Experimental Investigations on DDT Enhancements by Shchelkin Spirals in a PDE

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An experimental investigation was carried out on a multi-cycle pulsed detonation engine, running on a propane-oxygen mixture using a rotary-valve injection system and a low energy ignition source, to study the effectiveness of Shchelkin spiral parameters on the deflagration-to-detonation transition (DDT) phenomenon. Various configurations were tested using spirals with blockage-ratios ranging from 34.7 to 55.6 % and spiral length to diameter ratio of 12.5 and 24.4. The results showed that only spirals with the highest blockage-ratio were able to achieve successful and sustained DDT in the shorter length configuration. However, further studies revealed that lower blockage-ratio spirals were able to achieve successful DDT when their lengths were 24.4 times that of the detonation tube diameter. Higher levels of peak thrust production were observed in these cases. Hence, applications which do not place any operating constraints on the PDE tube length may benefit from using lower blockage-ratios but longer Shchelkin spirals. Lastly, practical operating issues regarding the use of Shchelkin spirals are discussed in this paper.

Nomenclature

| BR | Blockage ratio |
| CJ | Chapman-Jouguet |
| D  | PDE tube inner diameter, 24.3 mm |
| d  | Shchelkin spiral wire diameter |
| DAQ | data acquisition system |
| DDT | Deflagration to Detonation Transition |
| L  | PDE tube section lengths |
| L_{S1} | Shchelkin spiral length, 304 mm |
| L_{S2} | Shchelkin spiral length, 594 mm |
| PDE | pulsed detonation engine |
| PT | Pressure transducer |
| TOF | Time-of-flight |

I. Introduction

Developments in pulsed detonation engine (PDE) technology have increased significantly over the recent years due to viable applications of the technology in propulsion systems, energy-production and other engineering systems. Numerous experimental, numerical and theoretical studies have been carried out or are currently underway to understand how this technology can be implemented in practical propulsion systems. The realization of...
a successful PDE propulsion system is contingent on improving its ability to operate under the inherent extreme temperature and pressure conditions at high firing frequencies, while making use of robust ignition systems as well as achieving a reasonable relative physical size. Attaining repetitive and consistent detonations for significant lengths of time remains a major hurdle for any current PDE system, due to the highly unsteady pressure and thermal loading. Furthermore, to accomplish DDT within a feasible physical detonation tube length (relative to its diameter) puts even more engineering constraints on the optimization of PDE systems.

There are presently several conceptual ways to achieve detonations in PDE systems, which can be broadly classified into three types: First is the use of high-energy sources to detonate the fuel-oxidizer mixtures directly with various means such as high-energy arc discharges, lasers, explosives, etc. Arc discharges are thought to impart more energy to the gas mixture, than conventional spark ignition systems, with the intention of inducing DDT rapidly. However, this is not efficient and the associated circuitry is heavy and bulky. Secondly, low-energy ignition sources are used in conjunction with a DDT enhancing mechanism such as spirals, grooves and obstacles along the deflagration path. Lastly, a hybrid or two-stage system whereby a primary fuel and oxidizer is caused to detonate and then the detonation wave continues into a secondary chamber filled with the main fuel-oxidizer mixture. An example of such a system would make use of hot-jet initiation using small amounts of highly detonable fuel-oxidizer mixtures.

Earlier studies have already shown the efficacy of Shchelkin spirals in promoting the DDT and hence significantly reducing the PDE tube length requirements. Shchelkin spirals are generally believed to promote flame turbulence through the undulations caused by the spiral coils along the deflagration path which leads to flame acceleration. Successful and adequate flame acceleration enables the flame front to catch up and couple with the pressure front to produce a successful detonation in the form of a detonation wave. However, the use of Shchelkin spirals also leads to a blockage of the detonation tube and this could arguably result in a significant potential thrust loss if the spiral size were not selected properly. Hence, the selection of the Shchelkin spiral should be such that the spiral coils (or undulations) are sufficiently large enough to attain successful DDT-phenomenon but yet offer small blockage along the detonation tube. As a result of such requirements, Shchelkin spirals are usually indicated by their blockage ratios, which is the ratio of the cross-sectional area of the PDE tube covered by the spiral to the total inner cross-sectional area of the tube.

Detonation phenomenon in multi-cycle PDE systems will likely differ from that observed in single-shot PDE tests, as the highly complex behavior of the flow after each detonation cycle may influence the initial conditions and the developments of the subsequent cycles. Therefore, the sizing of Shchelkin spirals for continuous run PDE systems based on data obtained from single-shot experiments remains debatable. Hence, there remains a need to understand further how such DDT enhancements behave in multi-cycle PDE systems.

The aims of the present study are, first, to examine the effectiveness of Shchelkin spirals together with low-energy ignition, multi-cycle, gaseous-fuel, rotary-valve PDE. Secondly, the study aims to see if the unsuccessful low BR configurations could be improved on such that detonations would be achieved eventually. Lastly, to examine the physical effects on the Shchelkin spirals itself during the multi-cycle detonation tests. A stoichiometric gaseous propane-oxygen mixture was used in the study and the investigations made use of dynamic pressure measurements, time-of-flight (TOF) velocity measurements of the deflagration/detonation waves and thrust measurements to understand the above mentioned issues. Section II briefly describes the experimental setup and instrumentation, while Section III reveals the experimental findings obtained during this study. Section IV summarizes the results and their implications towards employing Shchelkin spirals in a multi-cycle PDE system.

II. Experimental Methods

The PDE was fabricated from Schedule 80 stainless steel pipe with an inner diameter of approximately $D = 24.3$ mm (see Figure 1). The PDE comprises of several major detachable sections, namely the propane-oxygen and purge-air injection chamber, ignition section, Shchelkin spiral section and the detonation “blow-down” section. These sections were joined using standard flanges welded to their ends. The entire tube length when assembled measured approximately 1134 mm or 46.7D.

Injection of propane, oxygen and purge air (150 psig compressed air) was synchronized via a rotary valve driven directly by a variable speed ½ HP AC motor with both propane and oxygen injection occurring 90° out of phase from the purge air injection. Thus, each complete revolution of the valve shaft would produce two full cycles of injections and purging. Consequently, the PDE firing rate could be altered by varying the rotational speed of the motor. All flow lines use ½ in. stainless steel metal tubing to ensure adequate flow rates. Flash arrestors were installed in the propane and oxygen lines prior to their injection into the 100 mm ($L_f = 4.1D$) long injection chamber through flexible metal hoses. The entire PDE tube assembly was placed on a horizontal linear guide system, to
enable the measurement of the thrust. The flexible metal hoses enabled the PDE tube to move smoothly along the linear guides, which was essential for force measurements. No pre-compression or pre-mixing of the gaseous mixture was used during the present study.

The ignition system comprises of an automotive ignition control module and coil set, capable of delivering 150 mJ per ignition spark, mated with a control circuit that enabled the timing of the spark via a TTL signal. A position marker on the motor shaft activated an Omron EE-671SX optical sensor to generate the TTL pulses. The spark was timed to fire when the propane and oxygen injection valves were fully opened. Custom-built ignition plugs were used, one for the ground electrode and the other for the high-voltage electrode. The spark plugs were screwed into the ignition section opposing each other. The spark gap can be varied from 2 to 4 mm. Larger spark gaps may cause the spark to be extinguished by the incoming gas, while shorter gaps result in smaller amounts of activation energy being imparted to the mixture. The ignition chamber has the same dimensions as the injection chamber.

A number of Shchelkin spirals were tested, as listed in Table 1. The spirals used were standard stainless-steel helical compression springs selected with outer diameters sized to fit the detonation tube. The wire diameter ranged from $d = 2.3$ to $4.0$ mm resulting in blockage ratios of $34.7$ to $55.6\%$. Two different spiral lengths of $304$ mm ($L_{S1} = 12.5D$) and $594$ mm ($L_{S2} = 24.4D$) were used to investigate the effects of spiral lengths. Spiral pitch was kept the same for the two different spiral lengths by compressing the springs to fit the tube section. Two reference empty PDE tube test cases without the use of any Shchelkin spirals were also carried out for comparison sake.

The primary diagnostic was pressure measurements of the detonation wave as they exited the Shchelkin spiral section and into the blowdown section measuring $630$ mm ($4D$) in length. Six piezoelectric dynamic pressure transducers (PCB Model 111A24, natural frequency of $450$ kHz) rated at $1000$ psig were located along the detonation blow-down section $100$ mm apart. Wave velocity is obtained from the TOF of individual detonation or deflagration wave as it passes by the pressure transducers (PTs). The PTs were housed in PCB 064A water jackets to protect them from the intense heat generated by the combustion process and also to mitigate the effects of temperature drift. The water jackets recess the PTs causing an insignificant amount of time delay, but improving spatial resolution of the shock waves. Thrust was measured by means of a piezoelectric dynamic load cell (PCB Model 201B05, maximum load of $5000$ lbs, natural frequency of $450$ kHz). The PTs and the load cell are connected to the DAQ through a PCB Signal Conditioner module. A type K thermocouple was also available to measure outside wall temperature at the spiral section.

The DAQ consisted of two National Instruments S series PXI 6133 modules (8 Channel, 2 MS/s per channel) housed in a 1042-Q chassis. The transducers were sampled at $100$ kS/s for $10$ seconds per run. The DAQ was connected to a remote PC, running LabVIEW, by means of an MXI-4 fiber optic cable system. The advantage of fiber optic cables is that they are immune to electro-magnetic interference. The PDE could be monitored and controlled in real time from the safety of the control room, where the PC was located. The captured data was subsequently processed using MATLAB to arrive at the final results. Figure 2 shows a photograph of the entire PDE system mounted on the linear guide and test stands, with the exhaust of the PDE system directed into a baffled steel pipe to diffuse the flow for safety reasons.

### III. Results and Discussion

A. Effects of Shchelkin spiral blockage ratio

The first five spiral configurations, shown in Table 1, were tested to study the variation of pressures and wave velocities with increasing BR. Firing frequency of the PDE system was capped at approximately $10$ Hz for all cases. It was found that out of the four spiral BR configurations tested, only the spiral with the highest BR of $55.6\%$ achieved successful cyclical detonations. A comparison between the successful test case and benchmark case is shown in Figure 3, for a single deflagration/detonation front. Figures 3(a)(i) and 3(b)(i) show the pressure profiles for each test case again for a single wave front. The figures are arranged so that the waveform nearest to the reader is from the PT closest to the spiral section (PT1). Figures 3(a)(ii) and 3(b)(ii) show the wave velocities obtained from a TOF analysis of the pressure profiles shown in the previous figures, while Figures 3(a)(iii) and 3(b)(iii) show the thrust produced by the single deflagration/detonation front considered here.

It can be observed for the reference case that the peaks of the pressure fronts registered levels close to $15$ bars up to the halfway point along the detonation section before they decreased drastically to approximately $7$ bars thereafter as they traveled towards the tube exit. The calculated TOF velocities between the pressure transducer locations also showed a clear trend of corresponding rapidly decreasing velocities, below the CJ velocity for propane-oxygen mixture, as the pressure front traveled down the tube. In view of these developments, it is not surprising that the thrust levels registered by the load cell reached only a maximum of between $15$ and $20$ N.
On the other hand, when the BR=55.6 % Shchelkin spiral was used, beneficial effects can be observed almost immediately. First, the pressure peak was above 15 bars halfway along the tube and increased abruptly to almost 30 bars thereafter. This observation suggests successful coupling of the flame and shock fronts to produce a detonation wave. The calculated TOF velocities further confirm that a detonation wave was achieved. The calculations show that the wave speed was in the vicinity of the theoretical CJ value. Correspondingly, the thrust levels measured by the load cell increased significantly with a peak level of approximately 120 N.

Spirals with lower blockage-ratios were apparently not successful and for brevity’s sake, their results are not shown here. Although they did have positive effects such as higher pressure levels, increased TOF velocities and better thrust levels incrementally, these quantities remained short of that of the CJ case. Also, it should be noted here that significant thrust level fluctuations exist after the deflagration/detonation fronts exit from the tube, as evident in Figure 3(a)(iii) and 3(b)(iii), and rarefactions existing within the tube. However, these after effects can be minimized if the firing frequency is increased.

B. Effects of Shchelkin spiral length

The previous section shows that the required BR of a Shchelkin spiral must be sufficiently large for successful detonations. In the present multi-cycle PDE system, the BR is 55.6%. This then raises the question of whether unsuccessful results from lower BR spirals could be reconfigured such that detonations could be successfully achieved, while not compromising pressure and thrust outputs. A series of studies was carried out to find out if the spirals with lower BR could produce DDT by increasing their lengths.

Figure 4 shows results for Shchelkin spirals with BR = 34.7 and 46.2 % respectively, both 304 mm long. Compared against Figures 3(a) and 4(a), Figure 4(b) shows improved performance in terms of shock front pressures and thrust levels, which reinforces the notion that increasing the BR has a positive effect on the DDT phenomenon. Similar to Figure 3(b), wave front pressure started off at approximately 15 bars before increasing to 30 bars just before the wave front exited the tube. However, calculated TOF velocities remained significantly lower than the predicted CJ velocity and thrust levels reached up to 60 N only.

When these unsuccessful test cases were modified by increasing their lengths to L_{52} (594 mm) however, detonation was successfully achieved, as shown in Figure 5. Calculated TOF velocities reached CJ velocity levels with pressure and thrust levels significantly increased for both test cases. However, it can also be seen from the figures that while the peak thrust levels reached 200 N and above, the durations were much shorter with much larger fluctuations. In fact, the peak thrust production was higher than the test case presented in Figure 3(b) although fluctuations were correspondingly higher as well. This suggests the possibility of elongated Shchelkin spirals imparting detrimental influence in sustained thrust production, although the exact mechanism is not clear.

From this series of tests, it can be concluded that low BR Shchelkin spirals may successfully promote DDT-phenomenon if they are sufficiently long. And that the required minimum transition lengths (for DDT) for the different blockage-ratio spirals could arguably be predicted through a detailed parametric study.

C. Operational issues

During the present study, several operational issues were noted. First, the most noticeable problem is the damage to the Shchelkin spirals during firing periods longer than only 10 seconds. With the exception of the BR=55.6 % Shchelkin spiral, all the other spirals either melted and the metal deposited along the inside of the tube (see Figure 6), or disintegrated totally and were expelled out of the detonation tube after 20-30 s of firing. This problem required that the spirals be replaced after each test run and presents a major problem in long duration tests. Initially, it was thought that the failure to achieve clean detonations was the reason. However, low blockage-ratio but elongated spirals, which allowed successful detonations, also exhibited similar disintegration. Hence, spiral material selection to survive the PDE environment is crucial. Practical PDE systems may require cooling of the spirals. One option might be to cut spiral grooves into the walls of the tube, with liquid cooling on the outside of the PDE tube.

Secondly, there is a need to remove the tremendous amount of heat produced during extended operations of the PDE. When the PDE was run for 20 s or longer, the stainless steel spiral section glowed red hot and expanded. It was found that the rate of heat produced was highest at the Shchelkin spiral section. To overcome this heating problem, an in-house water-cooling system was devised such that the heat can be effectively removed. The solution was to wrap the entire PDE tube with wetted rolls of cloth and to position a continuous water-sprinkle system over the entire tube length, constantly cooling the PDE tube during operation. The amount of heat removal can be appreciated by the great amount of steam produced during a typical operation as shown in Figure 7. Despite the water cooling, after a minute of run time, the pipe could be seen to warp, with the whole tube assembly curving upward. Seals and joints also experienced damage.
Another drawback to heat build up within the tube walls is pre-ignition. After the tube has been running for about 20 seconds, there is enough heat in the walls to cause the propane and oxygen to self-ignite as soon as they enter the tube. Thus the tube cannot be filled fully with the fuel-oxygen mixture and the ignition occurs before the spark is fired. This resulted in irregular firing, loss of thrust and unbalanced stresses and vibrations ensuing in material damage.

The spark plug is another crucial component that suffered severe damage. Initial tests during this study showed that several commercial automotive spark plugs do not hold up to the harsh detonations and the high temperatures. It was found that horizontally opposing electrodes were the simplest to implement and also effective for ignition, as they presented a minimal blockage to the flow, had a small profile and the spark gap could be changed as desired. Another aspect of the ignition spark is that it a prominent source of EMI that can severely drown out the transducer signals. Therefore, the spark current must be reduced by connecting appropriate resistors in series with the high voltage line of the ignition circuit. Also all signal cables and data transmission lines must be suitably shielded. The DAQ must also be housed in an EMI protected enclosure.

IV. Conclusions

An experimental investigation was carried out on a low ignition-energy, multi-cycle, rotary-valve based pulsed detonation engine, running on propane-oxygen mixture, to study the effects of Shchelkin spirals on the DDT phenomenon. Experiments using spirals with BR ranging from 34.7% to 55.6% with a length of 12.5 D showed that only spirals with the highest blockage-ratio were able to achieve successful DDT. However, lower blockage-ratio spirals were able to achieve successful DDT when their lengths were increased to 24.4 D. Higher levels of peak thrust production were observed in these cases, albeit with larger fluctuations. Practical operational issues observed in the course of the tests, in the context of operating a multi-cycle PDE system under prolonged durations, were also discussed.

Acknowledgments

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References

Table 1. List of test cases

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<th>Blockage ratio (%)</th>
<th>Spiral pitch (mm)</th>
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Figure 1. Schematic of the PDE system used in the present study, which shows the locations of the propane-oxygen injection system, high-voltage low-energy ignition electrodes, Shchelkin spiral section and the detonation “blow-down” section.

Figure 2. A photograph showing the entire PDE system mounted on a linear guide and test stand. The exhaust of the PDE system was directed into a hollow steel pipe lined with baffles to diffuse the flow.
Figure 3. Comparison between the benchmark case without Schelkin spiral and one using BR=55.6% Schelkin spiral.
(i) Pressure profiles

(ii) Time-of-flight (TOF) velocities

(iii) Force profiles

(a) BR=34.7% Shchelkin spiral wire of length $L_{S1}$

(b) BR=46.2% Shchelkin spiral wire diameter of length $L_{S1}$

Figure 4. Pressure profiles, TOF velocities and thrust levels of unsuccessful test cases using Shchelkin spirals of length $L_{S1}$ (304 mm) with lower BR than the successful BR=55.6 % test case.
Figure 5. Pressure profiles, TOF velocities and thrust levels of successful test cases using low blockage-ratio Shchelkin spirals of elongated length ($L_{S2}=594$ mm).
Figure 6. Photograph showing a low BR Shchelkin spiral that has melted and deformed within the PDE tube under prolonged testing periods. Much of the spiral has been ejected out of the tube during the run. This phenomenon limits the run time of the PDE to between 10 to 20 seconds.

Figure 7. Photograph showing a significant amount of steam being produced from the cooling water when the PDE system was running, on account of the tremendous amount of heat produced.