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Detonation Pulse Engine

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DETONATION PULSE ENGINE

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I. Introduction

The efficiency of an air breathing engine is constrained, in part, by the ratio of the maximum internal to ambient pressure. Engines with higher pressure ratio can, in principle, be made to be more efficient. Conventional engines use mechanical devices to compress the air before combustion. Demonstrated engines which are exceptions are the ram-jet, which converts inlet air velocity into pressure and has reasonable efficiency only when the inlet velocity is over Mach 2, and the pulse-jet, which is based on intermittent combustion at low chamber pressure and consequently has low efficiency. In the present paper, exploratory experiments with an air breathing propulsion device which uses detonative combustion to achieve high pressure in the combustion chamber, are reported.

The high gas pressures (> 10 - 100 atmospheres) and temperatures (> 2000°C) and very fast combustion make the detonative combustion process attractive for propulsion. From the late 50's until the early 70's, the feasibility of an engine operating with intermittent detonative combustion was studied at the University of Michigan[1,2,3]. Specific impulses over 2100 sec. were realized for a single linear tube operating intermittently with frequencies up to 35 detonations per second. Nicholls et al.[1] showed that an engine operating on intermittent detonative combustion will have some advantages over an engine using deflagrative combustion. One of the most obvious advantages of the detonation engine is the very high specific thrust. Since the engine does not require precompression of the gases before combustion, it should be very light and mechanically simple. Dunlap et al.[2] studied the feasibility of steady-state detonative combustion for engine applications. In this work it was concluded, on the basis of simplified

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Exploratory research of the detonative combustion as an alternative reaction mechanism for air-breathing and rocket propulsion was terminated in the late 60's due to lack of funding. The most promising results of the research were obtained in the intermittent detonation of H_2-air mixture in a shock tube-like device by Nicholls et al.[1]. They showed that intermittent detonation with a frequency of 35 and more detonations per second could produce a specific impulse over 2100 sec and specific thrust of 2400 lb/sec. The highest wall temperature reported in Ref.1 was 770°F. Industrial applications of detonative combustion were reported in the USSR[7,8]. It was reported in Ref.7 that a Detonation Reactor, operating with a frequency of 100 detonations per second, was tested for 2000 hours. Thus the development of a detonation engine with an operational life of thousands of hours, is feasible.

The motivation of the present study was to show the feasibility of an engine which uses intermittent detonative combustion and is recharged with fresh air-fuel mixture cyclically without a compressor or other external device. This type of an engine will use the unsteady wave propagation in the combustion chamber to acheive scavenging of the combustion products after each detonation and recharging with fresh mixture.

The study was conducted in two phases. In the first phase, initiation of a single detonation in the reaction chamber was examined and a parametric study was conducted to determine the sensitivity of various mixtures to spark ignition. In the second phase, intermittent (polycyclic) detonations were initiated continuously in the reaction chamber, and different chamber designs and fueling schemes were tested. Experimental details are given in Ref.10.

II. Experimental System

A simple laboratory test rig was designed and built for the experiments. Ethylene was used as fuel, and air as the main oxidizer. An automobile spark-plug activated by an automobile type spark generator was used for initiation of the detonation in the mixture. Recently, Monks[11] showed that ethylene-air mixtures could not be initiated by such an ignition system. Hasson[12] on the other hand showed that ethylene-oxygen mixtures could be initiated immediately whenever the mixture was ignited at pressures over 400 tor. Consequently, it was decided to first initiate primary detonations (using the automobile spark ignition system) in a limited volume of the ethylene-oxygen mixture. Then, the detonation waves issuing from a small detonation tube would be used to initiate detonative combustion of an ethylene-air mixture inside a main reaction chamber. Two small detonation tubes were designed with volumes of 4% and 2% of the total reaction chamber volume. The lengths of the tubes were respectively 20cm and 10cm. Two models of the main detonation chamber were built. The first one was a rocket type combustion chamber in which the products were evacuated through a nozzle (Fig. 1). The second model (Fig. 2) consisted of two concentric tubes, designed in such a way that the inner tube cross-sectional area was equal to the difference between the cross-sectional areas of the outer and inner tubes. There was a passage from the external tube to the inner one near the front cover of the chamber. The primary detonation tubes were connected to the front end of the chamber in the two models. The first model was tested mainly in the single detonation mode. The second model was used for testing with intermittent (polycyclic) detonative combustion.

A schematic diagram of the apparatus is shown in Fig. 3. The gas supply system consisted of three pressure bottles containing oxygen, ethylene and air. Two mixing chambers were used to mix ethylene with air and ethylene with oxygen prior to the single detonation tests. The concentrations of gases in the mixtures were determined by measuring partial pressures of the components. Mixing of the primary ethylene and oxygen in the polycyclic tests was achieved by injecting the gases simultaneously into the mixing tube connected to the detonation tube (Fig. 2). At the same time, ethylene was injected into the main detonation chamber during recharge of the chamber by the fresh air following overexpansion of the detonation products. The gas flow rates were controlled by keeping the inlet flow under choked conditions for most of the injection cycle. The gas supply pressure was reduced to 400 psi. by a regulator on the supply bottle. The gas pressure was reduced again at the entrance to the injectors to about 15 psig. This pressure was high enough to maintain choked flow through the injectors, but low enough to enable the use of an injector nozzle whose diameter could be kept over 1 mm, and would therefore avoid problems of plugging and difficulties in manufacturing . Good mixing of oxygen and ethylene was obtained by injecting the gases coaxially from opposite directions into the mixing tube. The flows of the gases into the rig were controlled by valves. Manually opearted valves were used in the single detonation tests, and remotely operated solenoid valves were used in the polycyclic tests. A signal generator was used for triggering the spark generator, and controlling the operating frequency of the intermittent detonation process. A block diagram of the polycyclic system is given in Fig. 4. Kisler piezoelectric (high response) pressure transducers were used for pressure measurements inside the detonation tube and detonation chamber. The pressure signals were viewed on a memory-oscilloscope screen and photographed later using a Polaroid camera.

III. Single Cycle Detonation Tests

The single detonation tests were performed in two stages. In the first stage, the detonation tube was tested separately. The mixture was prepared in a mixing chamber before it was introduced into the detonation tube. The tube was evacuated while its exit was closed by a rubber diaphragm. The mixture was introduced into the tube until the pressure inside the tube reached a pressure slightly lower than atmospheric pressure. In this way, the diaphragm was kept in place without mechanical attachment before ignition, and was ejected away as soon as the pressure rose. The spark plug was positioned about 5 cm from the front end of the tube. Two pressure transducers were positioned along the tube, the first at 3 cm from the spark plug toward the front end, the second near the tube's exit. The mixture was ignited by a spark generated by the plug. The combustion inside the tube developed almost immediately into a detonation wave. During these tests, the following parameters were changed: mixture ratio, the total pressure inside the tube, and mixing quality (by varying the time interval between introduction of the gases into the mixing chamber and the ignition of the mixture inside the tube). The mixture ratio (fuel/oxygen) was varied between 25% and 45%. The pressure inside the tube before ignition, was varied between 10.5 psia and 14.5 psia. The time interval between the introduction of the gases into the detonation tube and ignition, was varied between 2 minutes and 25 minutes. In all cases, detonation developed as soon as the plug fired. A typical pressure-time diagram at the two points along the tube is given in Fig. 5. By measuring the time it took the detonation wave to travel from one transducer to the other, the detonation wave velocity was calculated to be between 750 and 950 m/sec. This value, which is lower than the Chapman-Jouguet (C-J) velocity, indicates the transitional character of the detonation wave. The maximum peak pressure which was measured was between 250 and 350 psia. The maximum pressure following the detonation wave was about 100 psia., which corresponded to the pressure which would have been obtained in a constant volume combustion.

In the second mode, the detonation tube was connected to the reaction chamber, and the two were operated as a single unit. The ethylene-oxygen and ethylene-air mixtures were prepared in separate mixing chambers. The combined rig was evacuated while the chamber nozzle was closed by a rubber diaphragm in similar way to the previous tests. The ethylene-air mixture, whose volume (at standard conditions) was equal to the chamber volume, was introduced into the chamber through a valve which was connected to the front end of the detonation tube. Then the ethylene-oxygen mixture, whose volume was equal to the detonation tube volume, was introduced into the tube through the same valve. Using this procedure, it was possible to fill the detonation tube with ethylene-oxygen, and the reaction chamber with ethylene-air mixture. By changing the volume of the ethylene-oxygen mixture it was possible to enrich the main chamber entrance zone with oxygen, creating favorable conditions for initiating the detonation wave in the ethylene-air mixture in the reaction chamber. Pressure diagrams which were obtained, gave a good picture of the conditions inside the rig during its operation. It was clear that the ethylene-air mixture was initiated by the detonation wave which was generated in the detonation tube, and that a small amount of oxygen at the transition zone was very effective in stimulating this process. By calculating the area under the pressure-time diagram, and taking into account the amount of the fuel which was consumed, the specific impulse was calculated. It appears that values between 1000 sec and 1400 sec may be expected from a practical system. These values are similar to the specific impulse which is obtained in practical ram-jet engines operating at supersonic speeds, and consistent with those measured by Nicholls et al.[1]

Figures 5, 6, 7, and 8 show pressure-time diagrams which were recorded during various single detonation tests. In Fig. 5 the pressure-time diagram is shown for a typical detonation inside the detonation tube. Pressures P_1 and P_2 were recorded at the aft and front sections of the tube. In this figure, we can see that the detonation wave inside the tube is fully developed, and it has the same pressure at the aft and front ends of the tube. Figure 6 is a typical pressure-time diagram which was measured at the aft end of the detonation tube (point P_2, close to the chamber front entrance), and the aft end of the detonation chamber (point P_4, near the chamber exit nozzle). It can be seen that the detonation wave is generated in the detonation tube almost immediately after ignition and the shock wave pressure is about 350 psi, which is an agreement with the value which has been reported by Hasson[12] for C-J detonation. As the detonation wave travels into the diverging entrance of the main chamber (transition zone in Fig. 1), it is attenuated by the increasing volume and its velocity becomes subsonic. Following the transition, rather than degenerating further to a deflagration wave, the reaction front accelerates (interval 'a' in Fig. 7) and the pressure increases rapidly to 250 psi, which is still somewhat less than the C-J pressure. Following the passage of the front, the pressure decreases to about 100 psi, which is approximately the constant volume combustion pressure. The existence of deflagrative combustion and therefore lower pressure decreases the propulsion efficiency. It is desirable therefore to decrease the time interval over which subsonic combustion occurs. This can be done by enriching the transition zone with oxygen, as can be seen in Fig. 7. In this figure pressure-time diagrams which were measured at the aft end of the chamber (P_4), are given for two cases which differed one from the other by the amount of ethylene-oxygen mixture which was introduced into the detonation tube. In the upper curve the deflagrative combustion (interval a) is longer, and the peak pressure is very close to the average pressure (excluding the final decay). In the lower curve the interval of deflagration is shorter. The peak pressure is higher followed by a pressure dip, which is characteristic to a more developed detonation wave, and an additional pressure jump. This secondary jump is probably from a reflected wave.

In Fig. 8, the scale of the pressure at P_3 has been expanded to enable measurement of the various stages in the cycle to be distinguished:

a. accelerating deflagrative combustion
b. unsteady detonation
c. back flow of fresh air

The accuracy of the pressure in this diagram is poor and the data should be viewed only as a qualitative illustration of the changes in pressure. However, the time measurements are accurate. The time interval between the beginning of the cycle and the recharge with the fresh air was 6 msec. This value determines that the maximum frequency in which the rig can be operated in a repetitive (intermittent) detonation mode is 160 cps (9600 rpm). This value is similar to the frequency with which a small high speed piston engine can be operated.

IV. Intermittent (Polycyclic) Detonation Tests

Similar to the procedure of the first test phase, the detonation tube was tested separately at the beginning of the second phase. After an unsuccessful attempt to operate the rig while the gases were injected into the tube continuously, the ethylene and oxygen were injected intermittently, and the spark plug was fired as soon as the gas valves were closed. In this way, the system was operated similarly to the static firing conditions in the single detonation tests (see Fig. 9). The fuel/oxygen mixture ratio was changed between 25% and 35%, and the injection pressure (which controlled the flow rate) was changed between 9 psig. and 30 psig. The system was operated at frequencies up to 25 Hz, which was the maximum frequency at which the solenoid valve could be cycled. The next stage was to operate the combined rig. Referring to Fig. 4, in which the polycyclic combined rig is shown, the spark plug was installed in the front end of the detonation tube, the other end of which was connected to the front end of the detonation chamber. An annular ejector type fuel injector was positioned at the outlet of the detonation chamber outer tube. The gases were injected into the chamber and into the tube simultaneously. The spark plug was fired as soon as the valves were closed. Two pressure transducers measured the pressure inside the detonation tube and in the outer chamber passage. The pressure inside the internal chamber was not measured. The procedure was as follows:

a. The spark generator was operated.

b. The valves, which controlled the injection of gases into the tube, were operated intermittently, injecting pulses of gases into the tube.

c. The valve controlling the fuel injection into the chamber was operated, injecting the fuel into the chamber simultaneously with the other gases.

The repetitive injection of oxygen and ethylene into the detonation tube while the spark plug sequentially fired, generated a continuous train of detonation waves which traveled into the detonation chamber. Shutting off the spark generator while the valves were still operating interrupted the detonation wave generation. In some tests the detonation interruption was immediate. In others, it took several cycles to interrupt the intermittent detonation. This indicated that intermittent detonations could be initiated by hot spots inside the detonation tube. This led to the conclusion that the detonation tube might be operated successfully using only a glow plug, eliminating the need for an ignition coil, which is not a light component. Pressure measurements indicated that developed detonation waves were generated inside the tube while the peak pressures inside the chamber's outer tube were lower than the pressures which were generated in the single detonation tests.

The repetitive, intermittent detonation process was readily repeatable. Considerable change occured in both sound level and appearance of the flame generated in the chamber when the various gas valves were separately closed. Reopening the valves immediately restored the continously repetitive detonation process, which had the sound of a machine gun at close range, and the length of a test was limited only by the need to preserve the uncooled apparatus.

V. Considerations Affecting Practical Application

The present basic study proved the feasibility of the concept, but application in a practical propulsion system requires that the following practical problems be solved:

1. Achieving high power density. Three factors are involved in this task, namely;

   a. propulsion efficiency, which may be expressed through the specific impulse

   b. hardware weight

   c. cycle frequency.

The specific impulse depends on the thermodynamic properties of the products (which also determine the maximum chamber pressure) and on the mixture ratio. For a given fuel, there is little to be done about the thermodynamic properties of the products. The mixture ratio however is, within some limits, under our control. Referring to Fig. 10, which shows calculated values, it seems that the maximum specific impulse is obtained when using a lean mixture. Working with a lean mixture lowers the temperature of the products (compared to the temperature obtained while using stoichiometric mixture ratio) which reduces the thermal load to the hardware. Thus the use of mixture ratios close to the low detonation limit is recommended.

Reducing the weight of the hardware can be approached in various ways. For example, storing the fuel and oxidizer (which is needed for detonation initiation in the detonation tube) in liquid form at low pressure enables the use of light containers. From this point of view, ethylene and oxygen are not the best choice of primary gases since their critical temperature is lower than standard ambient temperature. Using a glow plug instead of a spark plug eliminates the need for an ignition coil which adds considerable weight and is a significant factor in low power engines. The use of self-propelled rotary valves (with the gas pressure as the power source) may be a way to reduce the injection system weight and to increase the detonation cycle frequency to the maximum which is allowed by thermodynamic limitations.

2. Obtaining reasonable efficiency. A specific impulse over 1000 sec (compared to 200-300 sec which is typical of rocket motors) seems to be feasible. This is an attractive figure if it is accompanied by high power density and low price.

3. Low price. The detonation engine has almost no moving parts, so that it may be designed to have a very simple structure. It is potentially a cheap and reliable system, however, these features must yet be demonstrated in a practical engine.

VI. Conclusions

The experimental results from single detonation tests showed that it is possible to initiate transient detonation waves in ethylene-air mixtures using primary ethylene-oxygen detonations in a small volume initiated by a simple automobile ignition system. The volume of the ethylene-oxygen mixture was only 2% of the volume of the ethylene-air mixture, which makes this initiation scheme feasible for practical applications.

It was also determined from the single detonation tests, that the duration of a single cycle was less than 7 msec. This short cycle duration will potentially permit operation of an intermittent detonation engine with a frequency of more than 150 detonations per second. This suggests a potential for very high power density.

The maximum effective (time-averaged) pressure in the detonation chamber was 100 psig., (for mixture ratios between 4% and 6%), yielding a specific impulse in a practical engine of between 1000 sec and 1400 sec. In Ref. 10 it was reported that after each firing, about 15% to 20% of the detonation products remain in the detonation chamber for the following cycle. The amount of the remaining detonation products will depend strongly on the chamber internal nonsteady aerodynamics, and it could be substantially reduced by small modifications to the geometry of the chamber. Efficient product evacuation will be especially important for operating a detonation engine at the high frequency.

Finally, based on the results of the present experiment, estimates show that a practical detonation engine with a main chamber volume of 1500 cc could be operated with detonation frequencies of 100 Hz. Such a system could weigh between 3 and 5 lbs. and generate thrust between 20 and 25 kg.

Acknowledgement

The present study was initiated and carried out under the Foundation Research Program which is sponsored at the Naval Postgraduate School by the Office of Naval Research. Laboratory support through the Naval Air Systems Command Air-Breathing Propulsion Program is also gratefully acknowledged.

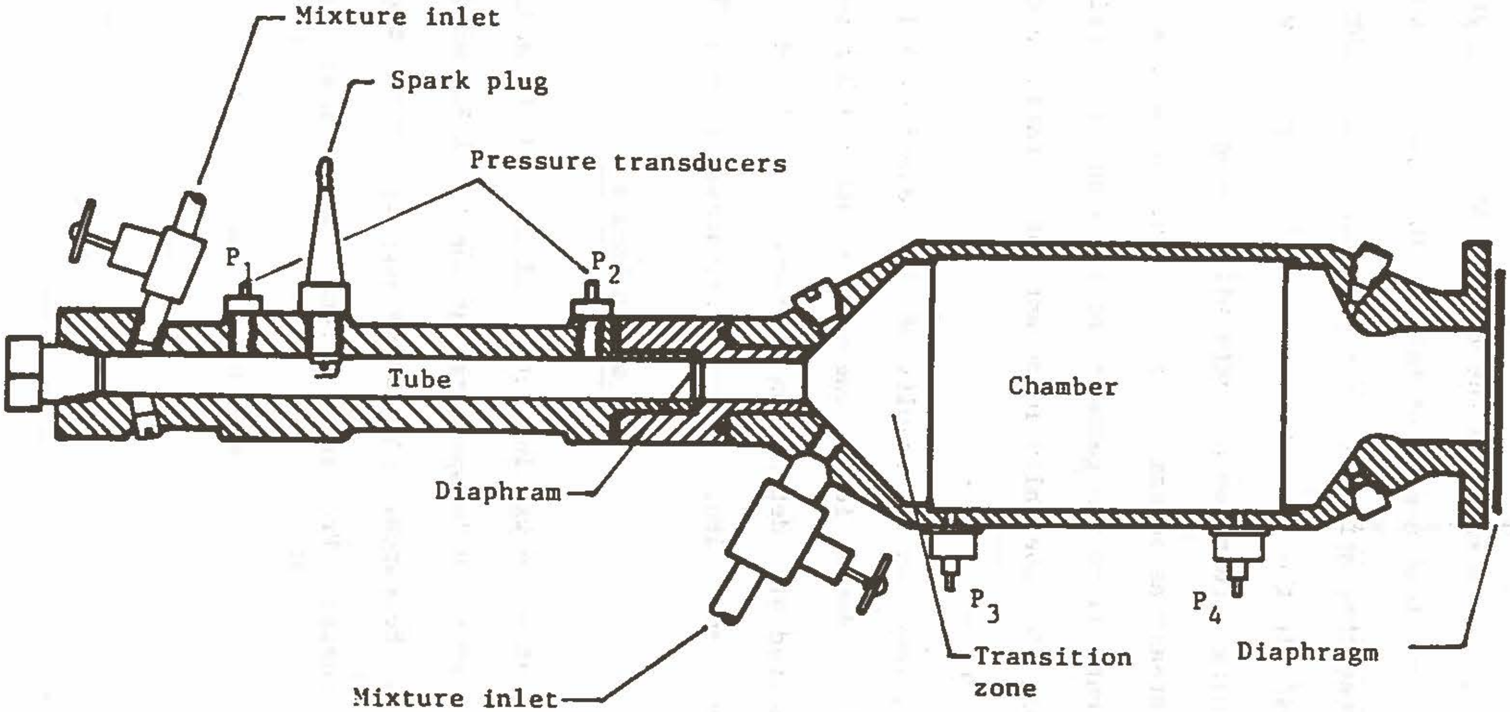

Figure 1. Single cycle testing rig.

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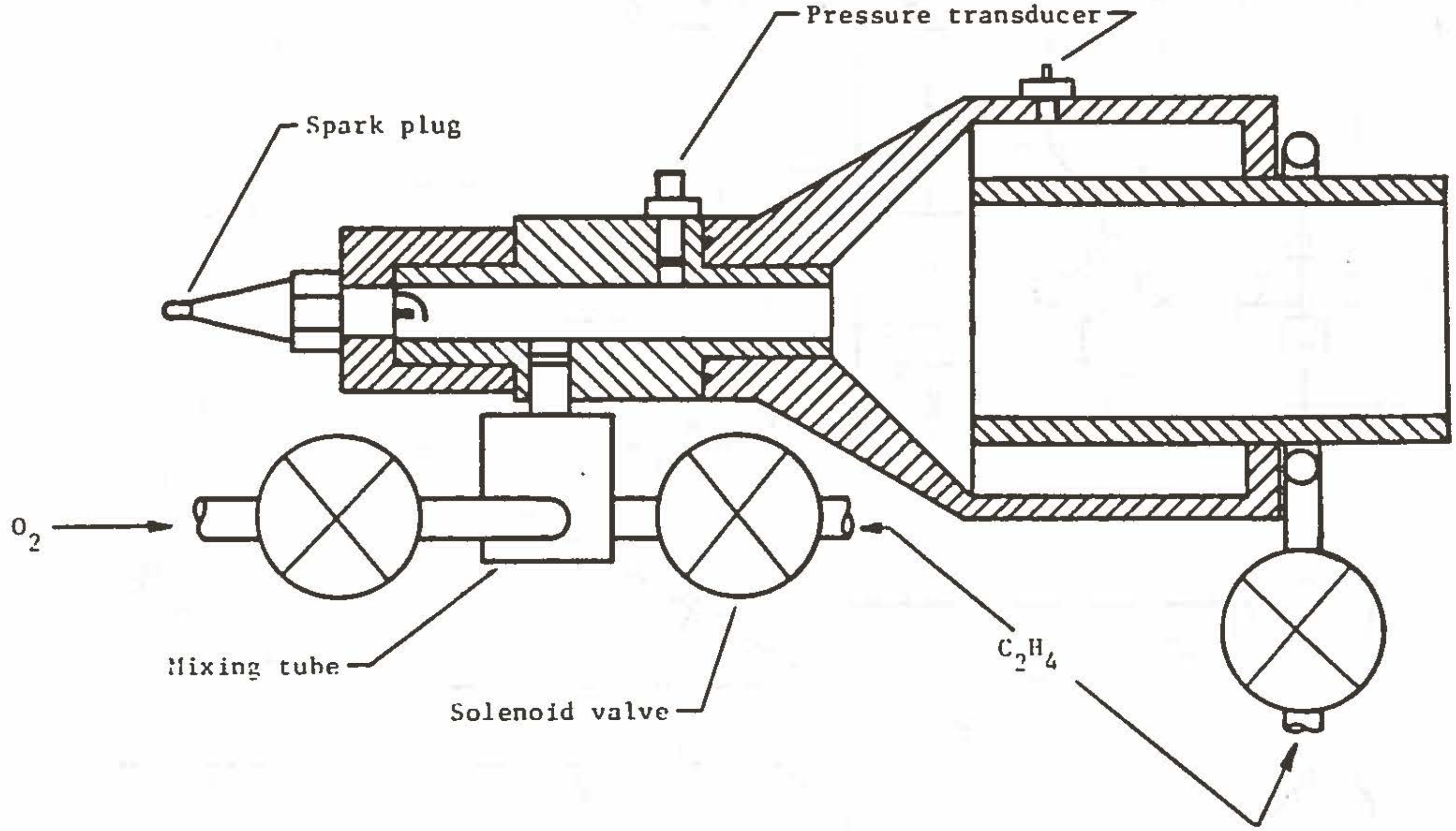

Figure 2. Polycyclic testing rig.

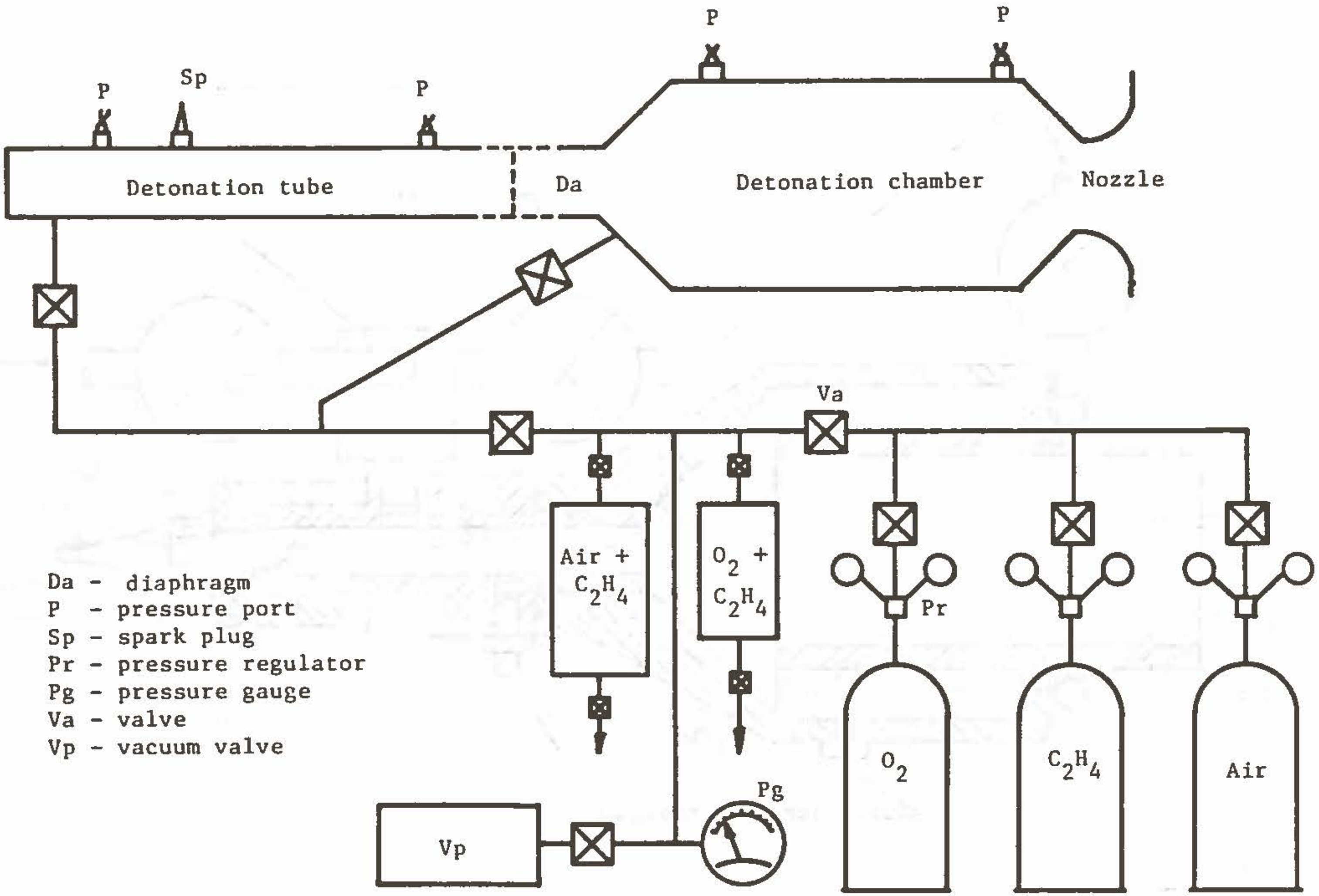

Figure 3. Unicycle test rig schematic.

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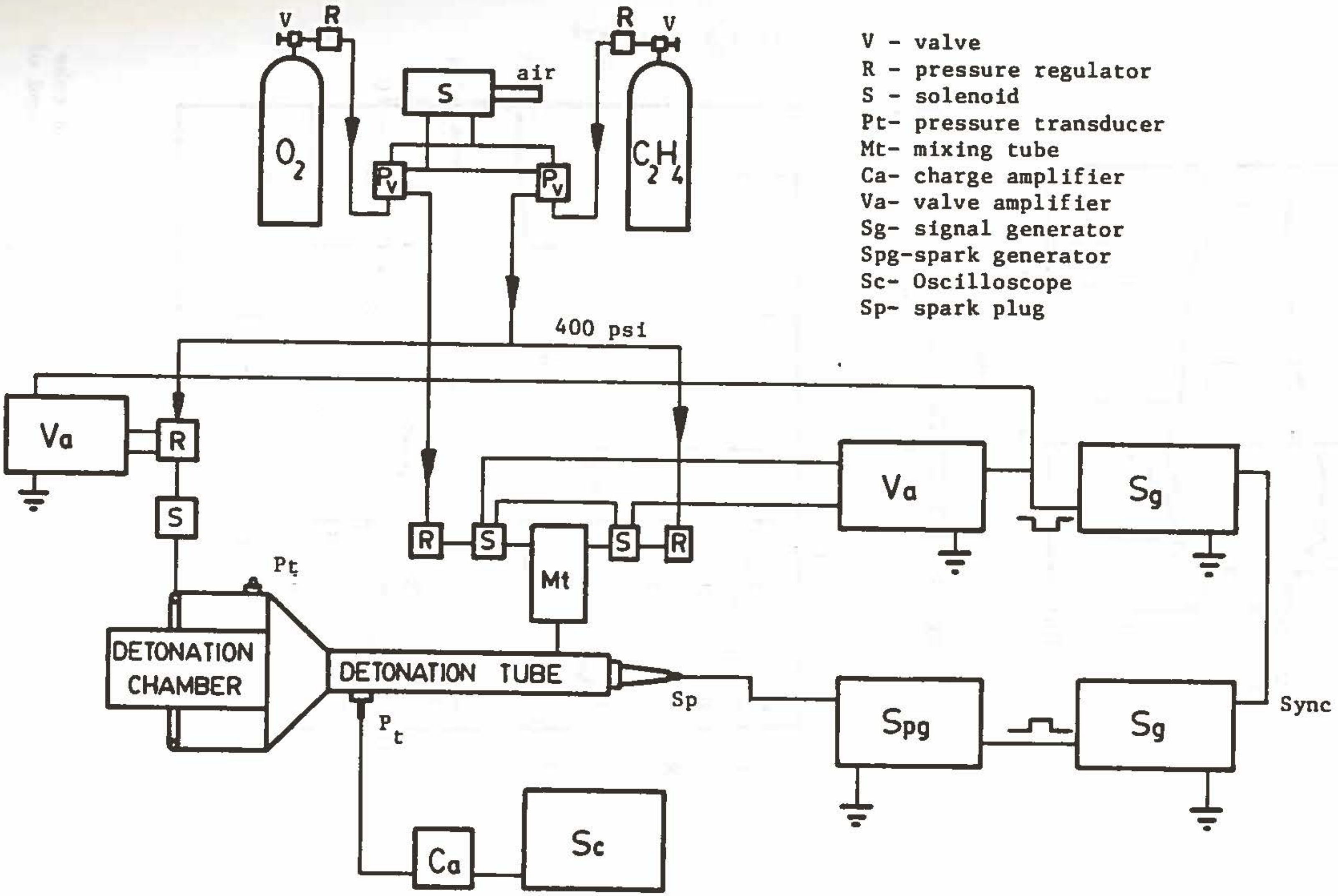

V - valve
R - pressure regulator
S - solenoid
Pt- pressure transducer
Mt- mixing tube
Ca- charge amplifier
Va- valve amplifier
Sg- signal generator
Spg-spark generator
Sc- Oscilloscope
Sp- spark plug

Figure 4. Polycyclic testing system schematic.

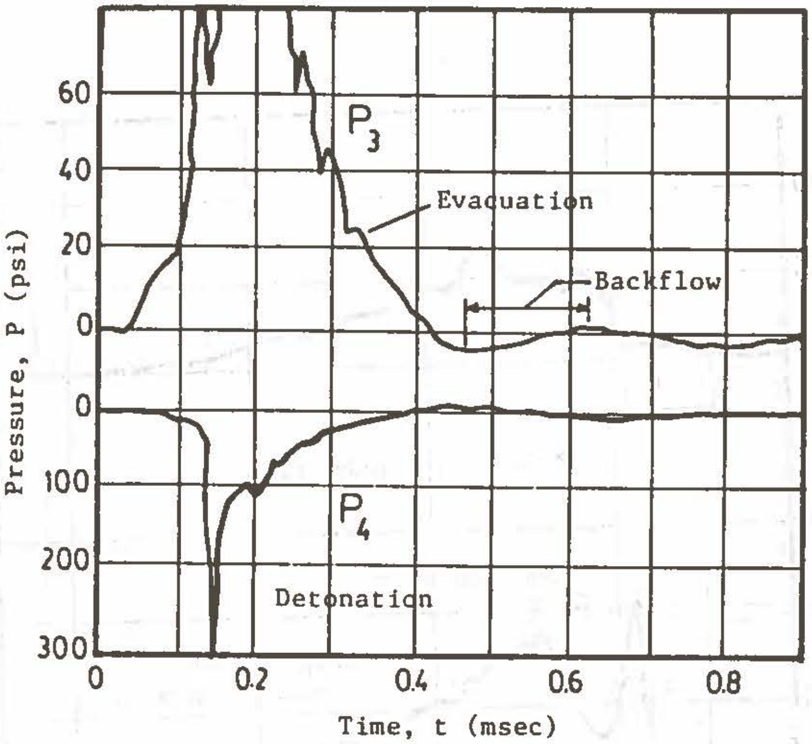

Figure 8. Pressure-time diagram in the chamber (detonation, evacuation, and backflow).

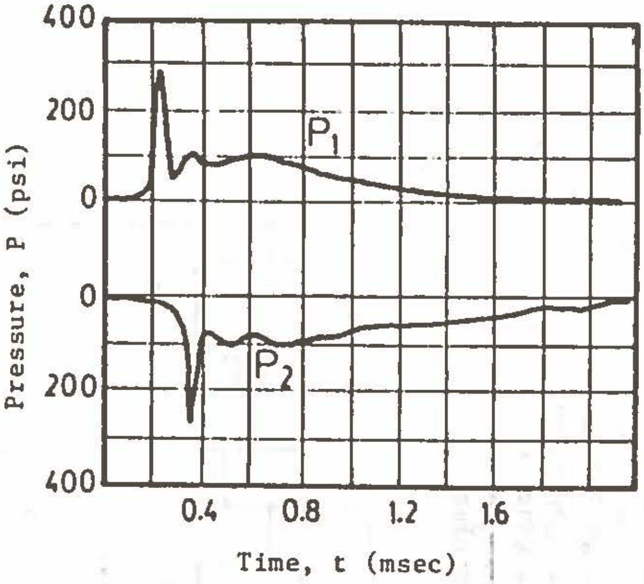

Figure 5. Pressure-time diagram inside the detonation tube.

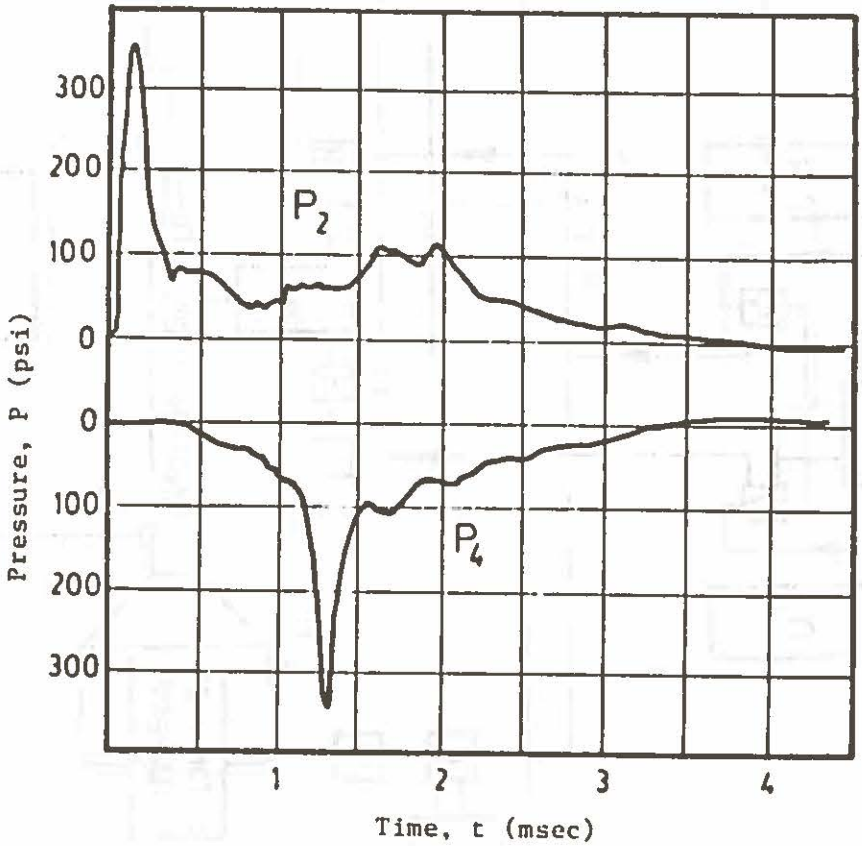

Figure 6. Pressure-time diagram in the detonation tube and the detonation chamber. (P_2 = aft end of tube, P_4 = aft end of the chamber.)

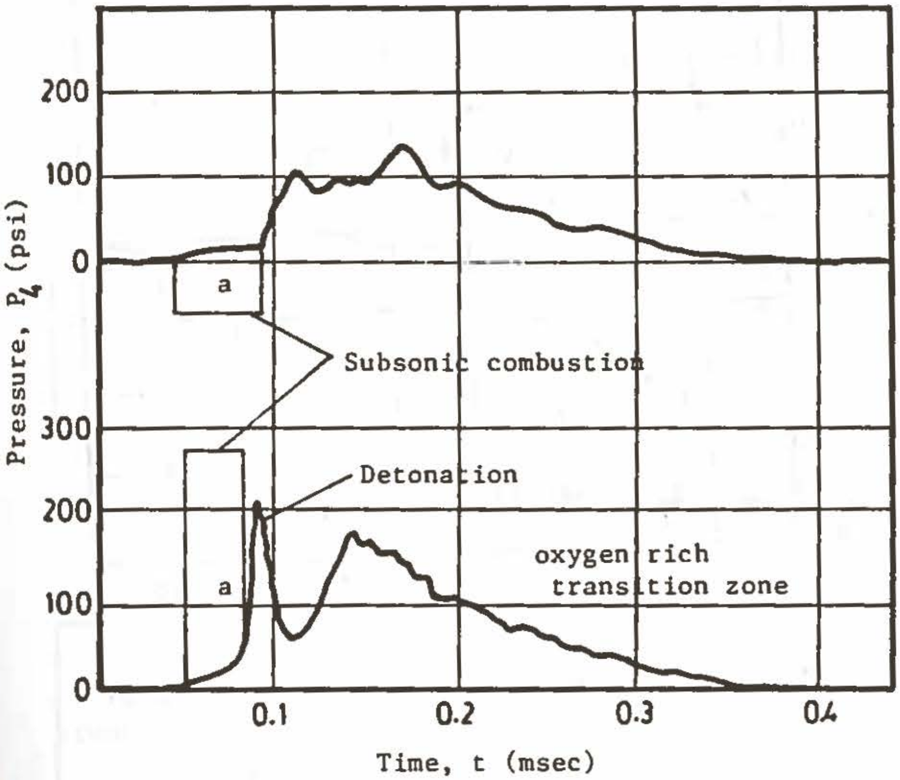

Figure 7. Effect of addition of oxygen into the transition zone on the pressure-time diagram.

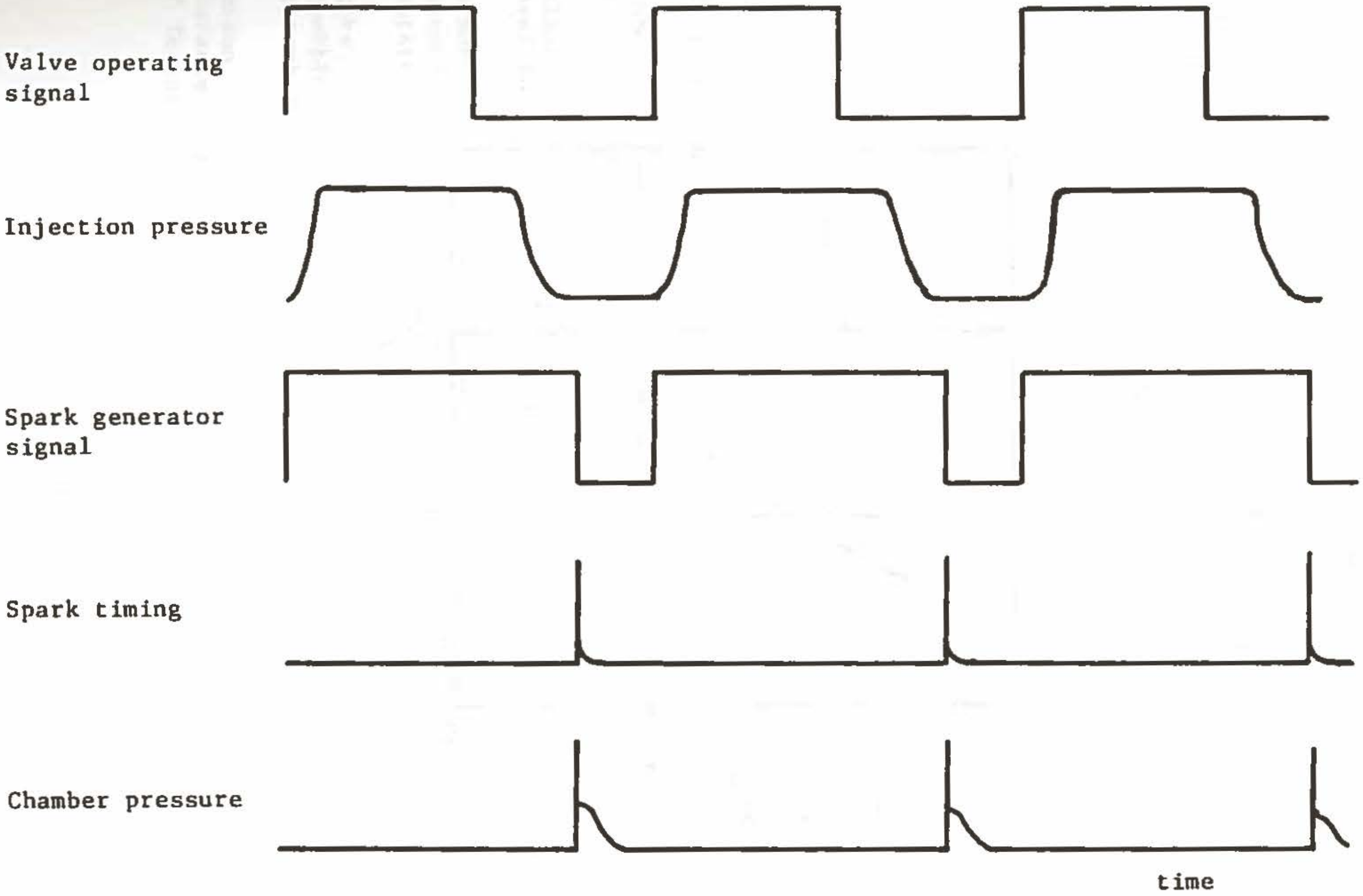

Figure 9. Operation sequence in polycyclic tests.

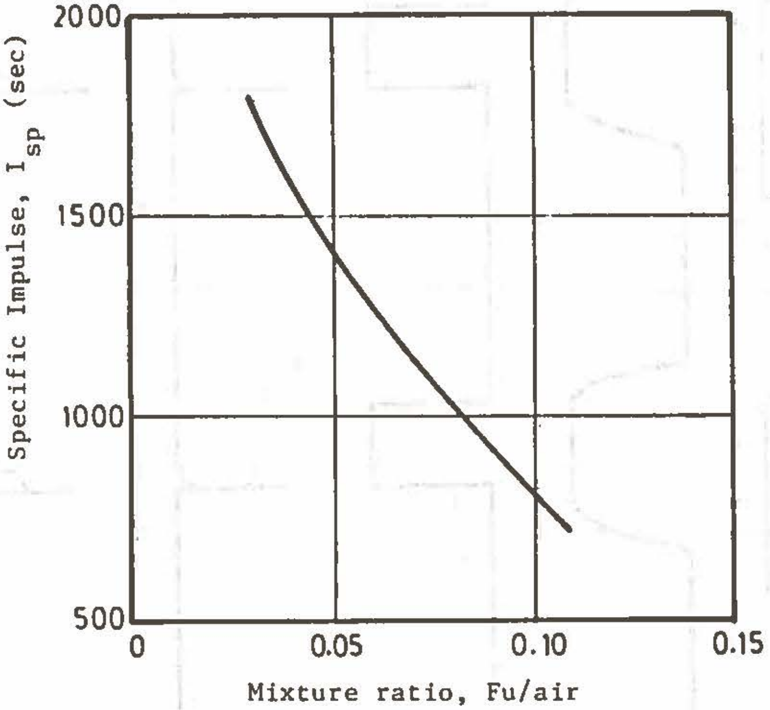

Figure 10. Specific impulse as a function of mixture ratio.

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