BRANCHED DETONATION IN A MULTI-TUBE PDE

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Abstract

The Air Force is conducting research on the use of a Pulse Detonation Engine (PDE) for a wide variety of applications. The PDE derives thrust through the development of a combustion-induced detonation wave in a tube. One research objective is to increase the firing frequency in multiple tubes by reducing the ignition and detonation initiation time. Increasing the firing frequency will produce an increase in thrust. In the baseline configuration, ignition of a stoichiometric hydrogen air mixture in a PDE tube occurs from a spark plug. A more powerful ignition method exploits the detonation energy from an adjacent thrust tube to rapidly ignite the fuel-air mixture. Rolling et al.[1] were able to branch a detonation wave from one tube to another through a crossover tube, ignite the fuel-air mixture in the second tube, and transition to a detonation using a deflagration to detonation transition (DDT) device. In the current work, the detonation arrival location has been moved to the head, and the overall benefits of reduced ignition and DDT times are quantified. Results show that the time required to ignite, DDT, and exit a detonation wave was reduced by 45.5 % to 63.1 % by using a branched detonation. Additionally, the time from ignition to full tube blow down was reduced by 16.6%. These reductions in time equate to an appreciable increase in the allowable firing frequency. Instances of detonation initiation were also achieved in the second tube without a DDT device.

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Motivation

The benefit of branching a detonation into the head of PDE thrust tube is the zero ignition delay time in the receiving tube. The arrival of the detonation, with its combustion driven shock wave, presents sufficient energy to quickly combust all the reactants in the head. If the detonation decouples while inside the closed end of the PDE tube, the shockwave still preheats the reactants and the deflagration zone behind the shock keeps the combustion going prior to entering a DDT device. Ideally, the detonation will reflect against the back wall of the head, and the pressure and temperature rise due to a Mach 4.8 detonation wave stagnation point will be sufficient to directly transition into a detonation without any required DDT device.

Experimental Setup

This research was performed at the Air Force Research Laboratory (AFRL) Pulse Detonation Research Facility at Wright Patterson AFB, Ohio. The facility incorporates two electrically driven cam shafts situated in a General Motors Quad 4 head. Four thrust tubes are attached where pistons would normally interact with head and its valves. Each thrust tube is a 5.2 cm diameter, 91.4 cm long steel pipe and can be fired at frequencies between 10 and 40 Hz. The rotating cams provide a three part cycle with equal time (120 degrees) spent to fill, fire, and purge the tube. The manifold pressure behind the valves is adjusted to provide the correct fill ratio at the desired operating frequency. The fill ratio is defined as the volume of the thrust tube filled when the fuel air mixture expands to atmospheric pressure at the open end of the tube. More information about the facility is given by Schauer et al.[2] For the work presented here, the fill fraction was 100% and the purge fraction was 50%. The manifold hydrogen air mixture temperature was 295 K (+/-3 K).

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Spark Ignition Setup

A single thrust tube was used to determine the spark initiated ignition and DDT times. A 12 Volt DC MSD® Digital DIS-4 Ignition System powered the spark plug. The system provided a series of 105 – 115 milli-Joule sparks[3] into the hydrogen air mixture via a capacitance discharge. The number of sparks per cycle was verified using a 27,000 frame per second camera and noted a 250 µs duration pulse every 1.1 milliseconds (+/-37µs) for 20 degrees of cam rotation.

Table 1. Number of sparks per detonation cycle

Frequency	10 Hz	20 Hz	30 Hz	40 Hz
Sparks	5	3	2	2

Branched Detonation Setup

A 5.23 cm diameter thrust tube with a conventional spark ignition setup was used to initiate a detonation which was branched using an instrumented, 91.4 cm long, 1.57 cm diameter crossover tube, over to a second 5.23 cm diameter, 91.4 cm long thrust tube. The photo in Fig. 1 below shows the initiator tube (1) to the left of the receiver tube (2) with the silver crossover tube between them.

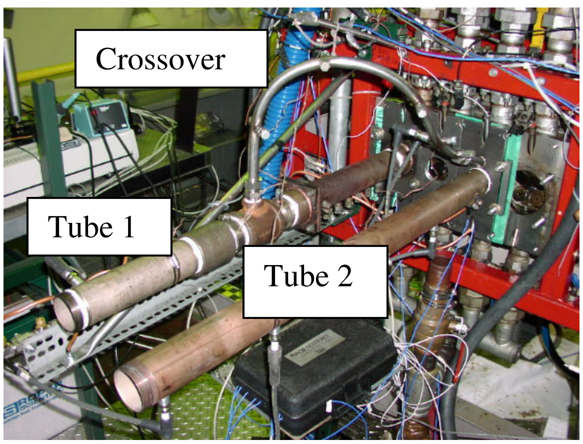

Figure 1. Crossover setup.

Firing Window

Due to the valve timing between the two thrust tubes, the branched detonation cases were limited to a firing window of between 2 and 4 milliseconds depending on the firing frequency. Specifically, the current cam setup closes the intake valves on second tube 90 degrees after the closing of the intake valves on the first tube and this becomes the earliest that tube one can be ignited. The maximum times are based on the overall firing window on tube one (120 degrees) after the intake valves close. Both times are adjusted for the ignition delay time and blow down time of the tube. Subsequently, no attempts were made to branch detonations at frequencies below 20 Hertz since the mixture leans out in the initiator tube with the longer spark delay times.

Spark ignition times were calculated between the time the first spark kernel was deposited in the fuel air mixture and the first pressure rise measured by two pressure transducers, each located 4.57 cm away from the spark plug. Coket et al[4] and Cheng[5] employed a rapid pressure rise signal to determine the ignition event. The two transducers were opposite one another and consisted of one PCB dynamic pressure transducers and one Kulite absolute pressure transducer. Both measured the ignition in close agreement.

Detonation wave speeds were measured using ion sensors which are triggered by the combustion wave. The wave speeds were used to determine the presence of Chapman-Jouguet (CJ) detonations. The initiator tube, the crossover, and receiver tube were instrumented to measure wave speeds during all testing.

Results

Detonations were achieved using spark ignition and a Shelkin-like DDT device for firing frequencies of 10, 20, 30, and 40 Hz. Detonations were achieved in tube 2 with the branched detonation ignition source for 20 and 35 Hz using the same DDT device. All detonations were repeatable and consistent in the initiator tube, the crossover, and the receiver tubes, and were within +/- 10 % of Glassman's[6] published CJ detonation wave speed of 1966 m/s. Examples of the wave speed data are shown in Fig. 2.

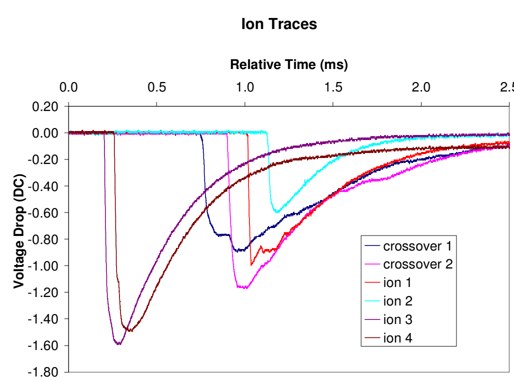

Figure 2. Ion sensor traces in crossover and receiver tube.

An important parameter controlling ignition performance is the initial pressure. The pressure in the closed end of the tube is varied by delaying the ignition initiation after the intake valves close. When the intake valves close, a low pressure region is created by the exiting mass of fuel and air varying in strength relative to the momentum of the flow (Fig. 3). Timing the spark relative to when the valves close effectively varies the pressure for the ignition and DDT regions. When the filling frequency is increased, the velocity of the air increases inside the tube. The resulting expansion waves are stronger and cause the ignition times to increase at the higher frequencies.

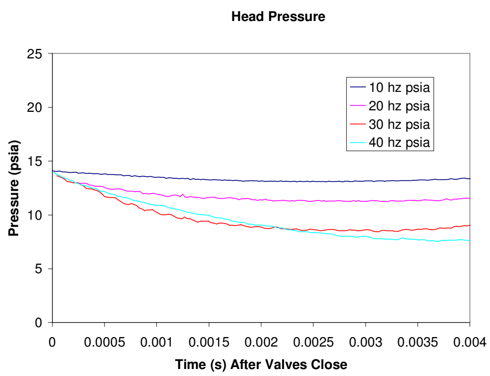

Figure 3. Head pressure after valves close.

The spark ignition time shows the importance of the initial pressure (Fig. 4). The ignition times increase as the initial pressure decreases. Ignition of gaseous hydrogen air combustion is controlled by the chemical reaction time. Lefebvre[7] states for this combustion that the minimum ignition energy is proportional to P^{-2}. This implies a reduction in ignition time with an increase in pressure for constant ignition energy. For the branched detonation initiation cases, the ignition time is considered zero. A better comparison is to consider the cumulative time from ignition (or detonation arrival) to exit a detonation wave from the tube. This is summarized later.

It is important to note that there is a finite amount of time to transmit a detonation from one tube to another. For the 91.4 cm crossover tube, it takes roughly 450 µs to reach the head of the second tube. This equates to roughly the same amount of time spent required to match the pressure rise in the spark initiated tube. Figure 5 shows two head pressure traces for the spark initiated and branched detonation initiated cases. The traces are shifted in time to match the tube blow down dynamics. The blow down time is the time required for the pressure in the tube to drop while expelling the combusted

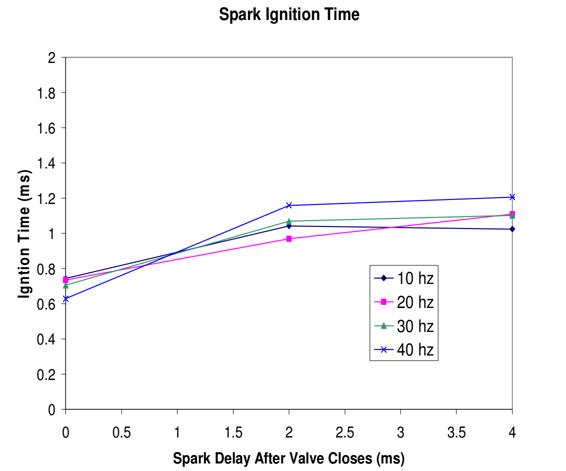

Figure 4 Variation of spark ignition times with change in spark delay after valves close.

products and generating thrust. The head pressures are the same for the last two-thirds of the cycle which signifies the thrust pressure (P3) doesn't change. For the 0.91 meter tube used in the tests, the blow down time for the spark initiated tube is 3 ms, but the detonation initiated tube is only 2.5 ms. This 16.6 % reduction allows for a faster recharge interval and provides another step to increasing the firing frequency for PDEs. The effects of the branched detonation initiation on thrust are not addressed in this paper.

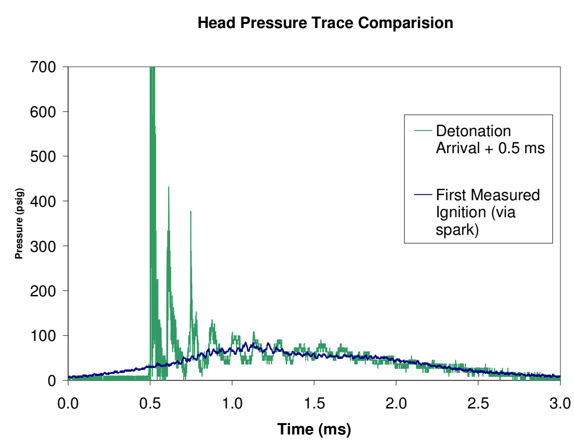

Figure 5. Head pressure traces after spark ignition and detonation arrival.

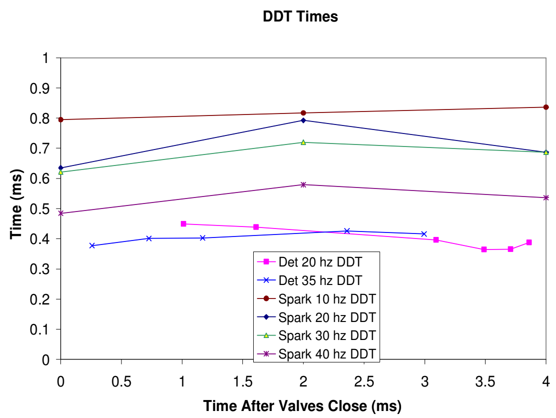

Figure 6. Comparison of DDT time with valve closure.

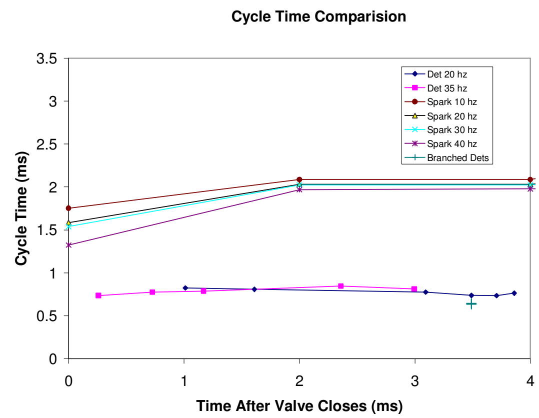

Figure 7. Comparison of combined ignition, DDT and detonation exit times.

The ignition mechanisms effect on DDT times (Fig. 6) shows a time reduction with an increase in the firing frequency. The overall DDT times are measured from the first initial pressure rise in the head to the detonation wave exiting the DDT device. Two mechanisms are influencing the trend. To fill the thrust tube at higher frequencies, higher manifold pressures are required. This translates to higher velocities in the tube and higher stagnation pressures on the DDT spiral. This encourages the formation of hot spots, which have been shown to enhance transition from deflagration to detonation (See Roy et al.[8]). Cooper et al.[9] noted a similar reduction in DDT time with increasing initial pressure. Turbulence intensity, though not measured here, should also favorably influence the DDT times. The branched detonation DDT times were consistent and did not show significant pressure or firing frequency dependence.

The complete time required to exit a detonation wave from the PDE tube from either the deposited spark or the deposited detonation is shown in Fig. 7. The spark ignition times dominate the trends. At the times closest to when the valves close, the detonation initiated time drops to 45.5% of the spark initiated time. As the time increases, the detonation further improves to 63.1% below the spark initiated times. The branched detonation initiated cases were not sensitive to initial pressure or frequency in transitioning to a detonation.

In four separate instances, a branched detonation ignited the reactants in the second tube and transitioned to a detonation without a DDT device in the tube. These cases are denoted with the (+) symbols in the lower right corner of Fig. 7. The cases were not consistently repeatable and were initiated with a decoupled detonation traveling at roughly 50% CJ velocities in the crossover. These detonations also occurred with at a leaner (0.9 to 0.95) equivalence ratio. More work in understanding this phenomenon is ongoing.

Conclusions

The arrival of a detonation, with its combustion driven shock wave, presents sufficient energy to instantaneously combust the reactants in the head of a PDE. Results show that the time required to ignite, DDT, and exit a detonation wave can be reduced by 45.5% to 63.1% by using a branched detonation over a spark initiated system. The reduction in cycle time significantly increases the allowable firing frequency, and the reduction in ignition time makes this a promising method to rapidly detonate more challenging fuels. Instances of detonation initiation were also achieved in the second tube without a DDT device. The reduction in overall tube blow down time by 16.6% provides an important improvement required to increase the firing frequencies of pulse detonation engines.

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