Experimental Investigation of Nozzle Effects on Thrust and Inlet Pressure of an Air-breathing Pulse Detonation Engine

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Abstract

Nozzle effects on thrust and inlet pressure of a multi-cycle air-breathing pulse detonation engine (APDE) are investigated experimentally. An APDE with 68 mm in diameter and 2 050 mm in length is operated using gasoline/air mixture. Straight nozzle, converging nozzle, converging-diverging nozzle and diverging nozzle are tested. The results show that thrust augmentation of converging-diverging nozzle, diverging nozzle or straight nozzle is better than that of converging nozzle on the whole. Thrust augmentation of straight nozzle is worse than those of converging-diverging nozzle and diverging nozzle. Thrust augmentations of diverging nozzle with larger expansion ratio and converging-diverging nozzle with larger throat area range from 20% to 40% on tested frequencies and are better than those of congeneric other nozzles respectively. Nozzle effects on inlet pressure are also researched. At each frequency it is indicated that filling pressures and average peak pressures of inlet with diverging nozzle and converging-diverging nozzle with large throat cross section area are higher than those with straight nozzle and converging nozzle. Pressures near thrust wall increase in an increase order from without nozzle, with diverging nozzle, straight nozzle and converging-diverging nozzle to converging nozzle.

Keywords: nozzle; effect; thrust; inlet pressure; air-breathing pulse detonation engine

Nomenclature

DDT  Deflagration-to-detonation transition
$M_{bc}$ Average Mach number of detonation tube exit section
$Ma_1$ Mach number of filling air
$Ma_D$ Mach number of detonation waves
$M_1$ Molecular weight of unburned gas
$M_2$ Molecular weight of burned gas
$k$ Specific heat ratio of air
$\gamma_2$ Specific heat ratio of burned gas
$\lambda$ Velocity factor
$q(\lambda)$ Non-dimensional density flow
$A$ Section area
$A_{cr}$ Critical area
$p^*$ Total pressure
$p$ Static pressure
$\rho$ Density
$v$ Velocity
$C$ Constant
$F_0$ Thrust produced on baseline condition
$F$ Thrust produced on conditions with nozzles

1. Introduction

Pulse detonation engines (PDEs) are currently an active area of propulsion research due to their potential
for improved performance and reduced mechanical complexity in comparison to conventional propulsion systems. Although ideal analysis suggests that the pulsed detonation propulsion cycle can be thermodynamically more efficient than its steady-flow counterparts, it needs to show whether a practical device can be developed to exploit these inherent advantages. Critical to the success of the PDE concept is the implementation of a nozzle capable of efficiently converting as much of the thermal energy in the exhaust gases into usable propulsive force \(^1\). Nozzle effects on PDE performance were investigated by many researchers recently \(^{1-10}\). Both experimental \(^{2-4}\) and computational \(^{5-10}\) studies were implemented extensively with single-shot or multi-cycle operation.

Cooper, et al. \(^2\) measured impulse through direct single-shot experiment. They concluded that straight nozzle generated the greatest increase in impulse and the effective of diverging nozzles on the impulse was slight. Allgood, et al. \(^3\) researched a multi-cycle PDE operation where the thrust augmentation levels provided by various converging and diverging bell-shaped exhaust nozzles were quantified. For each nozzle configuration, the operating fill-fraction was varied to quantify their corresponding partial-fill effects. It is concluded that the optimum area ratio was a function of fill-fraction. When the fill-fraction was less than 0.5, performance of the engine without nozzle was the best. When the fill-fraction was added to over 1, thrust enhancement was obtained with a converging nozzle. The diverging nozzles also showed a relative increase in their performance with increased fill-fraction. Owens and Hanson \(^1\) designed unsteady nozzle by numerical and experimental methods. They obtained the optimum area ratio of converging-diverging nozzle with computational method. They investigated three nozzles (converging-diverging nozzle, diverging nozzle and straight nozzle) computationally and experimentally and analyzed the results of two methods contrastively. It is concluded that diverging nozzle could generate the maximal single-cycle impulse. The nozzle with smaller throat area could provide higher fill pressure, which possibly benefited the multi-cycle operation of the engine. Wang, et al. \(^4\) investigated experimentally the effects of nozzle area ratio and length/diameter ratio on thrust and suggested that the converging nozzle produced the best thrust augmentation. The smaller the area ratio, the better the thrust augmentation. The diverging nozzle generated slight thrust augmentation and even reduced the thrust. The impact of converging-diverging nozzle was inferior to that of the converging nozzle. The length/diameter ratio of a nozzle affected the performance of an engine slightly and the averaged thrust declined slightly with the increase of length/diameter ratio.

As this research is experimental investigation, references about calculation \(^5-10\) are not presented in detail. Various effect factors such as nozzle shape, nozzle area ratio, partial fill and ambient pressure on PDE performance were explored extensively. Many conclusions on the report of PDE nozzles showed remarkable disagreements due to the differences of specific conditions of various experiments and calculations. Detailed reviews on the current level of PDE nozzle technology were given by Kailasanath \(^11\) and Allgood, et al. \(^3\) respectively. With regard to air-breathing PDE (APDE), filling air resistance has not been considered in nozzle investigations \(^6\), which is inconsistent with the practice. And the effects of various nozzles on inlet filling pressures and average peak pressures have not been researched before.

The current work is an experimental investigation of a multi-cycle two-phase valveless APDE operation where the thrust augmentation levels provided by various nozzles on 8, 10, 12, 15 Hz were quantified. And filling air resistance was discussed, which was prerequisite for the investigation of effects of APDE nozzles on thrust. The effects of various nozzles on inlet filling pressures and average peak pressures were also discussed. The tested nozzles in this paper included a straight nozzle, three converging nozzles, two converging-diverging nozzles and two diverging nozzles. The ratio of nozzle length to engine tube length was all about 0.1. Thus, for these nozzles of non-negligible length, partial-fill effects of these nozzles would have an insignificant impact on the PDE performance and could not be taken into consideration.

2. Experimental Setup

2.1. Experimental system

Figure 1 is the schematic of experimental system. A valveless APDE with 2 050 mm in length and 68 mm in diameter consisted of air inlet, mixing chamber, ignition chamber, detonation chamber and nozzle. Shchelkin spiral in detonation chamber was used to accelerate deflagration-to-detonation transition (DDT). The engine operated with gasoline/air mixture. Thrust and pressure were measured by piezoelectric thrust transducer \(^4\) and pressure transducer. The thrust calibrating system in Ref. [12] was adopted. A fuel tank was pressurized by high pressure nitrogen. A centrifugal injector was installed on the head of the engine. The engine was ignited by auto spark plug with 50 mJ ignition energy.

As shown in Fig. 1, nine piezoelectric pressure transducers are mounted along the engine. Locations 1-5 apart from thrust wall were 480, 300, 140, 50, 80 mm (minus represents that Locations 1-4 were upstream from the thrust wall) respectively. The distances of Locations 6-9 from the spark plug were 1 050, 1 150, 1 250, 1 350 mm respectively. The former five piezoelectric pressure transducers were used to measure the inlet filling pressures and the latter four were used to record the history of the pressure of detonation chamber.
2.2. Nozzles

Nozzles under investigation included a straight nozzle (S), three converging nozzles (C1, C2 and C3), two converging-diverging nozzles (CD1 and CD2) and two diverging nozzles (D1 and D2); their parameters are shown in Table 1. The baseline condition without a nozzle was presented by symbol U.

Table 1 Geometric parameters of nozzles used in present work

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline condition U</th>
<th>Straight S</th>
<th>Converging</th>
<th>Converging-diverging</th>
<th>Diverging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C1</td>
<td>C2</td>
<td>CD1</td>
</tr>
<tr>
<td>Area ratio</td>
<td>1</td>
<td>1</td>
<td>0.971</td>
<td>0.364</td>
<td>0.236</td>
</tr>
<tr>
<td>Exit diameter/mm</td>
<td>68</td>
<td>68</td>
<td>67</td>
<td>41</td>
<td>33</td>
</tr>
<tr>
<td>Throat diameter/mm</td>
<td></td>
<td></td>
<td>67</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Length/mm</td>
<td>0</td>
<td>210</td>
<td>210</td>
<td>210</td>
<td>210</td>
</tr>
</tbody>
</table>

C1 and CD1 were designed as follows: Firstly, average Mach number of detonation tube exit section was calculated according to the parameters of detonation:

\[ M_{0hbc} = (M_{0h} + M_{0d}) \left( \frac{M_1^2 - M_f^2}{M_2^2 - M_f^2} \right)^{\frac{1}{2}} - 1 \]  \hspace{1cm} (1)

Secondly, \( q(\lambda) \) was determined from gas dynamics function table according to \( M_{0hbc} \).

Then, exit section area of C1 was calculated by the following equation:

\[ q(\lambda_i)A_i = A_{cr} \]  \hspace{1cm} (2)

where the subscript "i" represents Section \( i \).

The throat area of CD1 was from the exit area of C1. Length of the diverging section of CD1 was calculated in terms of 10°-12° in conical angle.

In design of C1 and CD1, unsteady flow field was dealt with as steady flow field through the calculation of the average value. The idea could grasp the general trend.

Other nozzles were designed according to the increase or decrease of area ratio.

3. Results and Discussion

3.1. Thrust

3.1.1. Baseline condition

The test condition is that the pressure of filling air is a little higher than 101 325 Pa and the ambient temperature is 0 °C approximately. The oxidant is air and fuel is gasoline. The pressure and speed of detonation wave calculated by CEA \(^{[13]}\) code in the condition are 2 MPa and 1 799.3 m/s respectively.

Working conditions are selected from the tests without nozzle as shown in Table 2. The pressure of gasoline tank is 709 275 Pa and air pressure is about 101 325 Pa. Figure 2 shows the histories of thrusts and pressures (\( p_1, p_5, p_8, p_9 \)) at frequencies of 8, 10, 12, 15 Hz at the four states without nozzle. The peak pressure on the 8th transducer is the highest and achieves the value from CEA. The average speeds of detonation wave between the 8th and 9th measuring locations at four frequencies are 1 666.67, 1 666.67, 1 538.46, 1 694.9 m/s respectively, which are a little lower than C-J detonation wave speeds obtained by CEA code. Considering the decay of detonation wave between the 8th and 9th measuring locations and imperfect mixing and atomization of gasoline and air, it is deduced that the fully-developed detonation wave forms.

Table 2 Working conditions in the experiments (baseline condition)

<table>
<thead>
<tr>
<th>Frequency/Hz</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline mass flow (mL·s(^{-1}))</td>
<td>6.0</td>
<td>7.2</td>
<td>8.2</td>
<td>11.0</td>
</tr>
<tr>
<td>Air mass flow (m(^3)·h(^{-1}))</td>
<td>510</td>
<td>630</td>
<td>690</td>
<td>880</td>
</tr>
</tbody>
</table>
3.1.2. Effects of nozzles on thrust

Figure 3 shows the thrust augmentation \((F - F_0)/F_0\) of various nozzles at four frequencies. On the whole, thrust augmentations of converging nozzles with smaller exit section diameter (C2 and C3) and converging-diverging nozzles with smaller throat section diameter (CD2) are lower. Thrust augmentations of diverging nozzle with larger exit section (D2) and converging-diverging nozzle with larger throat section (CD1) are the best and both of the augmentations at each frequency all range from 20\% to 40\%. Thrust augmentations of diverging nozzles are better than those of converging nozzles on the whole. With the increase of frequency, the mass flow of inlet air increases and the number of nozzles with better thrust augmentation tails off. In conclusion, for APDE, the size of exit section area and throat section area influences the thrust augmentation observably. The thrust augmentation improves with the increasing size of exit section area and throat section area which could bring about the decrease of flow resistance of the engine and enhance the ability of doing work by expansion. But C1 and CD1 are special. Though exit section diameter of C1 is 67 mm and smaller than 96 mm of D1, the thrust augmentations of them are equivalent. The thrust augmentations of CD1 and D2 are also equivalent and the best. Throat section diameter of CD1 is 67 mm and exit section diameter is 99 mm and smaller than 136 mm of D2. It is indicated that with regard to unsteady periodic detonations in APDE, thrust augmentation mechanism of nozzle needs deeper understanding. Unsteady flow field is dealt with as steady field in design of C1 and CD1. High subsonic (calculated by Eq. (1)) flow on engine exit reaches sonic through C1. High subsonic flow reaches sonic then expands into super-
sonic through CD1. C1 and CD1 excel other con-

generic nozzles of the same type.

3.2. Pressure analysis

Pressures of flow field in inlet are obtained by pressure analysis of Locations 1-5. Effects of filling air, propagating upstream of detonation wave and flame, as well as exhaust and nozzles on inlet pressures are revealed by measurement and analysis of inlet pressure, which is benefit for us to acquaint nozzle effects on APDE thrust.

Figure 4 shows the plots of pressure histories of Locations 1-5 in a cycle with a 210 mm-long straight nozzle. Figure 4(a) shows that detonable mixture in the engine is ignited. Then deflagration waves propagate towards two opposite directions. Deflagration waves propagate upstream through Location 5 to Location 1 along Line 1. Deflagration waves propagating downstream are strengthened by Shchelkin spirals and becomes detonation waves. Then most of detonation waves and burned gas discharge from engine exit. And a few shock waves propagate upstream along Line 2. Rarefaction waves from exit after the exhaust of detonation waves and air flow that is supplied by gas tank continuously are introduced into combustor. Rarefaction waves meet filling air, thus creating compressed waves which pass through five locations along Line 3. The pressure of filling process between Line \( a \) shown in Fig. 4(b) and Line 1 is steady. Nozzle effects on average filling pressure in this steady process will be discussed in the next section.

Figure 4 show the pressure magnitude at five locations. Pressures are rather low on Location 1 and Location 2 and rise on Location 3 and Location 4, especially highest on Location 3 and reduce again on Location 5. Pressure magnitude is relative to the location of pressure measuring point and flow condition there. In steady filling phase, there exists Bernoulli’s equation:

\[
p^* = p + (\rho v^2) / 2
\]

Total pressure \( p^* \) does not change largely in flow and \( v \) is big on Location 1 which is on intake, so \( p_1 \) is small. On Location 2, air is inbreathed in engine at a speed due to the ejection of filling air, which causes that \( p_2 \) is also small and even negative. Two parts of air join on Location 3. Equivalent cross section here is grate. According to continuum equation,

\[
A_n v_n = C
\]

where subscript “\( n \)” represent Section \( n \).

It is obvious that \( v \) is small on Location 3. And it is obtained that \( p_3 \) is large according to Eq. (3). Cross section area on Location 4 is smaller than that on Location 3. According to Eq. (4) it is obtained that \( v \) on Location 4 is larger than that on Location 3. In accordance with Eq. (3), it is obtained that \( p_4 \) is smaller than \( p_3 \). Air flows from Location 4 to Location 5 through transition section. Air is mixed with liquid fuel. These could cause a mass of total pressure loss. And the cross section area of Location 4 and Location 5 is equivalent, so \( v \) is invariable and \( p_5 \) is very small.

In detonation phase, detonation wave is weak when propagated to the head of engine. Therefore the pressure of each location increases a little and pressure relative magnitude of each location hardly varies.

3.2.1. Nozzle effects on filling pressure of Locations 1-5

Figure 5 shows the plots of averaged filling pressure of Locations 1-5 on each nozzle at 8, 10, 12, 15 Hz respectively. It is indicated that filling pressures of Locations 1-4 with diverging nozzle and converging-diverging nozzle with large throat cross section area are higher than those with straight nozzle and converging nozzle on the whole at each frequency. Inlet filling pressure without nozzle is higher than that with nozzle. It is relative to the expansion ratio of nozzles. With large expansion ratio, burned gas produces excessive expansion on engine exit, which causes the fact that little shock wave transmits in reverse and little rarefaction waves transmit in engine from inlet. A nozzle with larger expansion ratio causes lower pressure (e.g., pressure of Location 5 is negative) and larger...
velocity in detonation tube. But velocity of Locations 1-4 does not increase rapidly, which results in pressure rising. Figure 5(a) shows that filling pressures of Locations 1-4 with D2 are the highest and on Location 1 the pressure presents positive, which is due to that excessive expansion produced by D2 is the strongest. The trend of nozzle effects on pressure of Location 5 is quite obvious and basically in an increase order from without nozzle, with diverging nozzle, with straight nozzle, with converging-diverging nozzle to with converging nozzle. The pressure of Location 5 increases with the decrease of expansion degree of nozzles. The reason is that larger expansion degree causes lower back pressure in engine in filling phase. Figure 5(d) shows that with C1 the pressures of Locations 1-4 are the highest and that of Location 5 is the lowest. The reason is that at 15 Hz air mass flow is the largest and it is close to choked state. The nozzle achieves the strongest expansion.

3.2.2. Nozzle effects on average peak pressures of Locations 1-5

Figure 6 shows the plots of average peak pressures on each pressure measuring location when shock waves transmit upstream at each frequency in detonation process. On Locations 1-4, Fig. 6 shows that pressures of shock waves transmitting upstream with diverging nozzle and converging-diverging nozzle are higher than with converging nozzle and straight nozzle, which is up to expansion degree of the nozzles. When shock waves transmit upstream to Location 5, detonation waves have propagated out of engine. It is in low pressure situation after the expansion in the detonation tube. The effects of nozzle expansion degree on pressure magnitude of Location 5 are obvious. Figure 6 shows that the pressure of Location 5 is generally consistent with the regularity described previous section.
4. Conclusions

Nozzle effects on thrust and inlet filling pressure are obtained on a multi-cycle APDE operation system. Thrust augmentation levels provided by various nozzles are quantified. It is concluded that

1) Thrust augmentation of converging-diverging nozzle, diverging nozzle or straight nozzle is better than that of converging nozzle on the whole. Thrust augmentation of straight nozzle is worse than those of converging-diverging nozzle and diverging nozzle.

2) Thrust augmentations of diverging nozzle with larger exit section (D2) and converging-diverging nozzle with larger throat section (CD1) have the largest thrust augmentations and both of them at each frequency all range from 20\%/8 to 40\%/8.

3) Thrust augmentations of converging nozzles with smaller exit section diameter (C2 and C3) and converging-diverging nozzle with smaller throat section diameter (CD2) are lower.

4) C1 and CD1 are designed with the method that unsteady flow field is dealt with by the method of steady field and excelled respective congeneric other nozzles.

5) With the increase of frequency, the mass flow of inlet air increases and the number of nozzle with better thrust augmentation tails off.

6) At each frequency it is indicated that filling pressures and average peak pressures of inlet (on Locations 1-4) with diverging nozzle and converging-diverging nozzle with large throat cross section area are higher than those with straight nozzle and converging nozzle.

7) Pressure near thrust wall (on Location 5) increases in an increase order from without nozzle, with diverging nozzle, straight nozzle and converging-diverging nozzle to converging nozzle.

References


Biographies:

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