 [5–11]. Generally, longer ejectors outperform the short ones [11–14], and divergent ejectors tested are much more effective at improving thrust augmentation than the straight ones [14, 15]. Another parameter of importance is the axial position of the ejector inlet relative to the PDE tube exit. Downstream ejector placement between one and two PDE diameters provides optimum levels of thrust augmentation [16–18]. In addition to ejector geometry and axial position of the ejector, there are still other operating parameters that have been shown to affect the performance of a PDE, such as fill fraction that represents the proportion filled with detonable mixture relative to the PDE tube volume. Although the PDE thrust has been shown to decrease with a reduction in fill fraction, better specific thrust performance is obtained at lower operating fill fraction [11, 14, 18]. However, the acoustic signature, as another important influence on PDE performance, receives much less attention. It is proved that ejectors would have an impact on the acoustic signature of PDE. An experimental study by Glaser et al. [19, 20] was carried out using a straight cylindrical ejector. The results show that the optimum ejector (based on sound attenuation) is found to be the $D_{\text{Ejector}}/D_{\text{PDE}} = 3$, at a downstream axial placement of $x/D_{\text{PDE}} = 1$.

This paper presents an experimental investigation into the effects of the geometry and axial position of the ejector on PDE performance, including thrust augmentation and detonation acoustic. The detonation acoustic of PDE, both Peak Sound Pressure Level (*PSPL*) and Overall Sound Pressure Level (*OASPL*), are analyzed with different ejector lengths and shapes, resulting in an improvement on detonation acoustic formation mechanisms. The results are of great significance for design and control of PDE with ejector to obtain optimal performance on both thrust and acoustic.

Experimental setup

In order to explore thrust augmentation and detonation acoustic of PDE with ejector, the experiment system is set up as shown in Figure 1.

***Corresponding author: Chun-sheng Weng,** National Key Lab of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, P.R. China, E-mail: wengcs@126.com
Gui-yang Xu: E-mail: xuguiyang90@163.com, **Ning Li:** E-mail: stokim@gmail.com, **Xiao-long Huang:** E-mail: 534947491@qq.com, National Key Lab of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, P.R. China

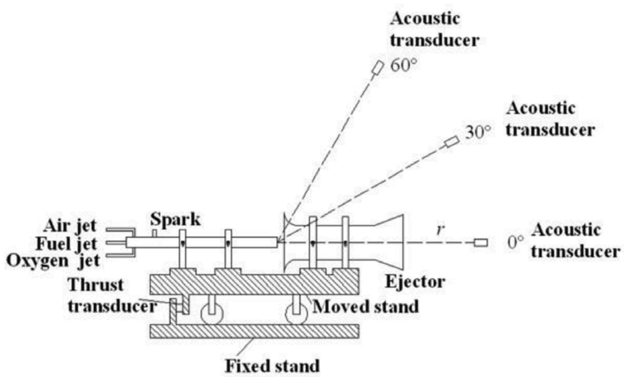

Figure 1: Schematic of the experimental setup.

The system is composed of PDE tube, ignition control system and test system. Compressed air and compressed oxygen as oxidizer are injected into the PDE tube by tangential forms. Enhanced mixing of the fuel gasoline and oxidizer is achieved by combined atomizing nozzle and venturi tube. Ignition control system is composed of signal control system, high-energy igniter and spark. PDE cycle frequency is controlled by signal control system. A detonation event is produced via a spark and high-energy igniter.

Dynamic thrust transducer is used in the test system, mounted in move stand. Circular microphone array of three microphones at radius arranged in the distance from 1,000 mm to 3,000 mm from the PDE exhaust provides the means of collecting PDE noise data at directivity angles from 0° to 60°. In this paper, directivity angle is defined as the angle from the PDE tube centerline to the microphone at 0° being directly downstream. The thrust and noise data of PDE are acquired at 500 k samples/s from all transducers simultaneously.

Ejector hardware

As depicted in Figure 2, three typical ejectors are used during testing: straight ejector, divergent ejector and convergent ejector, named for their exhaust section shapes. All

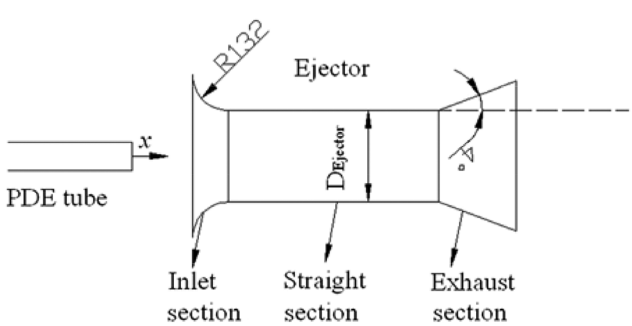

Figure 2: Diagram of the ejector geometry.

ejectors have the same rounded inlet diameter of 132 mm and the same ejector diameter of 280 mm which is defined as the diameter of the straight section. The lengths of the ejectors are varied by extending the straight sections, respectively. The divergent ejector sections have a 4 half-angle of divergence at a fixed length of 200 mm. The convergence ejector sections have the same half-angle and fixed length. The axial position $\times$ is the distance from the PDE tube exit plane to the ejector inlet plane. A positive axial position value means the ejector inlet being placed downstream of the PDE exit. For a negative value, the ejector is mounted upstream of the detonation tube exit.

Evaluation parameters

The amount of PDE thrust augmentation produced by the use of an ejector is defined as follows:

$$\alpha = \frac{T_{\text{Ejector}} - T_{\text{PDE}}}{T_{\text{PDE}}} \times 100\% \quad (1)$$

where T_{Ejector} is the time-averaged thrust generated by the PDE with ejector, and T_{PDE} is the baseline time-averaged thrust of the system with no ejector installed.

The detonation acoustic of PDE with an ejector is quantified through PSPL and OASPL, shown as follows:

$$PSPL = 20 \lg \left(P_{\text{peak}}/p_0\right) \quad (2)$$

$$OASPL = 20 \lg \left(P_{\text{RMS}}/p_0\right) \quad (3)$$

$$P_{\text{RMS}} = \sqrt{\frac{1}{T}\int_0^T p(t)^2 dt} \quad (4)$$

where p_0 is the reference noise pressure with value of 20×10^{-6} Pa and T is 132 ms. (The PDE cycle is 132 ms at the condition of 1 for fill fraction.)

Results and discussion

Baseline testing of pulse detonation engine

The baseline testing is carried out in the 1,900 mm length PDE detonation tube (80 mm diameter) without an ejector. Figure 3 shows the thrust time traces and detonation noise pressure time traces at 0° direction in 3,000 mm during PDE running at the condition of 1 for fill fraction. A time-averaged thrust value of 94.28 N is measured at the PDE cycle. First, the fast rising edge that appeared in

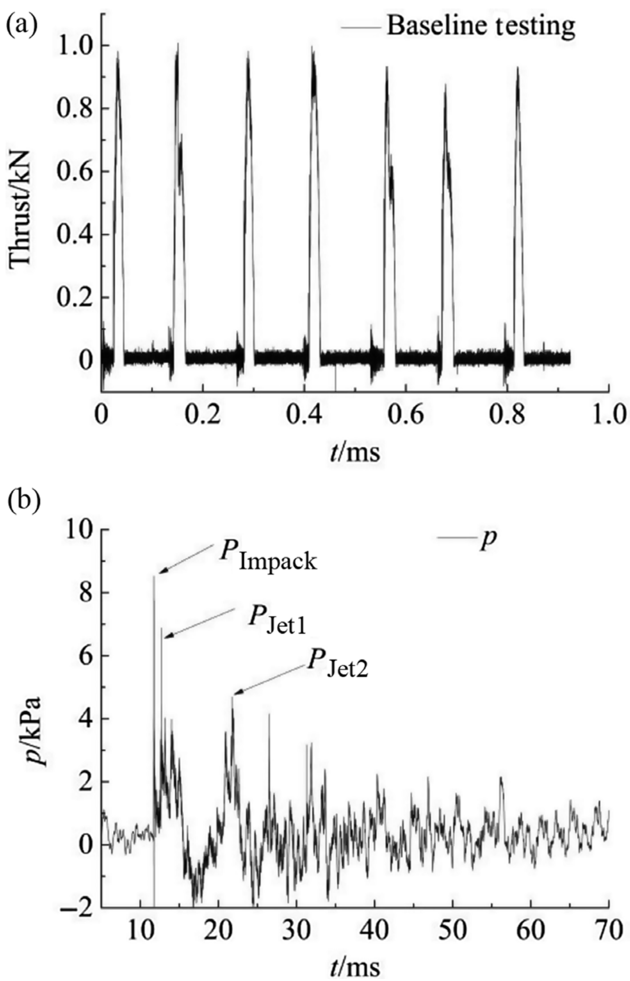

Figure 3: Thrust time traces and detonation noise pressure time traces in the baseline PDE running. (a) Thrust time traces in the baseline testing. (b) Detonation noise pressure time traces at 0° direction in 3,000 mm.

detonation noise pressure time traces represented the arrival of shock wave noise, as shown in Figure 3(b). The peak of first fast rising edge P_{Impact} is 8.53 kPa which is called impact noise. A series of rising edges $P_{\mathrm{Jet}N}$ appeared 0.95 ms after, because vortexes which are caused by jet are formed there.

The corresponding *PSPL* and *OASPL* values under different directivity angles are listed in Table 1 in the baseline PDE running. The maximal *PSPL* is obtained at 30° direction, which is 175.06 dB. It is noteworthy that the *OASPL* is the minimum at 30° direction, which is 148.18 dB.

Table 1: Baseline *PSPL* and *OASPL* ($r = 3{,}000$ mm).

Directivity angle	*PSPL*/dB	*OASPL*/dB
0°	172.60	151.93
30°	175.06	148.18
60°	172.33	148.89

Effect of ejector length on PDE performance

The effect of ejector length on PDE performance is investigated at a fixed ejector axial position, $x/D_{\mathrm{PDE}} = 0$. The lengths of ejectors could be varied by changing the length of the straight sections as depicted in Figure 1, resulting in an increase in $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ from 1.18 to 4 during the experiment. As shown in Figure 4(a), the thrust augmentation generally increases with an increase in $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ for all ejectors, while an inflection in the curve appears which is located at the $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ of 2.61. The reason is that primary exhaust flow cannot entrain enough secondary flow when the ejector is too short. An extension in ejector length would lead to a fast increase in additional secondary flow, but the effect would not be obvious when the ejector is long enough.

The effect of $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ on detonation acoustic features, *PSPL* and *OASPL*, continues to be a matter of great interest in PDE performance research, as shown in Figure 4(b) and (c). It can be seen that the extension in divergent ejector length exhibits an increase in *PSPL* at both 0° and 30°. The amplification effect is most prominent for the $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ of 4 at 0°, where an amplification of 4.37 dB is achieved. The multiple reflections would contribute to the intensity enhancement in the peak of detonation wave. However, the wave radial propagation at 60° may be refrained by ejector configuration, resulting in a reduction in *PSPL* with increasing ejector length. The maximum reduction is up to 2.63 dB at $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ of 4. Reductions in *OASPL* with increasing $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ are observed in the experiment for all the directions, shown in Figure 4(c). The maximum reduction, about 3.12 dB, appears with the longest divergent ejector ($L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}} = 4$) at 60°. It can be seen that reductions in *OASPL* would not be obvious when the ejector is long enough. Based on sound attenuation and thrust augmentation, it can make a conclusion that the optimum $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ is 2.61 in this portion of study.

Figure 5 shows the effect of detonation noise pressure time traces with ejector at 60° and 30°. It can be observed that $P_{\mathrm{Jet}N}$ which is caused by turbulence is restrained at 60° and 30° for PDE testing with ejector. These may be probably due to the decelerating effect from secondary flow by divergent ejector on detonation exhaust of high temperature. It is one reason for reductions in *OASPL* at 30° and 60°. As shown in

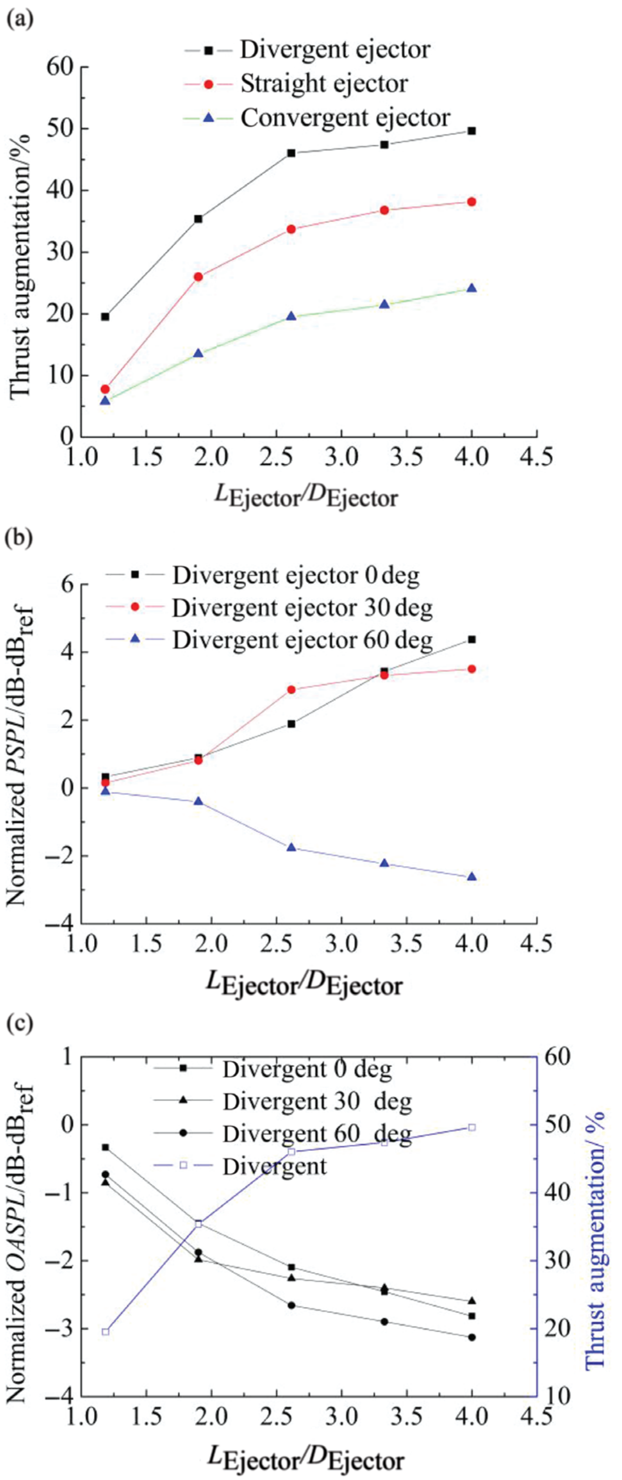

Figure 4: Effect of ejector length on thrust augmentation and detonation noise. (a) Effect of ejector length on thrust augmentation. (b) Effect of ejector length on *PSPL*. (c) Effect of ejector length on *OASPL*.

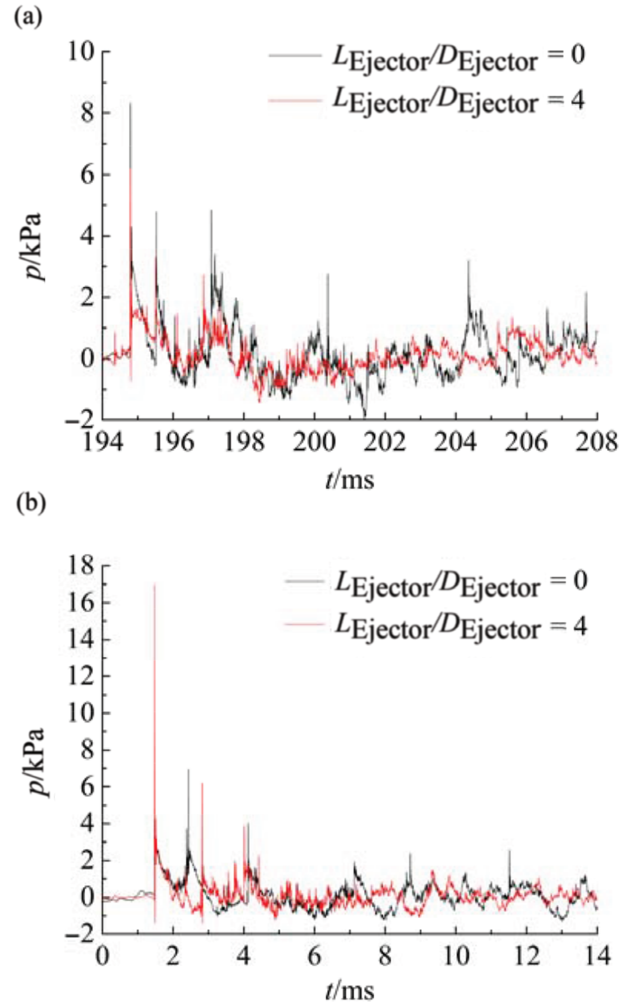

Figure 5: Contrast diagram of detonation noise pressure time traces. (a) Contrast diagram of detonation noise pressure time traces at 60 degree. (b) Contrast diagram of detonation noise pressure time traces at 30°.

Figure 6(b), a phenomenon worthy to be pointed out is that P_{Jet1} is delayed at 30°. It is the other reason for reductions in *OASPL* at 30° and 0°.

Effect of ejector shape on PDE performance

There are three kinds of ejectors (straight, divergent and convergent ejectors) tested in this portion of study. All ejectors are mounted at an axial position of $x/D_{PDE} = 0$. As shown in Figure 4(a), it indicates that the best thrust augmentation curve is obtained for a divergent ejector at all $L_{Ejector}/D_{Ejector}$. Figure 6(a) shows the contrast diagram of thrust time traces at $L_{Ejector}/D_{Ejector}$ of 2.61. Installing ejectors exhibits a reduction in the peak of thrust time traces but augmentation in the duration of thrust time traces. The maximum thrust durations is achieved for a divergent ejector. It is due to this that the diverging section appears to be that of a subsonic diffuser, reducing static pressure on divergent ejector [16], increasing

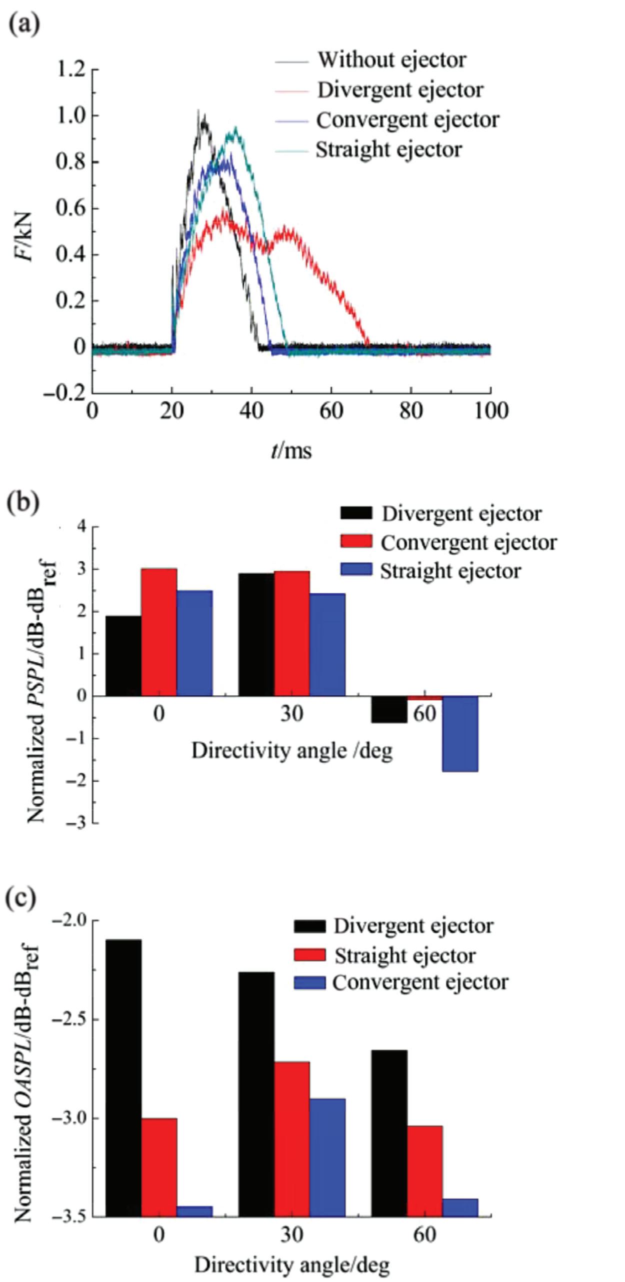

Figure 6: Effect of ejector shape on thrust augmentation and detonation noise. (a) Contrast diagram of thrust time traces. (b) Effect of ejector shape on *PSPL*. (c) Effect of ejector shape on *OASPL*.

secondary flow rate and thrust duration. The phenomenon of blocking caused by convergent ejector leads to the secondary flow rate and thrust duration declines.

The effect of ejector shape on *PSPL* is shown in Figure 6(b). One trend that can be observed clearly is that all of the ejectors exhibit a reduction in the *PSPL* at 60° but amplification at 0° and 30°. The most prominent amplification is obtained for straight ejector at 0°, where an amplification of 2.94 dB is achieved. The best reduction is obtained at 60°, where a reduction of 1.77 dB is achieved for convergent ejector.

The reduction in *OASPL* caused by the different ejectors is shown in Figure 6(c). It can be seen that *OASPL* is reduced at all angles with all ejectors. The reduction effect is most prominent at 0°, where a reduction of 3.45 dB is achieved for the convergent ejector. This behavior can be attributed to the weakest oscillation of detonation noise pressure of convergent ejector, as shown in Figure 7. The phenomenon of blocking caused by convergent ejector leads to the secondary flow rate declines. The turbulence causes oscillations of detonation noise pressure, and the deceleration of jet speed results in restrained oscillations.

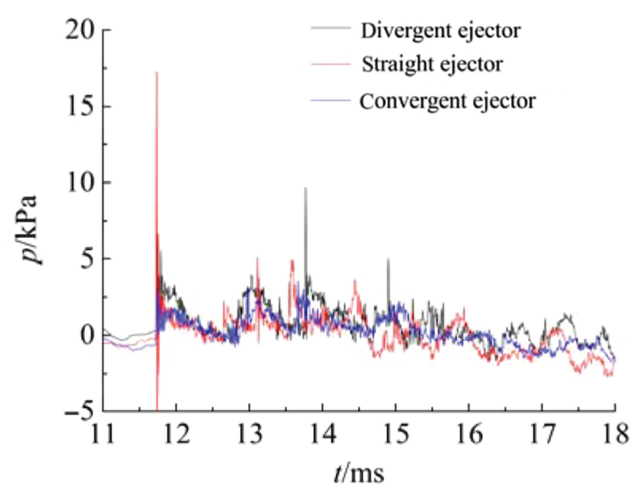

Figure 7: Contrast diagram of detonation noise pressure time traces at 0°.

Effect of ejector axial position on PDE performance

Previous work has shown that PDE performance is sensitive to the ejector axial position relative to the PDE exit [15, 16], and maximum thrust augmentation occurred with divergent ejector. Here, the effect of axial position is investigated in an installed divergent ejector with $L_{Ejector}/D_{Ejector}$ of 2.61. A detailed mapping of PDE performance as a function of axial position is obtained and shown in Figure 8(a). The increase in thrust augmentation is obvious with the increasing x/D_{PDE} from −3 to 2, due to the improvement in the secondary flow restriction from limited flow area. The maximum thrust augmentation is at $x/D_{PDE} = 2$ for the divergent ejector by an augmentation of 50.15%. Obviously, this is the very critical position where the PDE performance is the best. With further movement downstream, the velocity of the

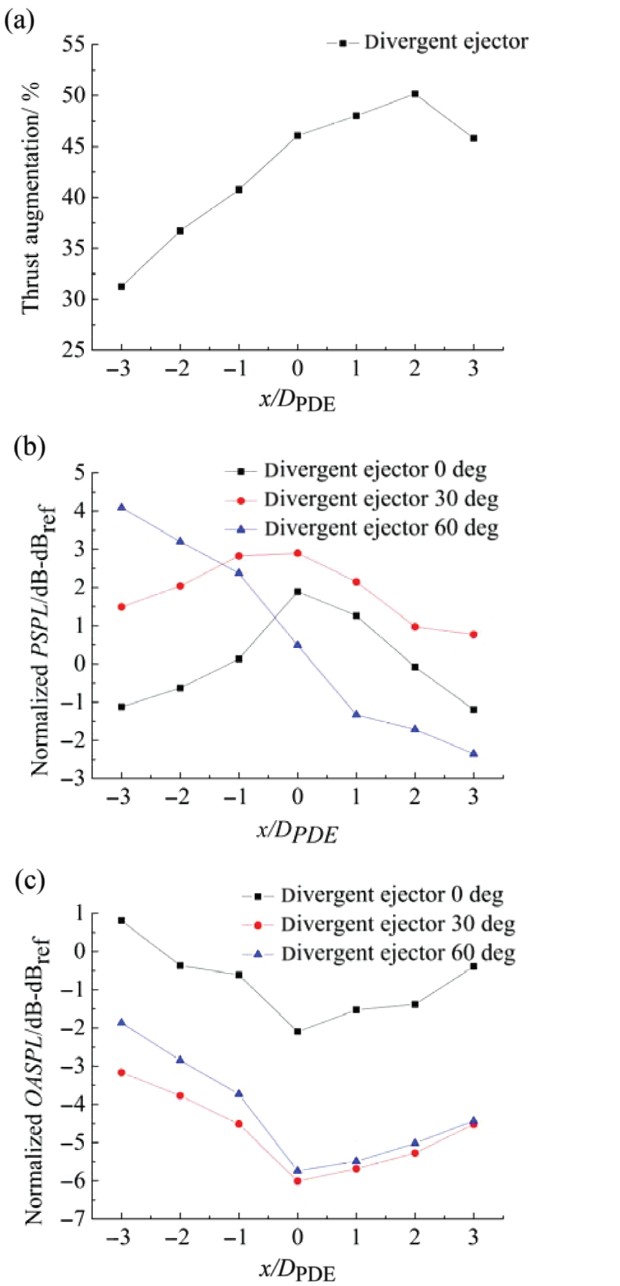

Figure 8: Effect of axial position on thrust augmentation and detonation noise. (a) Effect of axial position on thrust augmentation. (b) Effect of axial position on *PSPL*. (c) Effect of axial position on *OASPL*.

primary exhaust flow suffered a serious deceleration when ejector inlet is too far away from the tube exit so the primary exhaust flow does not have enough power to entrain the secondary flow, resulting in a reduction in thrust augmentation when x/D_{PDE} is more than 2.

The effect of axial position on detonation noise on *PSPL* is shown in Figure 8(b). For both 0° and 30°, *PSPL* increases at first and then decreases with increasing the axial position $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ from −3 to 3. Results indicate that *PSPL* reaches its maximum of 1.89 dB and 2.89 dB at $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}}$ of 0. *PSPL* at 60° is decreasing with increased axial position, resulting in the highest reduction of 2.35 dB in experiments.

Generally, divergent ejector is helpful for reducing the *OASPL* during PDE running. The *OASPL* exhibits good agreement in changing trend for experimental curves at all directions, as shown in Figure 8(c). The maximum reduction appears at the x/D_{PDE} of 0, and movement of ejector downstream or upstream further would increase the *OASPL* obviously. The maximum reduction values are 2.09 dB at 0°, 6.01 dB at 30° and 5.74 dB at 60°. The time between P_{Impact} and P_{Jet1} is increased when x/D_{PDE} is away from 0, as shown in Figure 9. This behavior can be attributed to the phenomenon that the secondary flow is accelerated when ejector position is away from PDE exit.

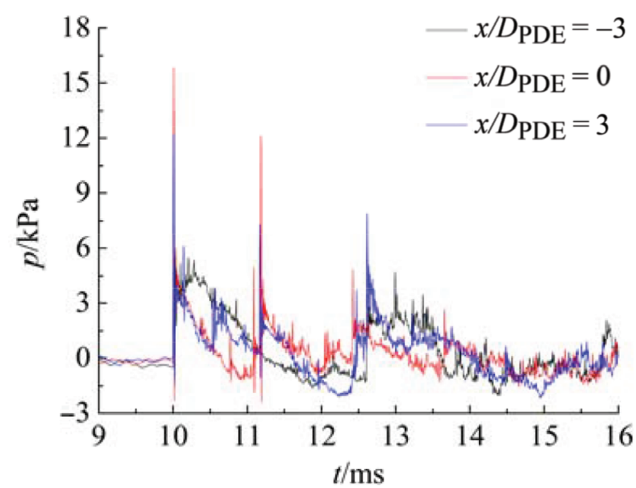

Figure 9: Contrast diagram of detonation noise pressure time traces at different axial position.

Since previous work has shown that $x/D_{\mathrm{PDE}} = 2$, $L_{\mathrm{Ejector}}/D_{\mathrm{Ejector}} = 2.61$ and divergent ejector provided the best performance, propagation of PDE detonation noise with those factors is analyzed in this portion of the study. The investigation of detonation noise characteristic is carried out in the range from 1,000 mm to 3,000 mm at three different angles. The divergent ejector affects *PSPL* change and *OASPL* change at 0° as shown in Figure 10. Baseline detonation noise amplitude is mapped as a function of radial distance. It is found that P_{Peak} and P_{RMS} rapidly decrease with radial distance. With increased distance, the decay rate of P_{Peak} and P_{RMS} slows down. As shown in Figure 10, the divergent ejector shows significant influence on *PSPL* and *OASPL*. It can be

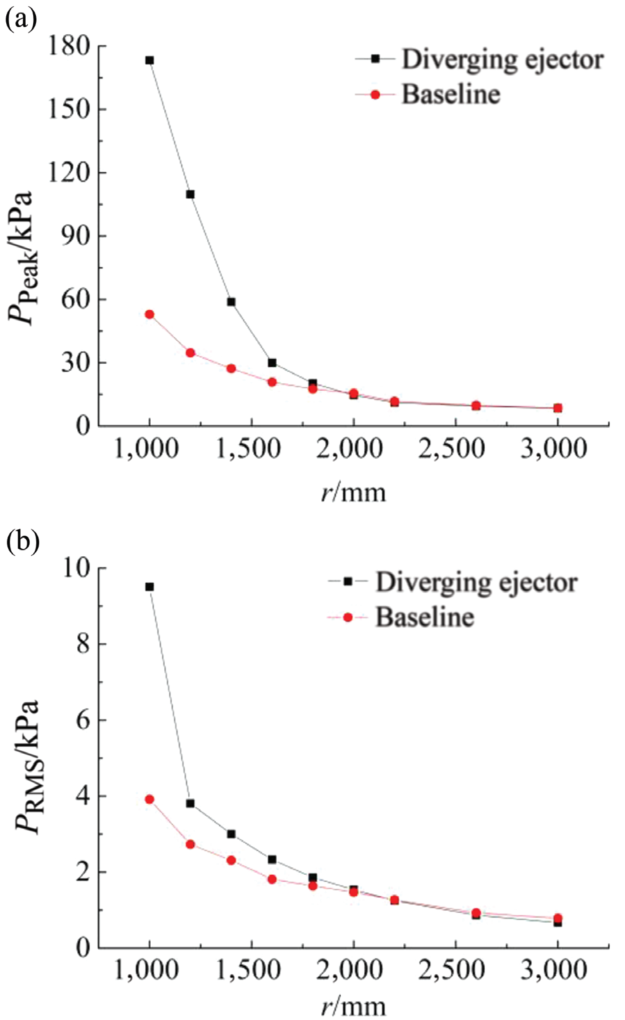

Figure 10: Effect of detonation noise with divergent ejector in different *r*. (a) P_{Peak} in different *r*. (b) P_{RMS} in different *r*.

observed that for ejector, amplification is obtained at short distance, but reduction at long distance. The decay rate of P_{Peak} and P_{RMS} for the divergent ejector is faster than baseline.

Conclusion

In this study the effects of ejector geometry and ejector axial position on ejector performance are investigated. It is shown that increasing the ejector length increases the level of thrust augmentation and *PSPL* at 0° and 30°, while the *OASPL* at all angles and *PSPL* at 60° reduces with increasing ejector length. This increase in augmentation is the result of an additional secondary flow increase with increasing ejector length. The best $L_{Ejector}$ is located at the $L_{Ejector}/D_{Ejector}$ of 2.61.

The ejector shape also greatly affects the performance of the PDE ejector system. The best thrust augmentation curve is obtained for a divergent PDE ejector. It is due to this that the diverging section appears to be that of a subsonic diffuser, reducing static pressure on divergent ejector, increasing secondary flow rate and thrust duration. The reduction effect for *OASPL* is most prominent at 0°, where a reduction of 3.45 dB is achieved for the convergent ejector. This behavior can be attributed to the weakest oscillation of detonation noise pressure of convergent ejector, as shown in Figure 7. All of the ejectors exhibit a reduction in the *PSPL* at 60° but amplification at 0° and 30°. The most prominent amplification is obtained for straight ejector at 0°. The best reduction is obtained at 60° for convergent ejector.

The effect of ejector axial position is also studied with divergent ejector whose $L_{Ejector}/D_{Ejector}$ is 2.61. It can be clearly seen that maximum thrust augmentation occurred at $x/D_{PDE} = 2$ for the divergent ejector, where an augmentation of 50.15% is achieved. *OASPL* first decreased and then increased when the axial position increased, and the optimum axial position is at $x/D_{PDE} = 0$ for all angles. *PSPL* at 0° and 30° first increases and then decreases with the change of the axial position from −3 D_{PDE} to 3 D_{PDE}, while the maximum *PSPL* reaches 1.89 dB and 2.89 dB at $x/D_{PDE} = 0$. *PSPL* at 60° decreases with increasing axial position. The best reduction is obtained at 60°, where a reduction of 2.35 dB is achieved.

The investigation of detonation noise characteristics is carried out in the range from 1,000 mm to 3,000 mm. It can be observed that for ejector, amplification is obtained at short distance, but reduction at long distance. The decay rate of P_{Peak} and P_{RMS} for the divergent ejector is faster than baseline.

Acknowledgment: The authors gratefully acknowledge the support of The National Key Lab of Transient Physics.

Funding: National Natural Science Foundation of China (item No. 11472138); National Natural Science Foundation of China (item No. 11372141); National Defense Pre-Research Foundation (item No. 9140C300205140C30137); Fundamental Research Funds for the Central Universities (item No. 30920130112007).

Nomenclature

D_{PDE}	detonation tube diameter, m
$D_{Ejector}$	ejector diameter
$L_{Ejector}$	ejector length
OASPL	Overall Sound Pressure Level

PSPL	Peak Sound Pressure Level
x	ejector position (distance from PDE exit to ejector inlet)
r	radius from PDE exit
P_{Peak}	peak sound pressure
P_{Impact}	peak impact pressure
$P_{\mathrm{Jet}N}$	*N*th peak jet sound pressure

References

1. Caldwell N, Pal S, Woodward R, Santoro R. Experimental studies of the unsteady ejector mode of a pulse detonation rocket-based combined cycle engine. AIAA 2010–688.
2. Caldwell N, Gutmark E, Hoke J, Bradley R. Investigation of fundamental processes leading to pulse detonation engine/ejector thrust augmentation. AIAA 2008-116.
3. Wang K, Fan W, Yan Y, Jin L. Preliminary studies on a small-scale single-tube pulse detonation rocket prototype. Int J Turbo Jet Engines 2013;30:145–51.
4. Huang XQ, Li Y, Chen L, Mu Y, Zheng LX. Experimental study on thrust augmentation of ejector driven by pulse detonation engine. J Northwestern Polytechnical Univ 2013;31:55–9.
5. Allgood D, Gutmark E, Katta V. Effects of exit geometry on the performance of a pulse detonation engine. AIAA 2002-0613.
6. Wilson J, Paxson DE. Unsteady ejector performance: an experimental investigation using a resonance tube driver. AIAA 2002-3632.
7. Paxson DE, Wilson J, Dougherty KT. Unsteady ejector performance: an experimental investigation using a pulsejet driver. AIAA 2002-3915.
8. Glaser AJ, Caldwell N, Gutmark E. Effects of tube and ejector geometry on the performance of pulse detonation engine driven ejectors. AIAA 2006-4790.
9. Wilson J, Sgondea A, Paxson D, Rosenthal B. Parametric investigation of thrust augmentation by ejectors on a pulse detonation tube. J Propul Power 2007;23:108–15.
10. Yi T, Wilsony DR, Hoke J, Luy FK. Detonation wave propagation in an ejector-augmented pulse detonation rocket. AIAA 2006-953.
11. Allgood D, Gutmark E, Hoke J, Bradley R, Schauer F. Performance studies of pulse detonation engine ejectors. J Propul Power 2008;24:1317–24.
12. Peng CX, Fan W, Zhang Q, Yuan C, Chen WJ, Yan CJ. Experimental study of an air-breathing pulse detonation engine ejector. Exp Therm Fluid Sci 2011;35:971–7.
13. Gao Z, Fan W, Mu Y, Yan Y, Chen W. Effect of axial position of ejectors with variable cross-section area on performance of a pulse detonation rocket engine. J Propul Technol 2012;33:826–30.
14. Glaser AJ, Caldwell N, Gutmark E, Hoke J, Bradley R, Schauer F. Performance measurements of straight and diverging ejectors integrated with a pulse detonation engine. AIAA 2006-1022.
15. Glaser AJ, Caldwell N, Gutmark E, Hoke J, Bradley R, Schauer F. Experimental study of ejectors driven by a pulse detonation engine. AIAA 2007-447.
16. Allgood D, Gutmark E. Performance measurements of pulse detonation engine ejectors. AIAA 2005-0223.
17. Wilson J, Sgondea A, Paxson D, Rosenthal B. Parametric investigation of thrust augmentation by ejectors on a pulse detonation tube. AIAA 2005-4208.
18. Allgood D, Gutmark E, Hoke J, Bradley R, Schauer F. Performance measurements of multicycle pulse detonation engine exhaust nozzles. J Propul Power 2006;22:70–7.
19. Glaser AJ, Caldwell N, Gutmark E. Experimental investigation into the acoustic performance of a pulse detonation engine with ejector. AIAA 2005-1345.
20. Glaser AJ, Caldwell N, Gutmark E. A fundamental study on the acoustic behavior of pulse detonation engines. AIAA 2007-444.