# Experimental Study on DDT Characteristics in Spiral-Configuration Pulse Detonation Tubes

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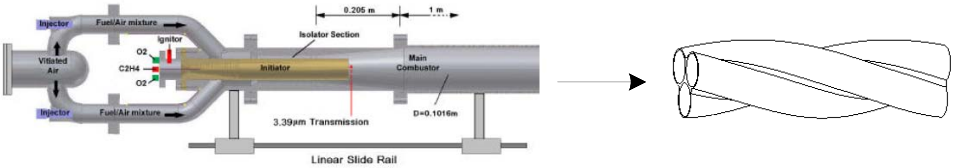
## 1 Introduction

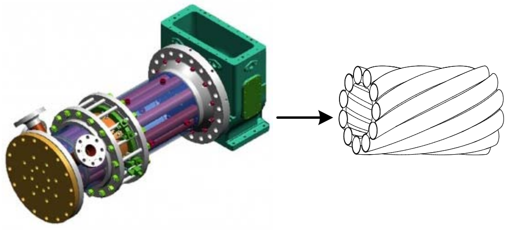
Pulse Detonation Engine (PDE) is a new-concept propulsion system utilizing repetitive detonations to produce thrust or power [1]. Because the fundamental advantages of high thermal cycle efficiency, in recent years researchers [2~5] use PDEs to replace traditional turbofan or turbojet engines, which named Hybrid Pulse Detonation Engine (HPDE). Theoretical calculation results [6] show that the performance of HPDE is much higher than the existing conventional engines. In order to improve the HPDE performance, one of the important points is to obtain a high performance PDE, and make it suit for the HPDE system.

In the studies of PDE, researchers always use low-initiation energy system to produce fully-developed detonations. The indirectly initiation use small ignition energy to produce deflagration flame, and after a deflagration-to-detonation transition (DDT) process, this deflagration transforms into detonation.

Due to the DDT process, the axis length of the detonation tube is always longer than the current combustion chamber, and it is inconvenient in the engineering application of HPDE. In order to reduce the axial length of detonation tube, the practical way is reducing the DDT distance. The common-used methods are adding various types of obstacles in the detonation tubes, such as Shchelkin spiral [7], orifice plate [8], etc. compared with the tubes without obstacles, these methods greatly reducing the DDT distance. But the reduced distance is not enough; the tube axial length is still too long. According to Austin [9], the DDT distance is at least 10 times greater than the cell size, and therefore the cell sizes for high hydrocarbon fuel and air are generally around 0.05m, so the DDT distance is more than 0.5m. Moreover, if the distance used for the mixing of fuel and air is taken in into consideration, the axial length of the PDE chamber is much longer than the traditionally length of aircraft engine combustion chamber.




(a) Spiral tube application in the single detonation chamber



(b) Spiral tube application in the multi-tube detonation and HPDE
Figure 1. Bending mode of straight detonation tube to spiral detonation tube

A practicable way to reduce the axial length of the detonation tube is to replace straight chamber with a curve one. For example, the axial lengths of the Naval Postgraduate School single-tube PDE [10] and GE's multi-tube pulse detonation turbine combustion system [11] are both longer than 0.8m, and if the tubes are changed like the right figure of Figure 1, the axial length of the detonation tube is a shorter one, and this spiral detonation tube could be a better one for HPDE system.

In the previously work, some experiments of spiral tubes have already been performed [12], and the objective of the research outlined in this paper is add some experiments and to acquire the transition rule of DDT, which would provide the design data and theoretical basis in the curved detonation chamber.

## 2 Experimental Setup

Adding obstacles in straight tube will increase flow resistance of the tube, and this flow resistance increase can reduce the DDT distance. Bending straight tube to a spiral one can also increase the tube flow resistance, so it is necessary to study the flow resistance of different spiral tubes, and the results could offer some assistance to the analysis of the detonation experimental data.

One metal tube was used in all the flow resistance experiments, and the tube length is 2000mm, the internal diameter is 60mm. In the flow resistance experiments, one simple shape frame has been used to shape the spiral in different diameter and pitch. Table1 lists all the spiral tubes geometry parameters, where L is the axial length of spiral section, *RC* and *RT* is radius of curvature and radius of torsion of the spiral tube, and they are defined as Equation (1) and Equation (2) respectively. P is the spiral pitich, D is the spiral diameter, and they are explianed in Figure 2.

Table 1. Geometric parameters of the 9 different detonation tubes

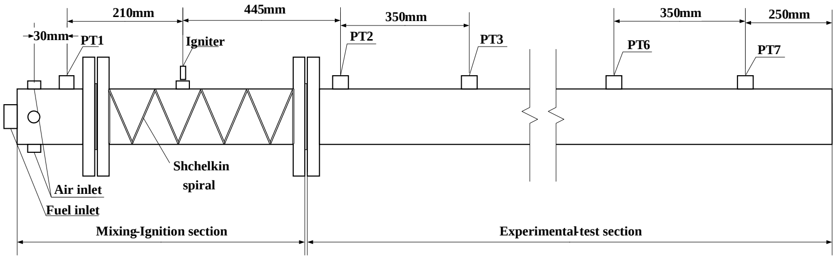
| | Spiral1 | Sprial2 | Sprial3 | Sprial4 | Sprial5 | Sprial6 | Sprial7 | Sprial8 | Straight |
|---|---|---|---|---|---|---|---|---|---|
| P (mm) | 1440.0 | 1440.0 | 1080.0 | 1080.0 | 720.0 | 720.0 | 480.0 | 480.0 | |
| D (mm) | 300.0 | 400 | 400.0 | 300.0 | 400.0 | 300.0 | 400.0 | 300.0 | |
| *RC* (mm) | 500.2 | 462.6 | 347.7 | 347.0 | 265.7 | 237.5 | 229.2 | 188.9 | |
| *RT* (mm) | 327.4 | 403.7 | 404.6 | 302.8 | 463.7 | 310.9 | 600.0 | 370.9 | |
| L (mm) | 1674.1 | 1507.3 | 1303.5 | 1507.3 | 994.3 | 1214.1 | 713.7 | 907.2 | 2000.0 |

$$RC = \frac{(D/2)^2 + (P/2\pi)^2}{(D/2)} \quad (1)$$

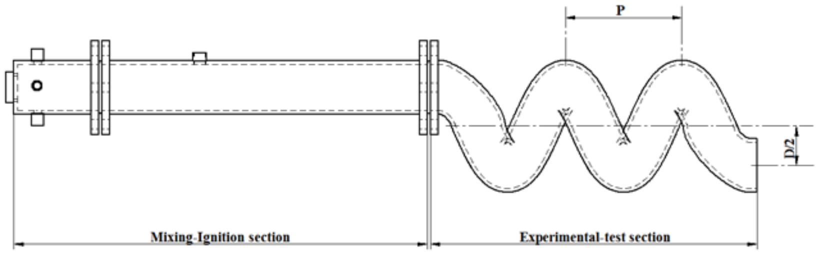
$$RT = \frac{(D/2)^2 + (P/2\pi)^2}{(P/2\pi)} \quad (2)$$

Figure 2 shows the pulse detonation tube experimental setup. The detonation tube consists of two sections, one was mixing-ignition section, and the other was experimental-test section. The mixing-ignition section was a straight tube with Shchelkin spiral, and it was designed to make the gasoline/air mix as well as possible in a short distance while the igniter was used to ignite the detonable mixture reliably. The length of the mixing-ignition section was 660mm and the internal diameter was 60mm. The spiral-test section was a metal hose which can be shaped as a spiral tube, and the total length of this section was 2000mm, the internal diameter was 60mm. In the experiments, one simple shaping machine was used to shape the metal hose as a different spiral tube with different pitch (P) and diameter (D) as Figure 2(b) showed. Moreover, the spiral tube geometry parameters were the same as table1 showed.

In all the detonation experiments, liquid gasoline was used as the fuel; air was used as the oxidizer. The mass flow rate of air was around 0.075kg/s and the equivalence ratio was around 1.1. The ambient pressure and temperature were around 0.1MPa and 295K, respectively. The working frequency of the detonation tubes were 2Hz. Because the working frequency was low, the interval time of two adjacent ignitions was long enough to neglect the influence of two neighboring working cycles, in other words, the experiment can be regarded as a single working cycle.




(a) Schematic of straight pulse detonation chamber experimental setup




(b) Schematic of spiral pulse detonation tube

Figure 2. Schematic of experimental setup

The fuel was supplied into a small vessel and then fed into the tube by one fuel pipe; one twin-fluid air-assist atomizer was used for liquid gasoline injection. The fuel and air were introduced to detonation tube by adaptive control without any valves. For injection conditions, the detonative mixture flow rates depended on the volume of detonation chamber, equivalence ratio, and detonation frequency. For example, in the gasoline/air detonation experiments, in a 50 mm inner diameter, 2 m length detonation chamber, the detonation frequency was 5 Hz and the equivalence ratio is 1.0, the gasoline flow rate was 0.0082 kg/s and 0.023 kg/s for air.

The detonative mixture was initiated by one initiation system, the igniter of automotive spark plug was used to initiation the mixture, and the delivered energy can be controlled. For ethylene/air experiments, the ignition was set 50mJ and 1.0J for gasoline/air experiments. Moreover, the detonation frequency was based on the spark plug ignition frequency, and the ignition frequency was controlled by the signal generator.

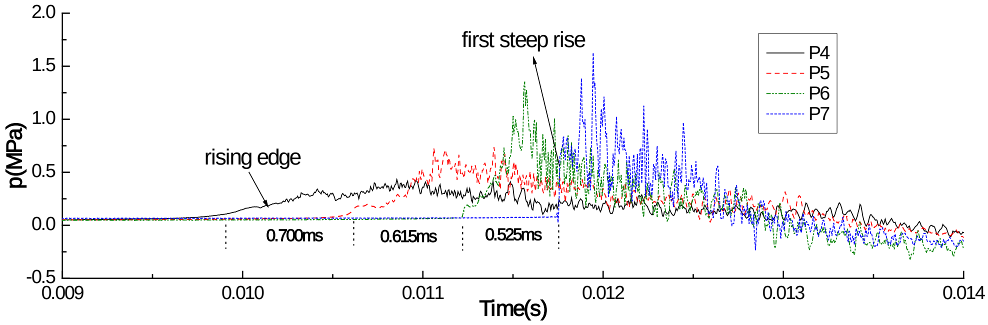
Piezoelectric pressure transducers (PT1~PT7) were mounted along the flow path to capture the wave dynamics and verify that Chapman-Jouguet (CJ) detonations were obtained, and the corresponding pressure files were named P1~P7. The locations of the transducers are shown in Figure 2(a). The transducer PT1 is used to monitor the pressure in the air inlet. The distance of transducer 1 and 2 from the spark plug was 210mm and 445mm, respectively. The distance between the two adjacent pressure transducers (PT2~PT7) was 350mm. In the experiments of spiral detonation tubes the locations of the transducers were kept the same as the straight tube and this arrangement will make sure all the pressure transducers are in one spiral line, thus the RC is the same.

The output signal from the pressure transducers was sent to a charge amplifier and then sampled by the DEWETRAN data acquisition and processing system. The sampling rate was 200K samples per second.

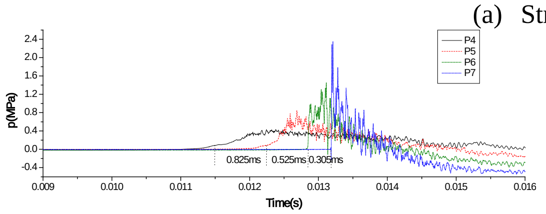
# 3 Results and Discussion

Figure 3 shows the pressure profiles of the straight and two of the eight spiral detonation tubes at the locations of PT4 to PT7. According to figure 3(a), all the pressure profiles of straight tube at PT4~PT6 had a longer rising edge, the first pressure steep rise generated at the position of PT7, in another word, the shock wave was first obtained at PT7, and the pressure peak value was 1.6MPa. According to pressure profiles of P6 and P7, the velocity of the shock wave at the position of PT6 to PT7 was 667m/s, just 36% of the CJ velocity. As a result, in the straight detonation tube before PT7 there was no detonation wave formed.

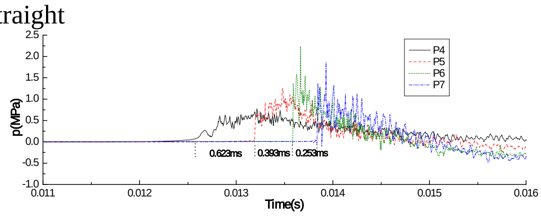
According to figure 3(b)~figure 3(c), only the pressure profiles of P4 like the pressure profiles of straight tube had a longer rising edge, and these pressure profiles illuminated the compression waves had already formed at the position of P4. And all the rising edges of P5 were shorter than the straight tube, especially in figure3(c), the pressure profiles of P5 have a steep rise, which illuminated that shock wave have already formed. These results showed that the spiral configuration can accelerate the detonation wave formation.




(a) Straight




(b) Spiral 1




(c)Spiral 8

Figure 3. Pressure profiles of detonation tubes of P4~P7

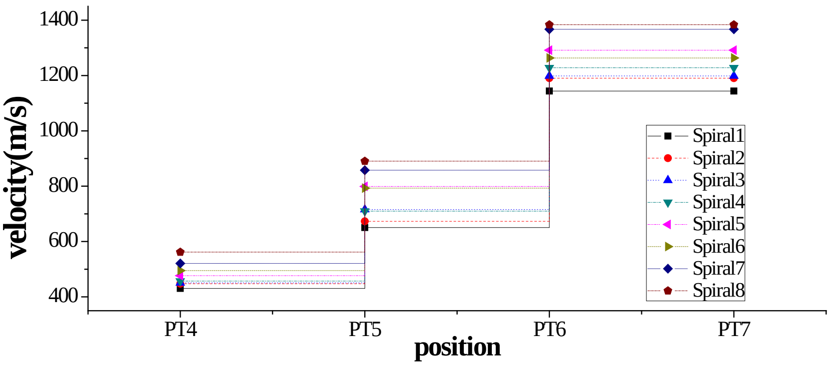



Figure 4. Compression wave velocities in the spiral detonation tubes

The mean velocities of compression wave in the spiral detonation tubes are presented in Figure 4. According to Figure 4, for all the spiral detonation tubes, the compression waves mean velocities between PT4 and PT5 were at 424~562m/s, and after an acceleration the velocities between PT5~PT6 were at 667~890m/s, and the wave velocity was increasing to 1147~1383m/s between PT6 and PT7, all the shock waves velocities were above half of the CJ velocity (910m/s), in the meantime the pressure peak value of P6 was 2.0MPa, above the 1.86MPa (CJ pressure). Due to the effects of two-phase flow, such as the distribution of liquid fuel, and the mixing of fuel and oxidizer, the wave speed of detonation was lower than the calculated CJ value. Moreover, the tube was an obstacle-laden system, according to research of Peter [13], the detonation had already formed, and this detonation was a low-velocity detonation. So the location of PT6 can be considered as where the detonation formed. Compared with the result of the straight tube, it can be found out that in spiral tubes the detonation wave was successfully formed, and the location was near the position of PT6.

This result shows that the spiral geometry structure can reduce the DDT distance and time, and the quantitative relationship between the DDT characteristics and spiral geometric parameters was needed to be found out further.

Figure 5 presents the ratio of spiral tubes characteristic time which was divided by that of straight tube. Where $t_{Det}$ represents the detonation time, and it is defined as the time interval from spark discharge to the formation of detonation wave, it is equal to the summation of $t_{delay}$ and $t_{DDT}$. $t_{ij}$ stands for the time interval of Pi to Pj, and the origin time is when the pressure at PTi increases to 10% of the peak pressure of Pi, the end time is when the pressure at PTj increases to 10% of the peak pressure of Pj. i and j represent the number of pressure traducers. $t_{delay}$ represents ignition delay time, and it was defined as the time from spark discharge to the formation of a deflagration flame. $t_{DDT}$ is the DDT time, it was the time needed for a deflagration flame transition to a detonation. Moreover, the measured time interval in the straight tube was served as the standard time, all the time intervals in Figure 5 were ratios of the measured time intervals to the standard time, for example, $t_{34}=t_{34,\ SP}/t_{34,\ ST}$, where $t_{34,SP}$ is the measured time interval from P3 to P4 in spiral1 tube, $t_{34,\ ST}$ is the measured time interval in the straight tube. The subscript of SP represents spiral, and ST represents straight, all the time interval were the average value of at least 10 experimental data.

From figure 5, it was obvious that, as *RC* decreasing, the DDT time decreasing, and all the DDT time of spiral tubes was smaller than that of the straight tube, and when *RC* was 188.9mm the DDT time decreased to the smallest one. Moreover, compared with the straight tube, the DDT distance has been reduced by at least 0.250m, the DDT time has been reduced by 6.2% ~ 19.8% of the straight tube.

However, all the ignition delay time of the spiral tubes were larger than that of straight tube. Moreover, it was found that except spiral5 the detonation time interval $t_{Det}$ of the other spiral tubes were larger than the time interval of the straight tube, this result was mainly caused by the increase of $t_{delay}$ in the spiral tubes, in order to reduce the detonation time in the spiral tubes, it was necessary to reduce the ignition delay time.

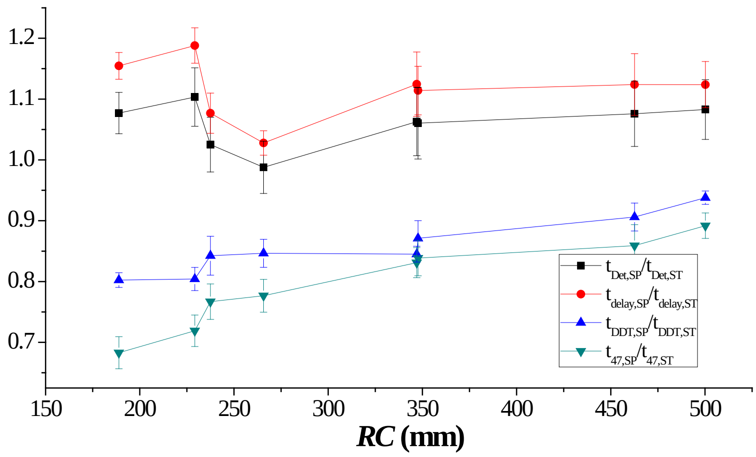



Figure 5. Ratio of spiral tubes characteristic times to straight tube characteristic time

In addition, according to the detonation experimental data, the minimum ignition delay time $t_{delay}$ was obtained in the straight tube, and the maximum DDT time decrease was obtained in the spiral8. In other words, the best performance of the ignition delay process was obtained in the straight tube, and the best performance of DDT process was obtained in the spiral8 tube. As a conclusion, in the detonation tube design process, the better configuration of DDT transition part was spiral8 (P=480mm, D=300mm, *RC*=188.9mm).

## 4 Conclusions

In this study, a series of detonation experiments have been performed, the detonation characteristics in the spiral tubes have been studied, and the experimental results show that:

In the straight tube, there were no detonation waves have been formed, but detonation waves have successfully formed at the position of P6 after changing the tube configuration into spiral one.

The DDT distance and DDT time have been reduced by the spiral detonation tubes. The DDT distance has been reduced by at least 0.250m, the DDT time has been reduced by 6.2% ~19.8% of the straight tube. Moreover, the DDT time of spiral detonation tube decreases with the decreasing of *RC*, and the minimum DDT time was obtained by spiral8.

As the experimental results show, in order to obtain a better performance detonation tube, one practical way was a spiral configuration for the DDT process. In this experimental study, the best performance tube was spiral8 configuration.

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