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Study on Influence of Diameter on Detonation Acoustic Characteristics of Pulse Detonation Engine

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Abstract: The experiment system of pulse detonation engine is set up to investigate on influence of diameter on detonation acoustic characteristic. The research of detonation acoustic characteristic of pulse detonation engine for four different diameters in different angles is carried out. Results from the test show that as the PDE diameter increasing, there are increases in amplitudes of impact noise in all angles, and the growth rate of amplitude of impact noise in the 90° direction is generally greater than that in the 0° direction. The smaller PDE diameter is, the distance of most obvious directivity at 0° turning to most obvious directivity at 30° is shorter. When the distance is shorter, such as 200 mm, the duration of detonation acoustic is increasing with the increase of PDE diameter, however, when the distance is longer, such as 3000 mm, it is just the opposite. The maximum duration of detonation acoustic is appeared in 3000 mm under 30 mm PDE diameter which reaches to 1.44 ms.

Keywords: aerospace propulsion system, pulse detonation engine, noise radiation, PDE diameter

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Introduction

The Pulse Detonation Engine (PDE) is an innovative propulsion system that utilizes repetitive high temperature and high pressure gas generated by detentions to produce thrust and power It is one of the research hotspots in recent years with the advantages of high thermal cycle efficiency, high specific impulse, hardware simplicity, light weight and high Thrust-to-Weight ratio. Compared with the same scale ramjet, PDE is twice the maximum thrust of the ramjet, while fuel consumption is only 60 % of the ramjet [1]. In 2012, NASA stated that PDE miniaturization research is the focus of its research, and PDE as a national strategy, placed on the latest development system technology roadmap. NASA's Marshell Space Center is expected to complete a full-size small-diameter PDRE engineering prototype within a few years [2]. Therefore, PDE has a broad application prospect in future aerospace and weapon fields. When PDE works, it produces strong impulse noise and vibration. The PDE acoustic radiation and vibration will directly affect the aircraft stealth and structural fatigue, which is one of the most serious threats to PDE performance and vehicle safety. With the rapid development of the PDE technology and the breakthrough of the key technical, the acoustical performance of PDE is valued, so the research on the acoustical performance of the PDE is a necessity. There are few studies on small-diameter gas-liquid two-phase PDE acoustic research. Experimental studies on the PDE acoustic characteristics have been carried out by Kohlberg et al. [3] and Allgood et al. [4–6]. Kohlberg et al. [3] measured the detonation acoustic at different distances outside the PDE tube through experiments, and proposed that the variation law of detonation acoustic can be predicted by the ideal blast wave theory. Allgood et al. [4–6] divided the detonation wave into a strong detonation wave and a weak detonation wave through the reference radius, and the peak attenuation of the detonation acoustic is predicted more accurately. In the reference radius, the peak attenuation of the detonation acoustic satisfies the cubic variation law; outside the reference radius, the peak attenuation of the detonation acoustic satisfies the one-time variation law. Zheng et al. [7, 8] found that the spectrum of PDE acoustic radiation is a broadband spectrum. Its energy is mainly concentrated in the low frequency part, which is composed of the fundamental frequency and harmonic frequency of

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the airflow pulsation. Xu et al. [9–12] studied the detonation acoustic of single-tube PDE, and analyzed the effects of nozzle, ejector and fill factor on the near-field acoustic characteristics of PDE. It is found that the PDE detonation noise is mainly composed of impact noise (which is produced by the shock waves) and jet noise (which is produced by the jet), and both the impact noise and the jet noise decrease as the distance increases. In the near-field region of PDE, the peak directivity of detonation acoustic is obvious, and the maximum value of detonation acoustic appears in the 0° direction. As the angle increases, the peak value of detonation acoustic gradually decreases. Huang et al. [13, 14] studied the near-field acoustic characteristics of multi-tube PDE. It is found that the peak sound pressure decay rate of detonation acoustic is the fastest near the PDE nozzle; the attenuation speed is gradually reduced from the far end of the nozzle. Shaw et al. [15] studied the detonation acoustic characteristics of four detonation tubes and found that the high-frequency energy of detonation acoustic dissipated rapidly in the atmosphere, causing the detonation acoustic to decrease rapidly with increasing distance.

Because PDE miniaturization research is the focus of future research, based on the research background, the PDE detonation acoustic test experimental system is set up based on previous research. The detonation acoustic characteristics of PDE under different PDE diameters are studied. The influence of PDE diameter on the peak sound pressure, directivity, duration and spectrum of detonation acoustic are analyzed.

Experimental setup

In order to study the influence of diameter on the detonation acoustic characteristics of PDE, the experimental system is designed and constructed. And the detonation acoustics of the PDEs with four diameters (30 mm, 60 mm, 80 mm and 100 mm) are studied. The schematic diagram of the experimental system is shown in Figure 1.

The system is composed of PDE tube, oxidant supply system, fuel supply system, ignition control system and test system. The PDE tube includes a mixing chamber, an ignition chamber, and a detonation chamber, as shown in Figure 2. The total length of the detonation tube is 1900 mm, and the ignition position is 1600 mm from the outlet. The mixing chamber uses the combination of tangential air inlets, fine atomizing nozzles and Venturi to increase the atomization effect of the gasoline. The oxidant flows from the tangential inlet hole into the detonation tube. The oil and gas mixture passes through the expanded section of the Venturi to form a viable mixture with good atomization, sufficient mixing, and uniform distribution. A spoiler and a shock reflector composed of a plurality of annular orifice plates are provided in the detonation chamber as an enhanced combustion device of the PDE.

In the experiment, gasoline is used as fuel, and compressed air and compressed oxygen are used as oxidants. The flow control of compressed air and compressed oxygen can be realized by adjusting the pressure of the gas, and real-time display of the flow through the Coriolis flowmeter. The switch of the compressed air and the compressed oxygen is realized by the control system controlling the solenoid valve. The oil supply system adopts a squeeze type oil supply method, that is, the gasoline stored in the oil tank is sent to the PDE nozzle by applying a certain pressure of inert gas. The flow control of gasoline can be realized by adjusting the pressure of the inert gas, and real-time display of the flow rate is realized by the Coriolis flowmeter, wherein the switch of the gasoline is realized by the control system controlling the solenoid valve. The control system includes an oxidant/fuel switch

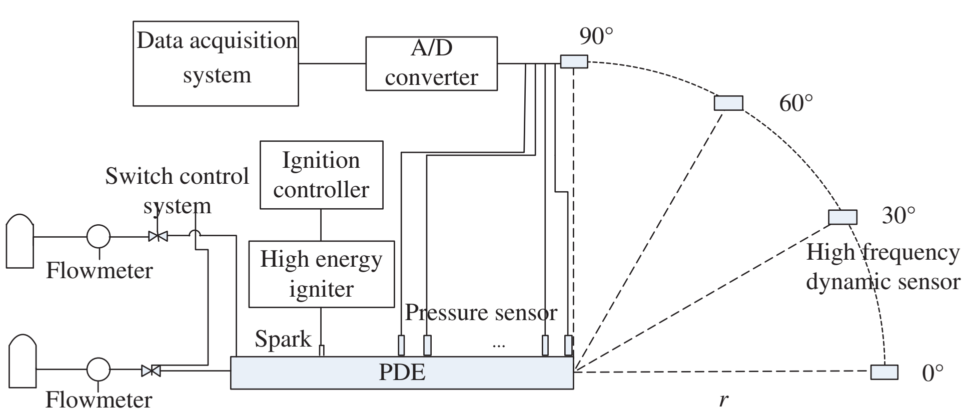


Figure 1: Schematic of the experimental setup.

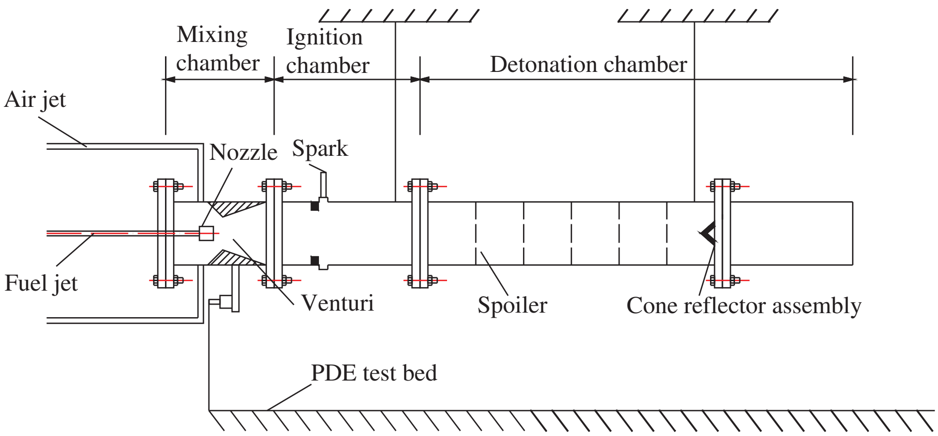


Figure 2: Diagram of the PDE.

control system and an ignition control system. The ignition control system consists of a signal control system, a high energy igniter and a spark. The signal control system consists of an ignition controller and a signal generator. In the experiment, the fuel and oxidant are always provided. The ignition interval of the spark is 100 ms. The fuel supply system and the gas supply system are controlled to ensure that the detonation acoustic test under different diameters is performed under the condition of full filling, equivalent ratio of 1 and detonation frequency of 10 Hz. The test system is consistent with the literature [10, 11], both use PCB high-frequency dynamic sensors, installed at multiple locations outside the PDE tube. The sensor is placed in the 0°, 30°, 60° and 90° outside the PDE tube, and the distance from the PDE outlet is *r*. The distance *r* can be adjusted according to the experimental requirements. Along the main direction of the detonation engine outlet airflow is defined as 0°, as shown in Figure 1. The collected thrust, pressure and acoustic electric signals are processed by the signal amplifier and A/D converter and recorded by the synchronous data acquisition system. The sampling rate is 500 k S/s. The practicality of PDE with different diameters is shown in Figure 3.

Figure 3: The practicality of PDE with different PDE diameters.

Results and discussion

Time domain analysis PDE detonation acoustic physical characteristics

In order to better understand the influence of the PDE diameter on detonation acoustics, the physical parameters of detonation acoustics, such as the impact noise and jet noise, are analyzed firstly. Figure 4 shows the waveform diagram of detonation acoustics along the 0° direction at a specific point, which is 800 mm from the exit of PDE with a diameter of 80 mm. The detonation

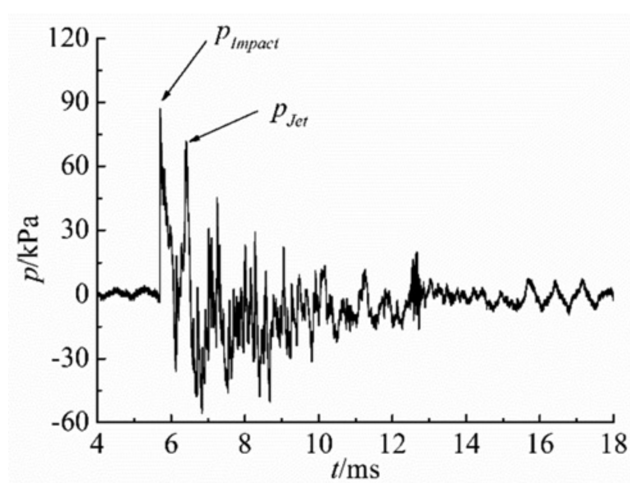
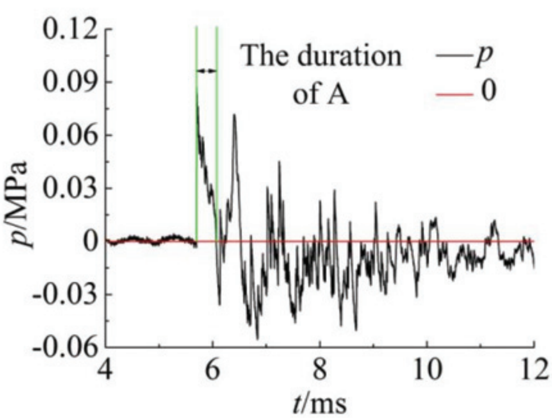


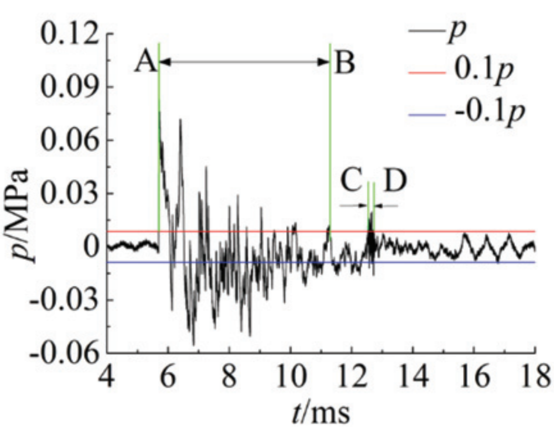
Figure 4: Detonation acoustic pressure time traces at 0° in 800 mm.

wave degenerates into a shock wave rapidly, after it passes the nozzle exit. When the shock wave flows through the specific point, the sound pressure of detonation noise rises rapidly, resulting in the formation of the first noise peak, reaching to 85.45 kPa, which is the peak of the impact noise (P_{Impact}). As the detonation gas jet arrives, a second noise peak occurs at 0.71 ms later, reaching to 71.78 kPa, which is the peak of jet noise (P_{Jet}). The detonation acoustic waveform oscillates due to the complex wave structure in the jet.

There are three durations of impulse noise, the duration of A (t_A), the duration of B (t_B), and the duration of C (t_c). t_A is the time required for the pressure waveform to rise to the main peak and then rapidly drop to ambient pressure, as shown in Figure 5(a). t_B is the duration of the main portion of the impulse noise



(a)



(b)

Figure 5: The duration of PDE detonation acoustic (a) The duration of A (b) The duration of B.

plus the time at which effective fluctuations are subsequently produced. The main part refers to the time when the initial pressure fluctuation is on the 20 dB range, and the subsequent pressure fluctuation is kept below the 20 dB range. In Figure 5(b), t_{AB} is the main part duration, and t_{CD} is the time after the effective fluctuation is generated. Since t_{CD} < 10 % of t_{AB}, t_B is equal to t_{AB}. t_c is the time within 10 dB below the peak sound pressure.

t_A and t_c are used for impulse noise and shock waves in the GJB2A-96 standard developed in 1996, while t_A and t_B are used for gun impulse noise. The definition of the duration of detonation acoustic is borrowed from gun impulse noise, and t_A is studied.

To make it easier to study the detonation acoustic directivity, the peak of PDE detonation acoustic is normalized, and the normalized expression is as follows:

$$\bar{P}_r^{\theta} = P_r^{\theta} / P_r^{0^0} \tag{1}$$

Where r is the distance between the test points and the nozzle; θ is the angle; P_r^{θ} is the peak of the detonation acoustic at the distance r in the angle θ; $p_r^{0^0}$ is the peak of the detonation acoustic at the distance r in the 0°; $\bar{P}_r^{\theta}$ is the dimensionless quantity after normalization of P_r^{θ}.

Influence of diameter on impact noise and directivity of detonation acoustic

Firstly, the amplitudes of impact noise in the 0° at different distances r is studied. The effect of diameter on the peak sound pressure of PDE detonation acoustic is showed in Figure 6. Under all diameters, as the distance r increases, the amplitudes of impact noise decreases. Under the same tube length, filling factor and stoichiometric ratio, the diameter of the tube increases, the total amount of reactants in the detonation tube increases, and the total energy generated by the chemical reaction also increases, so the diffraction energy of the detonation wave after leaving the nozzle increases, resulting in an increase in amplitudes of impact noise at all positions in all angles. This is why amplitudes of impact noise with a diameter of 100 mm is the largest at all positions, as shown in Figure 6. The ratio of amplitudes of impact noise in 100 mm diameter to 30 mm diameter at 200 mm in the 90° is 9.26, which is much larger than 4.27 at 200 mm in the 0°. It may be probably due to the radial effect, which causes the impact noise increasing faster in the 90° than 0°.

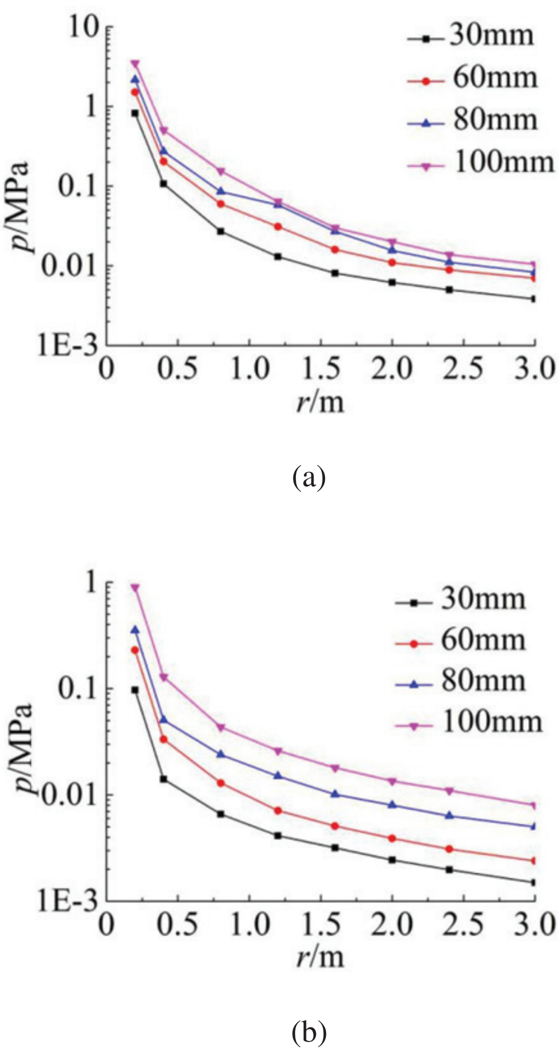


Figure 6: The amplitudes of impact noise with different PDE diameters at different angles (a) 0° (b) 30°.

The diameter also has an important influence on the directivity of the detonation acoustic. The directivity effect of diameter on PDE detonation acoustic at different distances is shown in Figure 7. As r increases, the direction of the maximum detonation acoustic is from the original 0°, slowly changing to the 30° under all diameters. It is due to the increasing distance r, impact shock wave becomes weak, increase the proportion of gas detonation jet noise. As the proportion of the dipole source caused by supersonic jet and quadrupole source caused by subsonic jet increases, the directivity changes. As the distance r increases, the $\bar{P}_r^{30^0}$ diameters of 30 mm, 60 mm, 80 mm, and 100 mm increased from 0.46, 0.61, 0.79, and 0.51 to 1.07, 1.10, 1.15, and 1.14, respectively. The smaller PDE diameter is, the distance of most obvious directivity at 0° turning to most obvious directivity at 30° is shorter. The turning points of the diameters of 30 mm, 60 mm, 80 mm and 100 mm appear at 1200 mm, 1600 mm, 2000 mm and 2000 mm, respectively. This is because the smaller the diameter, the earlier the jet as a dipole and quadrupole sound source, and the earlier the directivity changes.

Influence of diameter on t_A and spectrum

In order to study the influence of diameter on the t_A, the influence factors have been studied in advance. Figure 8 is a comparison chart of the time interval of impulse noise and jet noise and t_A at different positions in the 0° direction under the 80 mm pipe diameter. When it is closer to the nozzle, for example, r is 200 mm, the time interval between impulse noise and jet noise is less than the t_A. The t_A is jointly determined by impulse noise and jet noise at this time. Because the non-linearity of impulse noise is stronger than jet noise, the speed of impulse noise is greater than jet noise. Therefore, as the distance increases, the time interval between impulse noise and jet noise increases. When it is away from the nozzle, for example, r is 3000 mm, the time interval between impulse noise and jet noise is relatively long. As a result, when jet noise arrives, the detonation noise waveform has dropped to a negative value. Therefore, the time interval between impulse noise and jet noise is much longer than the t_A. At this time, the t_A is determined only by the impact noise.

The PDE diameter also has an important influence on the detonation acoustic t_A. The influence of PDE diameter on t_A in 0°, is as shown in Figure 9. When it is closer to the nozzle, for example, r is 200 mm, the peak of the jet noise follows the impact noise as the jet follows the shock wave. Due to the arrival of jet noise, the detonation noise waveform continues to rise after it has not dropped to a negative value, so the jet noise has an important influence on t_A. As the PDE diameter increases, the total gas volume increases, the gas jet intensity increases, and the jet noise duration increases, eventually resulting in an increase in detonation acoustic t_A. When the diameter is 100 mm, the t_A in 0° reaches to 2.60 ms Since the non-linearity of the impact noise is stronger than the non-linearity of the jet noise, the time interval between impact noise and jet noise increase as the distance increases. Furthermore, when the distance is long, such as r is 3000 mm, t_A is only determined by the impact noise. The smaller PDE diameter, the wider

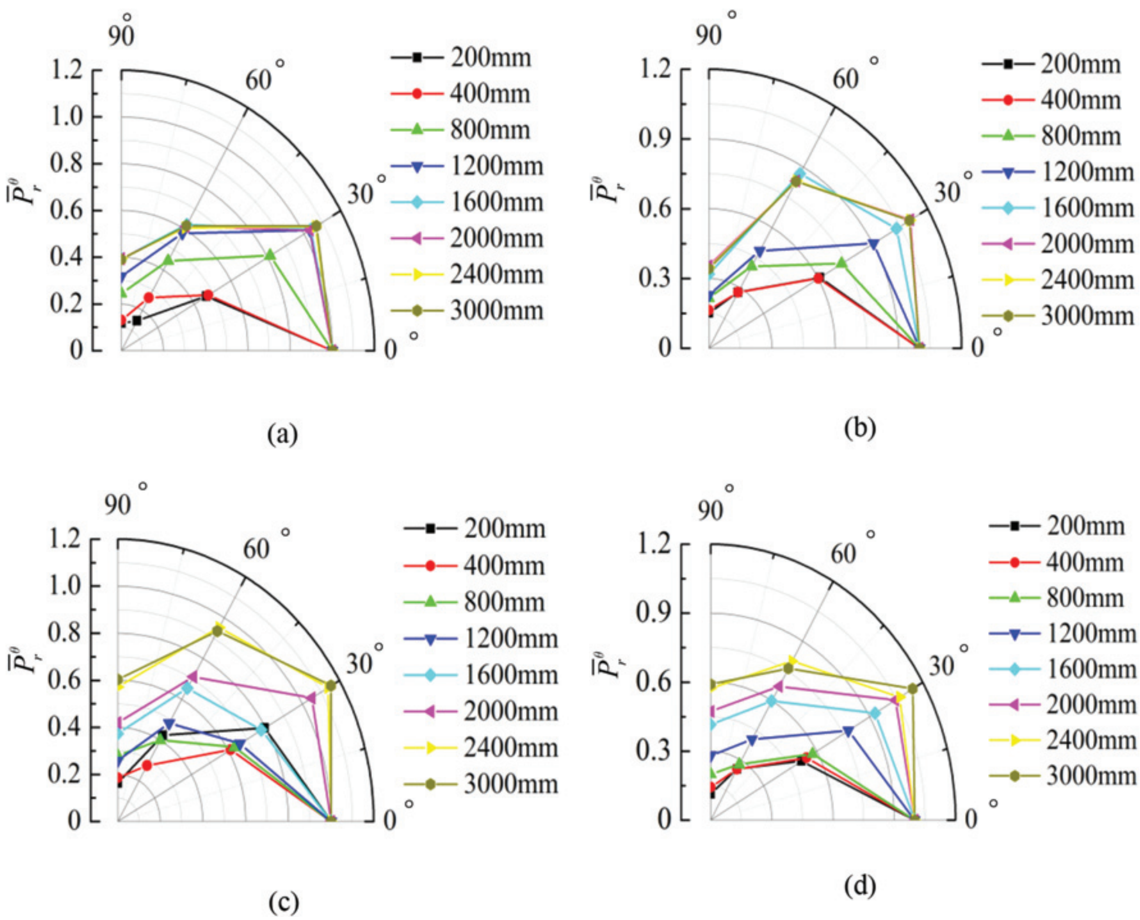


Figure 7: Directivity schematic of detonation acoustic with different PDE diameters at different distances (a) 30 mm (b) 60 mm (c) 80 mm (d) 100 mm.

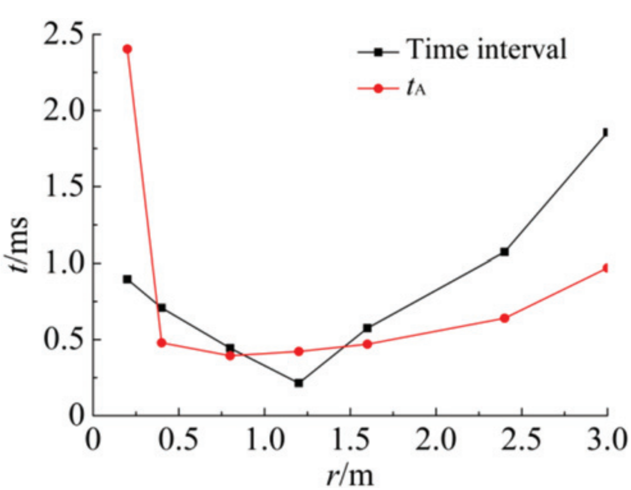


Figure 8: Time interval and the duration of A.

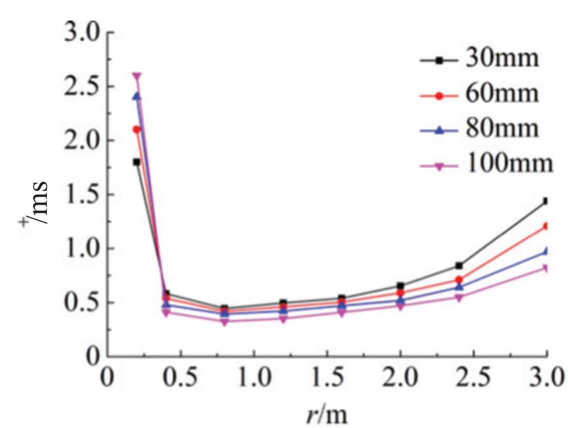


Figure 9: The duration of A with different PDE diameters at different distances.

impulse noise waveform and the longer t_A. The longest t_A appears at 3000 mm under the 30 mm PDE diameter, and its t_A can reach to 1.44 ms.

The PDE diameter also has an important influence on the detonation acoustic spectrum at 800 mm in the 0°, as shown in Figure 10. It shows that the shape of the

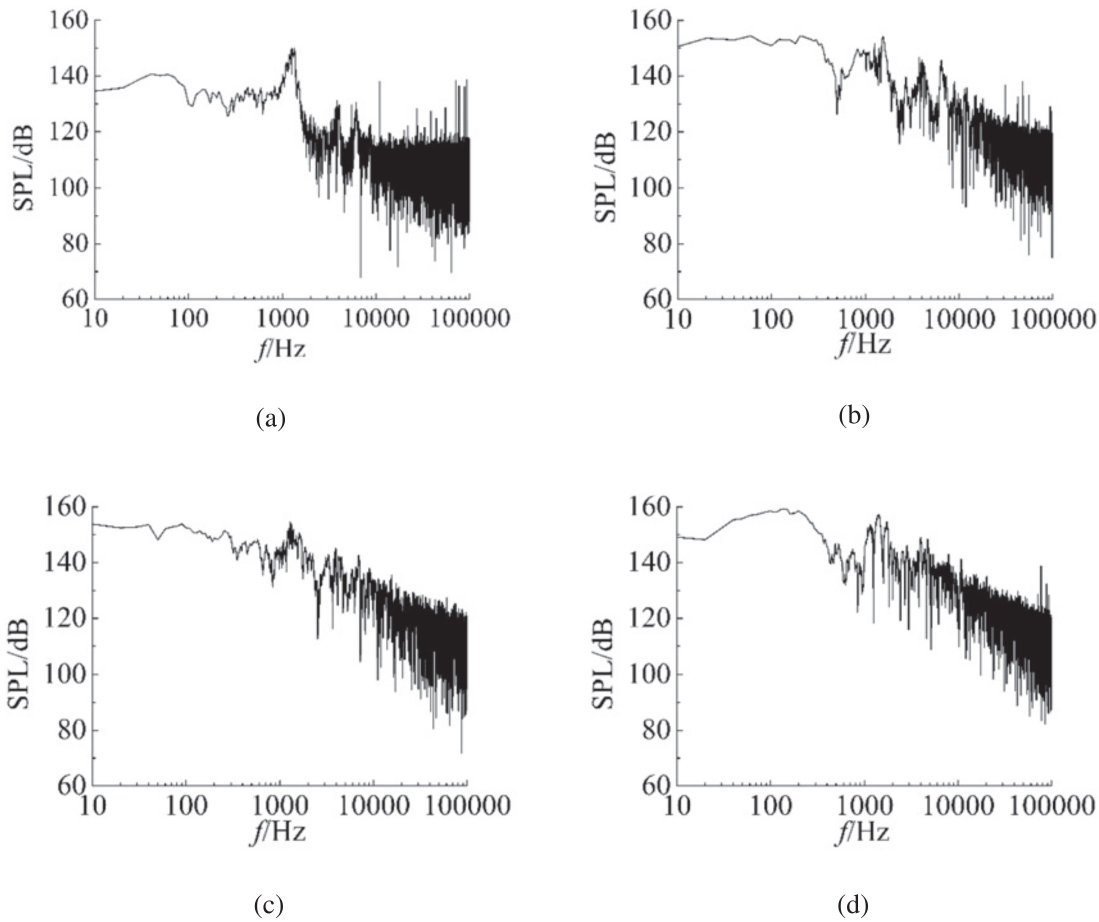


Figure 10: Spectrum of PDE detonation acoustic with different PDE diameters (a) 30 mm (b) 60 mm (c) 80 mm (d) 100 mm.

detonation acoustic spectrum under different PDE diameters is roughly the same. In the frequency band of 10 ~ 100 Hz, the intensity of the detonation acoustic signal remains basically unchanged with the increase of the frequency of the detonation acoustic in the spectrum. In the frequency range of 100 ~ 1000 Hz, as the frequency of detonation acoustic in the spectrum increases, the intensity of the detonation acoustic signal first weakens and then increases. In the frequency range of 1000 ~ 100 kHz, with the increase of the frequency of detonation acoustic in the spectrum, the sound pressure level of the PDE detonation acoustic frequency generally shows a downward trend. As the diameter increases, the total energy of the detonation acoustic increases. Therefore, the intensity of the detonation acoustic signal increases in the frequency band of 10 to 100 Hz, but the local maximum value of the intensity of the detonation acoustic signal occurring near 1000 Hz is almost constant.

Conclusion

By experimentally studying the PDE detonation acoustic characteristics of four diameters (30 mm, 60 mm, 80 mm and 100 mm), the following conclusions are drawn:

(1) As the PDE diameter increases, the amplitude of impact noise at all positions and directions increases. The growth rate of amplitude of impact noise in the 90° direction is generally greater than that in the 0° direction. For example, the increase rate in the 90° direction at the point of 200 mm from the nozzle exit is 9.26, which is much larger than that in the 0° direction, whose value is 4.27.

(2) As the distance r increases, the direction of the maximum detonation engine acoustic is changed from 0° to 30°. The smaller PDE diameter, the earlier directivity changes. The turning points of PDE diameters of 30 mm, 60 mm, 80 mm and 100 mm

appear at 1200 mm, 1600 mm, 2000 mm and 2000 mm, respectively.

(3) When the distance r is relatively close, such as 200 mm, the PDE diameter increases, the duration of jet noise increases, and eventually the t_A increases. When the distance r is far, such as 3000 mm, t_A is determined by the impact noise. The smaller PDE diameter, the smaller amplitude of impact noise, and the wider the impact noise waveform, the longer the t_A. The longest t_A appeared at 3000 mm under the 30 mm PDE diameter, which reach to 1.44 ms.

(4) The shape of the detonation acoustic spectrum under different PDE diameters is roughly the same. As the diameter increases, the intensity of the detonation noise signal increases.

Nomenclature

P_{Impact}	The amplitude of impact noise
P_{Jet}	The amplitude of jet noise
t_A	The duration of A
t_B	The duration of B
t_c	The duration of C
P_r^θ	The peak of the detonation acoustic at the distance r in the angle θ
$\bar{P}_r^\theta$	The dimensionless quantity after normalization of P_r^θ

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