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Metodrapport

Ulrika Carlsson

Examensarbete

Metod för mätning av flamfrontshastighet

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Sammanfattning (högst 200 ord)

För att verifiera att detonation sker i en pulsdetonationsmotor har tidigare tryckgivare använts, men eftersom dessa lätt förstörs och är relativt dyra har en alternativ metod undersökts I denna metod används tändstift. Förbränningsvågens utbredning mäts genom att detektera på förändringen i ledningsförmåga mellan tändstiftselektroderna då vågen passerar. Tidsintervallet mellan signalerna från flera efter varandra placerade tändstift med kända avstånd, mäts. Resultatet från dessa mätningar jämförs sedan med resultatet då tryckgivare används.
Att använda tändstift i ställer för tryckgivare är en lika god, och billigare, metod för verifikation av detonationsvågor. Skillnaden blir att vid användning av tändstift så registreras förbränningsvågen och vid användning av tryckgivare tryckvågen.

Nyckelord

Pulsdetonationsmotor, tändstift, LabVIEW

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Report title (In translation)

A method for measuring flame propagation speed.

Abstract (not more than 200 words)

To verify that a detonation occurs in a pulse detonation engine, pressure sensors have been used to measure the flame propagation velocity. However, pressure sensors are easily destroyed and quite expensive. An alternative method has therefore been examined in this project where the propagation of the flame is measured by detecting the time when the conductivity between the spark plug electrodes changes. The velocity is decided by the time intervals between the signals from several spark plugs, at known distances, placed after one another. The results are compared with the results from measurements using pressure sensors.

The use of spark plugs instead of pressure sensors to verify detonations showed to be an equally good as well as cheaper alternative. The difference from pressure sensors is that spark plugs record the combustion wave instead of the pressure wave.

Keywords

Pulse detonation engine, spark plugs, LabVIEW

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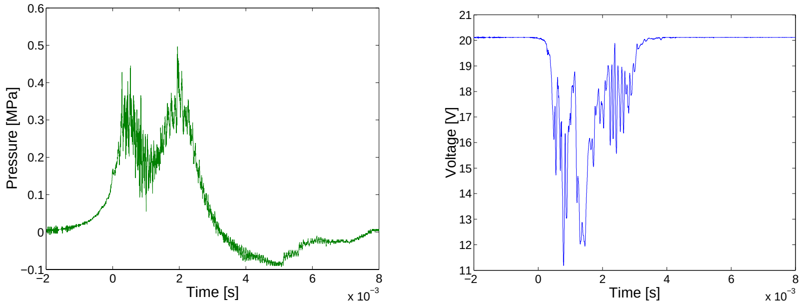
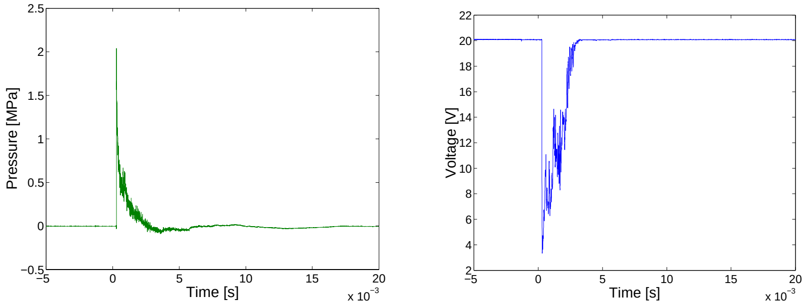
Sammanfattning

Vid institutionen för Framdrivning och Stridsdelar, avdelningen för Vapen och Skydd på Totalförsvarets forskningsinstitut (FOI) sker forskning om pulsdetonationsmotorn (PDE), delvis på grund av att den har en hög termodynamisk effektivitet och är förhållandevis enkel.

För att verifiera att detonation sker i denna motor har tidigare tryckgivare använts, men eftersom dessa lätt förstörs och är relativt dyra undersöktes en alternativ metod. Denna metod går ut på att använda tändstift. Förbränningsvågens utbredning mäts då genom att titta på förändringen i ledningsförmåga mellan tändstiftselektroderna då vågen passerar. Tidsintervallet mellan signalerna från flera efter varandra placerade tändstift, vid kända avstånd, mäts. Resultatet från dessa mätningar jämförs sedan med resultatet då tryckgivare används.



Figur 1: Trycket, och spänningen över tändstiftet, vid position G3 och med en blandning på 4 % syrgas.



Figur 2: Trycket, och spänningen över tändstiftet, vid position G9 och med en blandning på 14 % syrgas.

Figurerna ovan visar att utseendet på trycket stämmer väl överens med utseendet på spänningsfallet. När det sker en skarp ökning i trycket sker det också ett skarpt spänningsfall. Tiden vid vilken trycket ökar och spänningsfallet sker stämmer dock inte lika bra överens. I de fall då det inte sker någon lyckad övergång till detonation avlägsnar sig chockvågen från området där förbränningen sker. Detta bidrar till att det blir en tidsskillnad mellan den händelse som detekteras av tryckgivaren och den som detekteras an tändstiftet. Vid en lyckad övergång till detonation registrerar de olika mätinstrumenten samma sak.

Att använda tändstift i ställer för tryckgivare är en lika bra, och billigare, metod vid verifikation av detonationsvågor. Skillnaden blir att vid användning av tändstift så registreras förbränningsvågen och vid användning av tryckgivare tryckvågen.

Abstract

At the department of Warheads and Propulsion, division of Weapons and Protection at the Swedish Defence Research Agency (FOI) research about the Pulse Detonation Engine (PDE) takes place, partly because of its potentially high thermodynamic efficiency and simplicity.

To verify that there is a detonation that occurs in this engine pressure sensors were previously used but since these are easily destroyed and quite expensive an alternative method were examined. This method was to use spark plugs. The propagation of the combustion is then measured by looking at the changes in conductivity between the spark plug electrodes when the wave passes. The time interval between the signals from several spark plugs, at known distances, placed after one another are measured. The results are then compared with the results from measurements using pressure sensors.

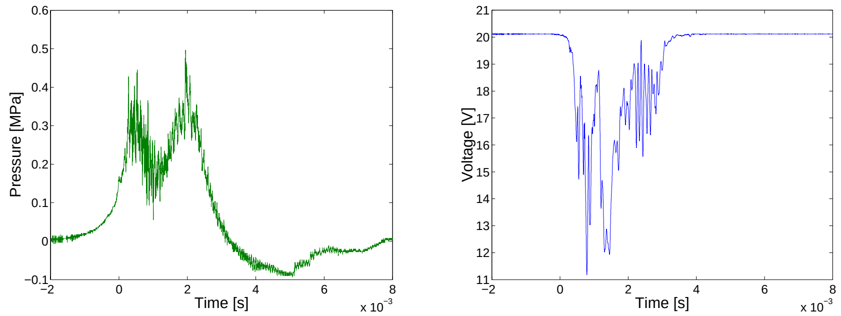


Figure 1: The pressure and the voltage over the spark plug, at location G3 with a mixture of 4 % of oxygen gas.

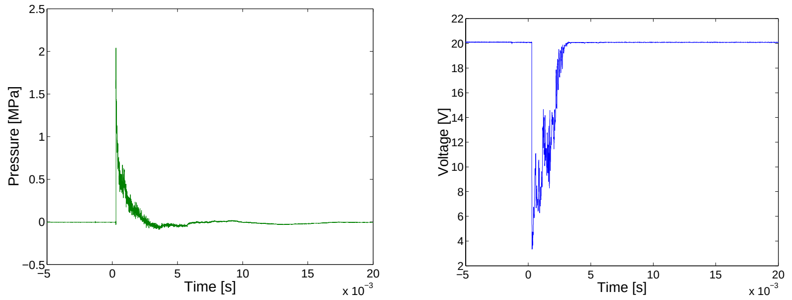


Figure 2: The pressure and the voltage over the spark plug, at location G9 with a mixture of 14% of oxygen gas

The figures above show that there is a good correspondence between the appearance of the pressure and the voltage drop. If there is a sharp rise in pressure there is also a sharp drop in voltage. Though for the cases when there is no successful transition to detonation the pressure rise and the voltage drop do not occur at the same time. The shock wave separates and travels ahead of the zone where the combustion takes place. Consequently, there will be a time difference between the events recorded by the pressure sensors and the spark plugs. However, in the case of a successful transition to detonation the two measuring devices will detect the same event.

So using spark plugs instead of pressure sensors to verify detonations is an equally good, and always cheaper, alternative. The difference from pressure sensors is that spark plugs record the combustion wave instead of the pressure wave.

Contents

Introduction

At the department of Warheads and Propulsion, division of Weapons and Protection at the Swedish Defence Research Agency (FOI) research is done about future technologies for rocket- and air-breathing engines. One example of such a technology of special interest for future technologies is the Pulse Detonation Engine (PDE), because of its potentially high thermodynamic efficiency and its simplicity. During experimental tests with this engine it is important to verify that there is a detonation that occurs. Previously this has been done by using pressure sensors, but since these are easily destroyed, due to the high pressure and temperature, and since these sensors are quite expensive alternative methods are needed. One method is to use spark plugs, which are much cheaper.

One way of using spark plugs to determine if it is a detonation is to measure the speed of the combustion wave. When the combustion wave passes the spark plug electrodes there is a change in conductivity between them, which can be measured. The time interval between the signals from several spark plugs, at known distances, placed after one another are then measured to determine the speed.

In order to use spark plugs in this way an electronic interface has to be built to be able to handle the data from the measurements.

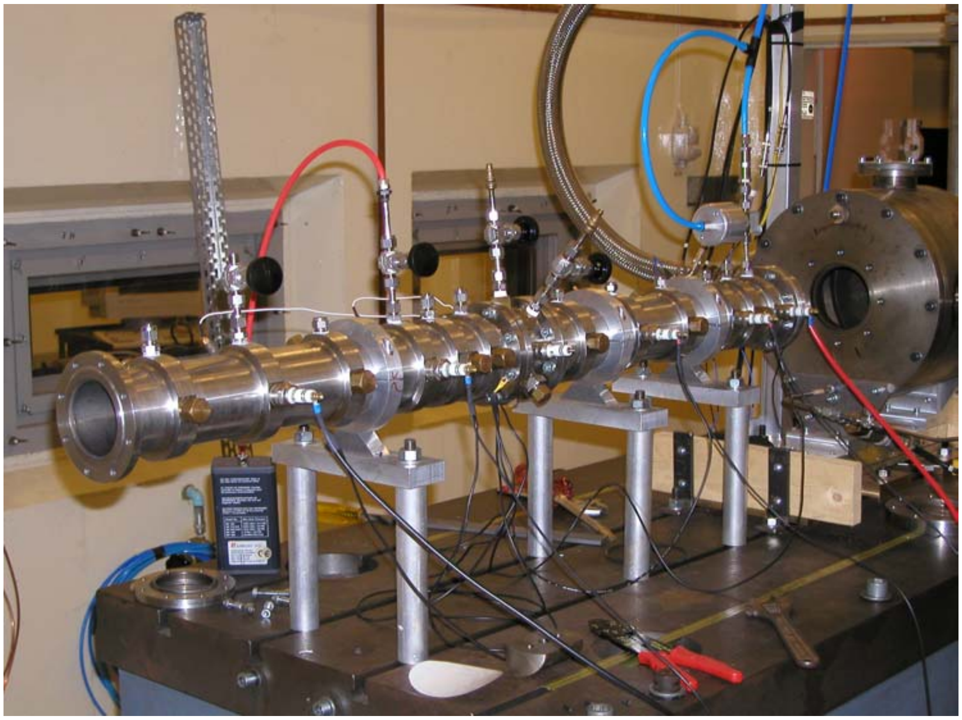


Figure 3: The PDE with spark plugs of which one (the one with the red cable) is used to start the combustion and four (the ones with the black cables) are used for measuring.

Pulse Detonation Engine (PDE)

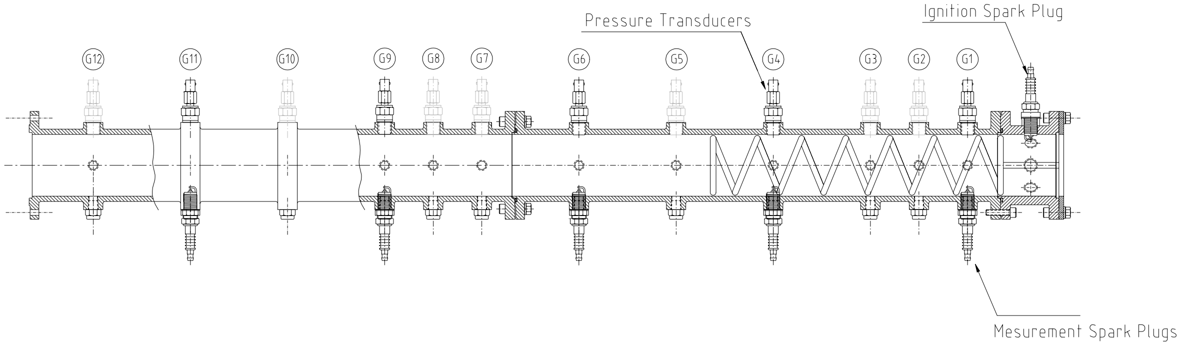
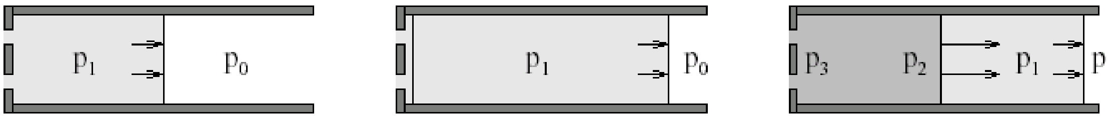


Figure 4: The PDE test rig with pressure sensors, spiral (used to enhance the transition from flame to detonation) and spark plugs.

The engine that was used for this project is a Pulse Detonation Engine (PDE), shown in Figure 4. The reason to why this engine is of interest is its high thermodynamic efficiency and because it is very easy to understand and build. It also has advantages in comparison with other engines since it may, in the future, be possible to use oxygen from the surrounding air while travelling.

The engine consists of a straight tube in which a mixture of hydrogen and air is injected. This gas mixture is ignited by a spark plug and pressure sensors are then used to verify that a detonation occur (a detonation in hydrogen air reaches pressures over 20 bar and propagates at around 2000 m/s).

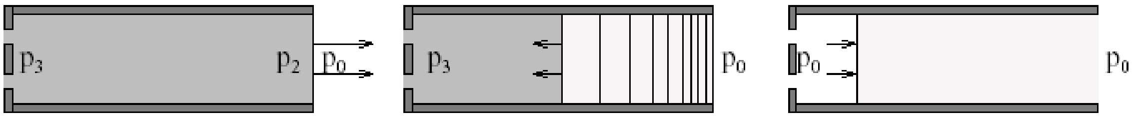
Getting a detonation either takes a lot of energy as a direct initiation, or something called a Deflagration to Detonation Transition (DDT). The flame then starts at a low speed, as a deflagration, and accelerates to a detonation.



1. The engine is filled with fuel–air mixture.

2. Initiation of the detonation.

3. The detonation moves through the engine. The pressure p_3 acts on the front plate and generates thrust.



4. The detonation leaves the engine.

5. Rarefaction waves move in from the exit and gradually lower the pressure at the front plate.

6. Exhaust of the combustion products.

Figure 5: Principle of the engine.

The name Pulse Detonation Engine makes it quite obvious that the engine operates in pulsating mode. Each pulse can be described as follows, see Figure 5: First the engine is filled with fuel and air. p_1 is the pressure of the fuel and air mixture and p_0 is the ambient pressure. The detonation then starts and propagates through the combustor so that combustion occurs. The major part of the thrust is now produced since the pressure p_3 acts on the front plate and therefore generates thrust. p_3 is substantially lower than the peak pressure of the detonation, p_2. The detonation then leaves the engine but p_3 is still acting on the front plate, generating thrust. Rarefaction waves (a pressure wave which lowers the pressure and density of the gas) move in from the exit and gradually lower the pressure at the front plate. Finally the combustion products are exhausted from the detonation chamber, and one cycle is ended.

A more thorough description can be found in Appendix 1, written by Jon Tegnér.

Experimental set-up

The PDE that was used for the experiments is built for periodic measuring during cycling pulses. Though, during these experiments only single pulse measurements were conducted.

The first series of experiments were conducted to determine the feasibility of this method, i.e. verification of detonation waves using spark plugs. Therefore only a “simple” set-up was built that consisted of the PDE test rig, four pressure sensors, four spark plugs, a circuit board and a computer. This set-up is shown in Figure 6.

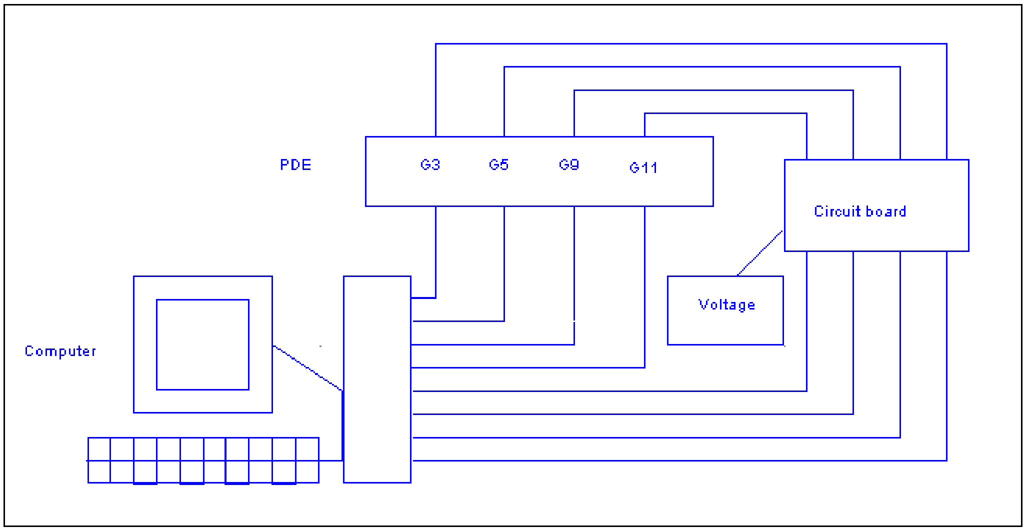


Figure 6: Schematic experimental set-up.

The spark plugs are placed at the upper side of the PDE test rig in the figure (where G3, G5, G9 and G11 are the locations at which the spark plugs and corresponding pressure sensors are located) and the pressure sensors at the lower side. The distances (in meters) between the front plate and position G1 (place of ignition), G1 and G3, G3 and G5, G5 and G9 and G9 and G11 are shown in Figure 7.

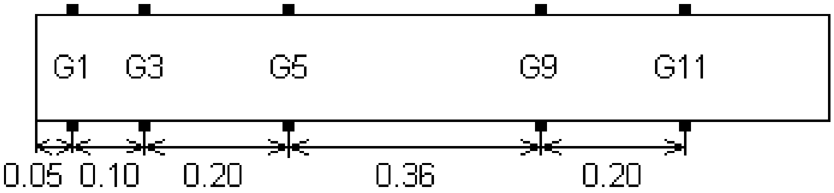


Figure 7: The distances between the different locations.

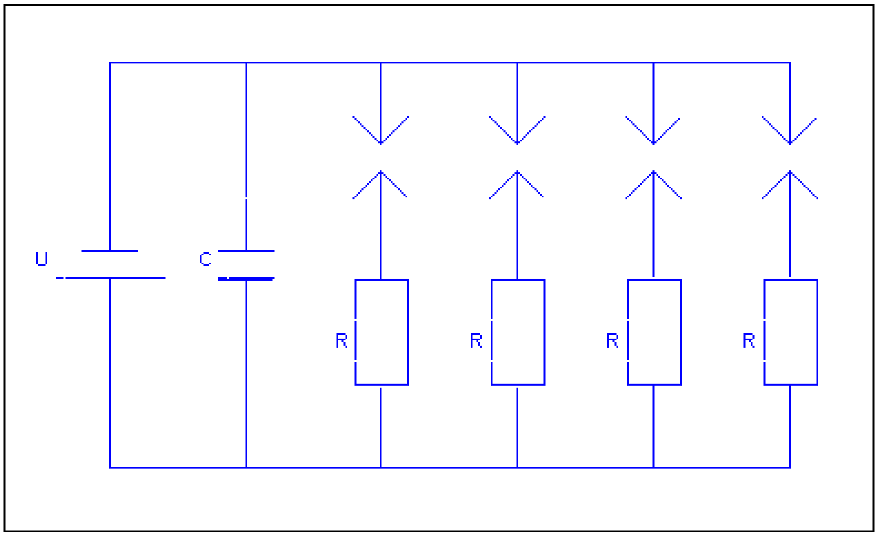


Figure 8: The electric circuit.

Figure 8 shows the electric circuit of the “simple” experiments. The circuit is fed by a voltage of 20 V (U = 20 V) and has a 1 μF capacitor (C = 1 μF). Each of the spark plugs are connected in series with a 2 kΩ resistor (R = 2 kΩ). The voltage was measured over the spark plugs to see how it drops due to the change in conductivity between the spark plug electrodes when the combustion wave passes.

The reason why the voltage drops is that because of the change in conductivity between the spark plug electrodes it works as a varying resistance. When the conductivity increases the resistance decreases. So, when there is “complete” conductivity the resistance is practically zero. From Ohms law

$$U = RI \tag{1}$$

we then get that when the resistance decreases, because of an increase in conductivity, so does the voltage. Hence, the voltage drops when the conductivity increases.

After verifying the functionality, a measurement system was built which directly gives the speed of propagation of the combustion wave instead of the voltage. The system consists of a counter/timer device (PCI-6602), a connector block (TBX-68) and a LabVIEW program. The experimental set-up for this case can be seen in Figure 9.

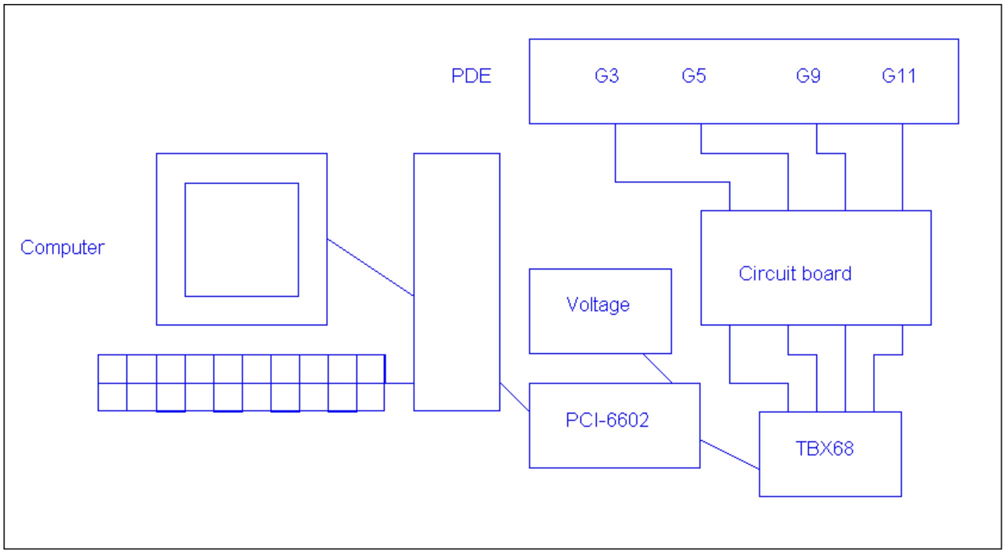
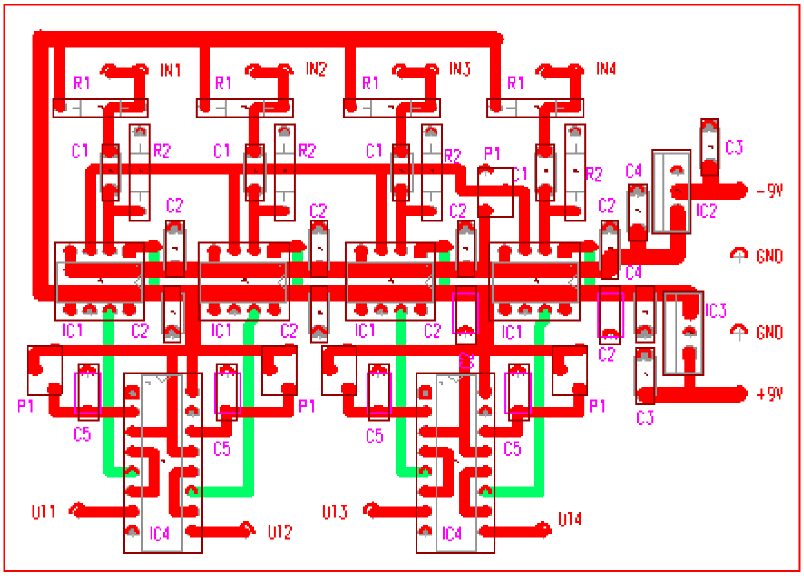


Figure 9: The experimental set-up.

The voltage signals from the spark plugs are connected to the circuit board, see Figure 10 and Figure 11, and via the connector block to the counter/timer device. The connections are done with coaxial cables. The counter/timer device is supplied with a 5 V voltage and a LabVIEW program communicates with it, which in the end gives the speed of propagation.



List of components:
IC1 = AD790JN
IC2 = 7806 (+5V)
IC3 = 7906 (-5V)
IC4 = 74HCT4538N
R1 = 2k
R2 = 10k
P1 = 10k (pot.)
C1 = 500pF
C2 = 100nF
C3 = 0.1uF
C4 = 0.33uF
C5 = 1uF

Figure 10: The appearance of the circuit board.

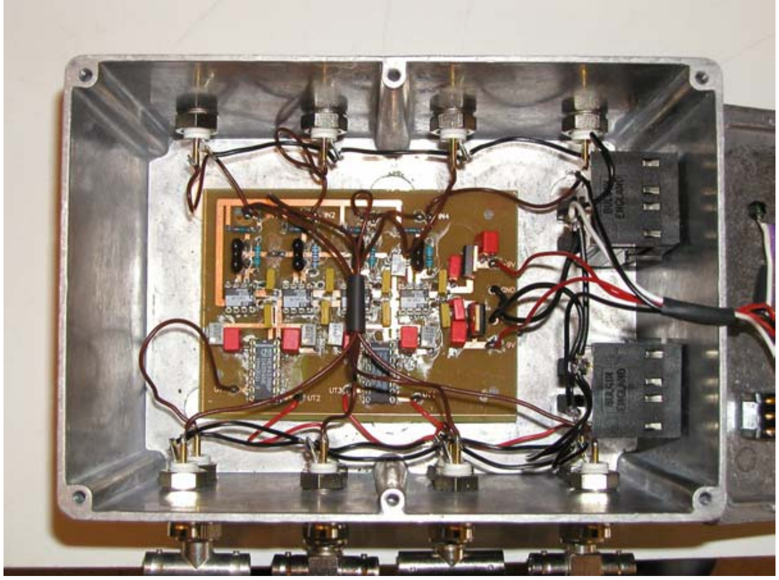


Figure 11: The circuit board placed inside a box.

The electric circuit, for this a little more complicated set-up, for a single spark plug is shown in Figure 12. The entire circuit is shown in Appendix 2.

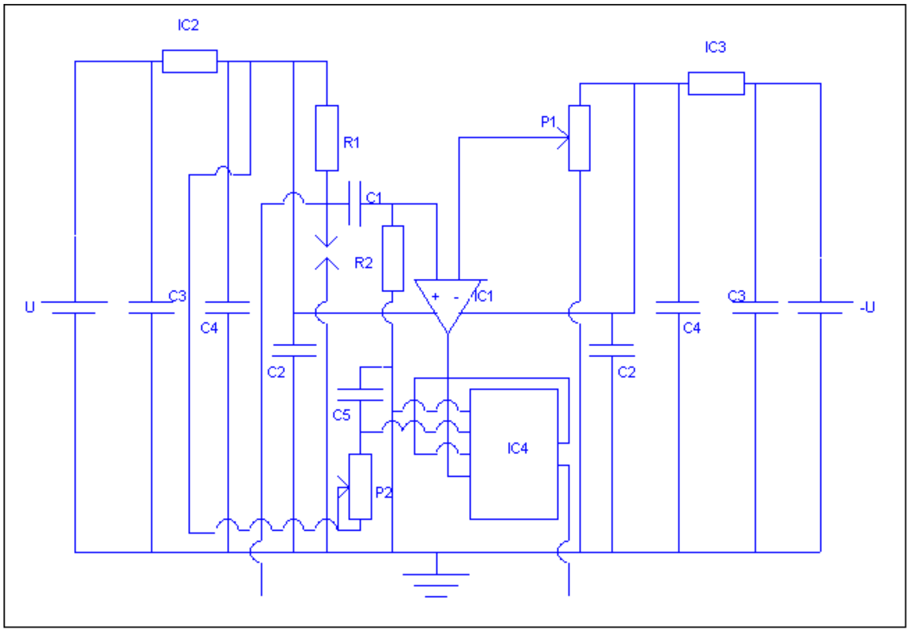


Figure 12: The electric circuit.

The circuit is fed by a 9 V voltage (U = 9 V). The spark plugs are still connected in series with a resistor. To be able to use the counter/timer device the signal has to be transformed into a digital signal. This is done by using comparators (IC1 = AD790JN) and a potentiometer that regulates the comparison signal. The signal is being "held high" for a certain time by monostable multivibrators (IC4 = 74HCT4538N) at the end.

Spark plugs

A spark plug is usually placed in the combustion chamber where the best ignition of the fuel-air mixture can be achieved. The spark between the electrodes ionizes[1] the space between the electrodes and starts an electric discharge. The released energy ignites the fuel-air mixture between the electrodes. From this ignition point a combustion wave propagates through the combustion chamber until the entire fuel-air mixture has been combusted.

The spark plugs used for these experiments were Bosch, W8CC, see Figure 13. The distance between the electrodes was 1 mm.

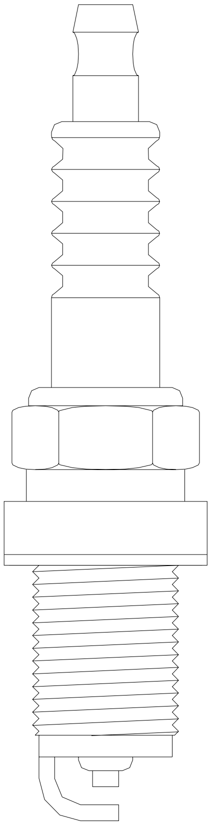


Figure 13: Spark plug.

Counter/Timer device (PCI-6602)

The 6602 device is a timing and digital I/O board for use with the PCI bus in PC-compatible computers, or PXI or compact PCI chassis. It offers eight 32-bit counter channels and up to 32 lines of individually configurable, TTL/CMOS-compatible digital I/O. The counter/timer channels have many measurement and generation modes such as event counting, time measurement, frequency measurement, encoder position measurement, pulse generation, and square-wave generation. For more information about this device, see National Instruments home page at www.ni.com.

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[1] ionization: due to the electric field between the electrodes the media in between becomes conductive

The PCI-6602 has many different counter applications, as shown in Table 1.

Application Class	**Application**
Simple Counting and Time Measurement	Simple event counting Gated-event counting Single-period measurement Single pulse-width measurement Two-signal edge-separation measurement
Simple Pulse and Pulse-Train Generation	Single pulse generation Single-triggered pulse generation Retriggerable single pulse generation Continuous pulse-train generation Frequency shift keying (FSK)
Buffered Counting and Time Measurement	Buffered event counting (continuos) Buffered period measurement (continuos) Buffered semi period measurement (continuos) Buffered pulse-width measurement (continuos) Buffered two-signal edge-separation measurement (continuos)
Other Counter Applications	Pulse generation for Equivalent Time Sampling (ETS) Buffered periodic event counting (continuos) Frequency measurement Buffered frequency measurement (continuos) Finite pulse-train generation Frequency division Reciprocal frequency measurement
Position Measurement	Quadrature encoders Two-pulse encoders
Miscellaneous Functions	Filters Flexible period and frequency measurements Digital I/O Prescaling Simultaneous arming of counters Pad synchronization Synchronous counting mode

Table 1: Counter-Based Applications.

In this experiment the application is a buffered two-signal edge-separation measurement. Then there are two measurement signals: AUX_LINE and GATE. An active edge on AUX_LINE starts the counting and an active edge on GATE stops the counting. The counter counts the number of rising edges on SOURCE between the active edge of AUX_LINE and the following active edge of GATE. For each active edge of GATE, the counter value is latched for software read. It is this counter value that is used by LabVIEW to calculate the speed of the combustion wave. Figure 14 shows three instances of buffered two-signal edge-separation measurement where the separation is four, three or two SOURCE rising edges.

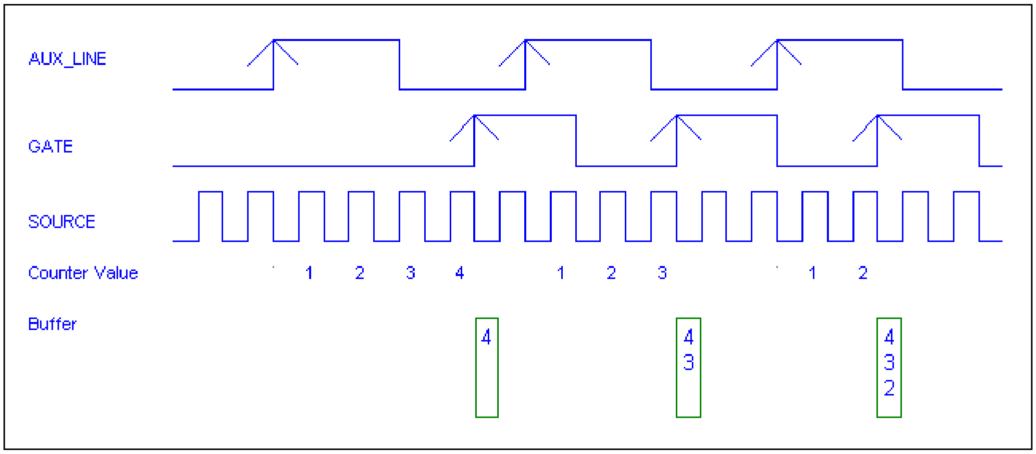


Figure 14: Buffered Two-Signal Edge-Separation Measurement.

On the first counter the signal from the first spark plug is connected to AUX_LINE (to start the counting) and the signal from the second spark plug is connected to GATE (to stop the counting). The second counter then gets the signal from the second spark plug on AUX_LINE and the signal from the third spark plug on GATE. Finally, on the third counter the signal from the third spark plug is connected to the AUX_LINE and the signal from the last spark plug on GATE. By this the counter/timer device gives the number of counts in between the signals from two consecutive spark plugs.

LabVIEW

LabVIEW, short for Laboratory Virtual Instrument Engineering Workbench, is a graphical programming environment for data acquisition, instrument control and data analysing. It works on PCs running Microsoft Windows, Mac OS, Sun SPARCstations and HP 9000/700 series workstations running HP-UX.

LabVIEW can be used to acquire measurements, control instruments, analyse data, present results to the user, make simulations and presentations, and for general programming.

For this application a LabVIEW program was written which calculates the speed of the combustion wave from the number of counts from the counter/timer device. The main program is shown in Figure 15, and the sub programs in Figure 16 - Figure 19.

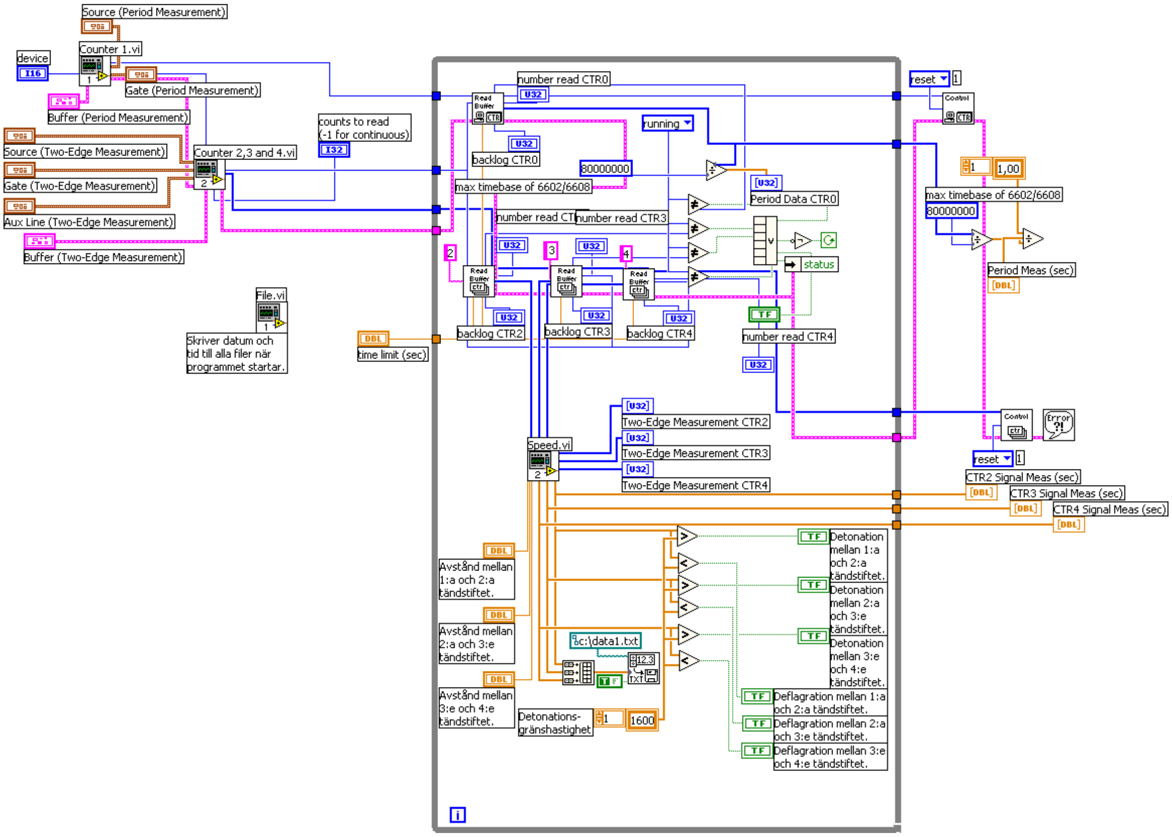


Figure 15: The main LabVIEW program.

The signals, both from GATE and AUX_LINE, are first collected in the sub programs Counter. These data that has been transformed into vectors are sent to the sub program Speed where the speed of the combustion wave is calculated. The speed is then compared to the limit for detonation speed so that if it exceeds the limit a green lamp is lit on the interface and otherwise a red lamp is lit. Finally the results are saved in a file in the sub program File.

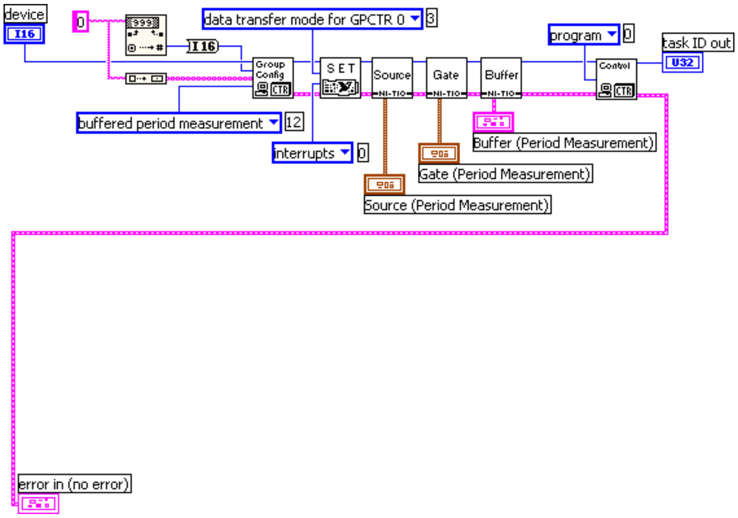


Figure 16: The sub program Counter1.

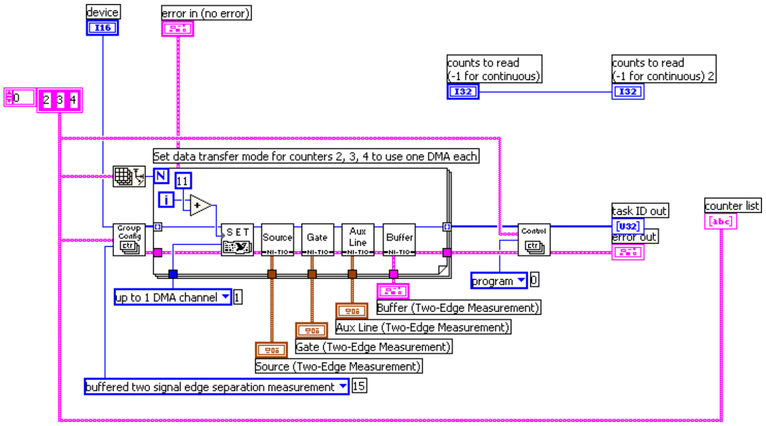


Figure 17: The sub program Counter234.

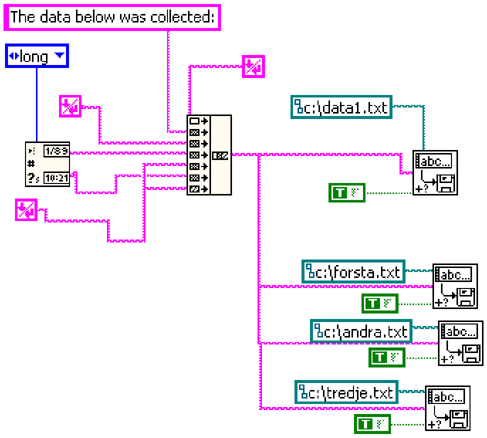


Figure 18: The sub program File.

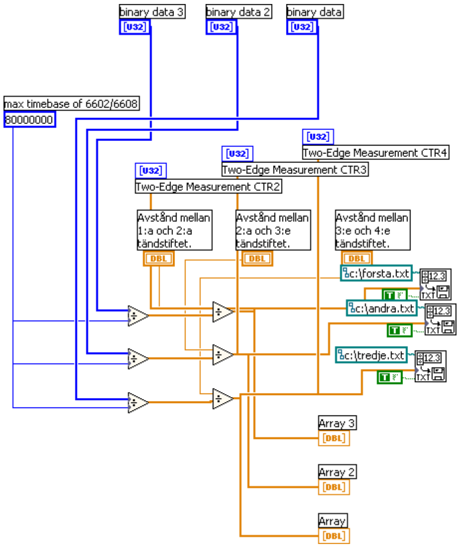


Figure 19: The sub program Speed.

Experimental performance

The experiments were done with several mixtures of different percentage of oxygen (4 %, 6 %, 8 %, 10 %, 14 % and 20 %), with or without the spiral, to get a variety of combustion speeds.

A hydrogen gas/oxygen gas/air mixture fills the main chamber that is sealed with a membrane in the open end. Before the filling starts the chamber is evacuated with a vacuum pump. Then the filling starts so that atmospheric pressure is reached. How much of each substance that is to be filled is determined by Table 2 and the true values is presented in Table 3. An ignition coil that starts an electric discharge over a spark plug initiates the combustion.

H_2	O_2	Air
0.2958	0.0000	0.7042
0.3180	0.0200	0.6620
0.3403	0.0400	0.6197
0.3625	0.0600	0.5775
0.3848	0.0800	0.5352
0.4070	0.1000	0.4930
0.4293	0.1200	0.4507
0.4515	0.1400	0.4085
0.4738	0.1600	0.3662
0.4961	0.1800	0.3239
0.5183	0.2000	0.2817
0.5406	0.2200	0.2394
0.5628	0.2400	0.1972
0.5851	0.2600	0.1549
0.6073	0.2800	0.1127
0.6296	0.3000	0.0704
0.6518	0.3200	0.0282

Table 2: With hydrogen gas as fuel and with $\Phi = 1$ the different partial pressures are chosen according to this table.

	Start pressure (mbar)	**H_2 (mbar)**	**O_2 (mbar)**	**Air (mbar)**
4 % oxygen	545	346	40	90
6 % oxygen	502	362	62	97
8 % oxygen	458	388	81	97
14 % oxygen	332	457	144	91

Table 3: The true values for oxygen and hydrogen gas during the first experiments.

Results

Signal comparison

The results from the "simple" experiments using mixtures of 4%, 8% and 14% of oxygen gas, and with the spiral, are presented below. Besides these three experiments with the spiral there was also one done with 6% of oxygen gas. Without the spiral experiments with mixtures of 8%, 14% and 20% were done. The results from these last four cases can be seen in Appendix 3.

4% of oxygen gas

With a mixture containing 4% of oxygen gas both speeds below and at detonation speed occurred. In Figure 20 - Figure 23 the signal over the spark plug is compared to the pressure signal, at the locations G3, G5, G9 and G11. They show that as the rise of the pressure signal gets sharper so does the voltage drop.

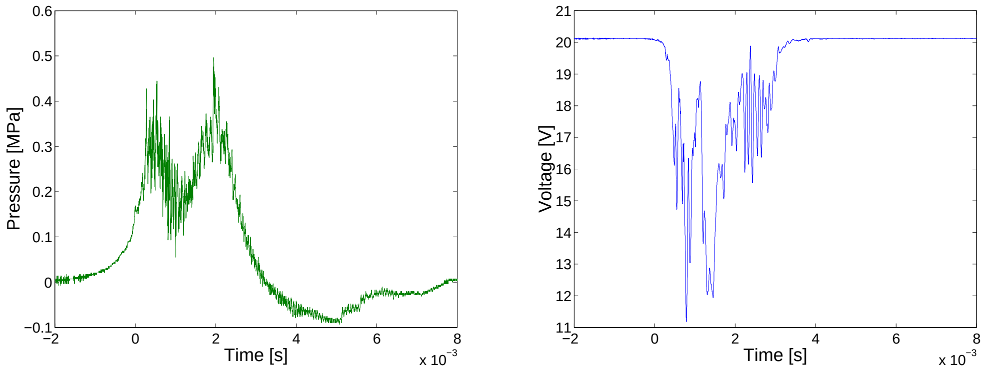


Figure 20: The pressure and the voltage over the spark plug at location G3.

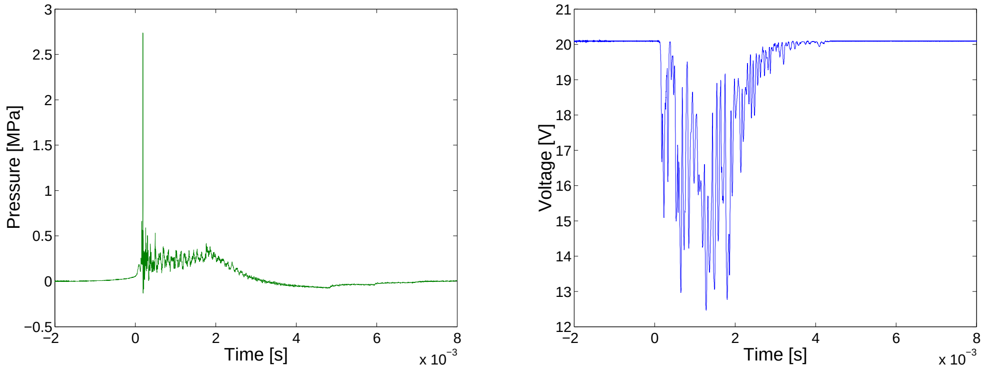


Figure 21: The pressure, and the voltage over the spark plug, at location G5.

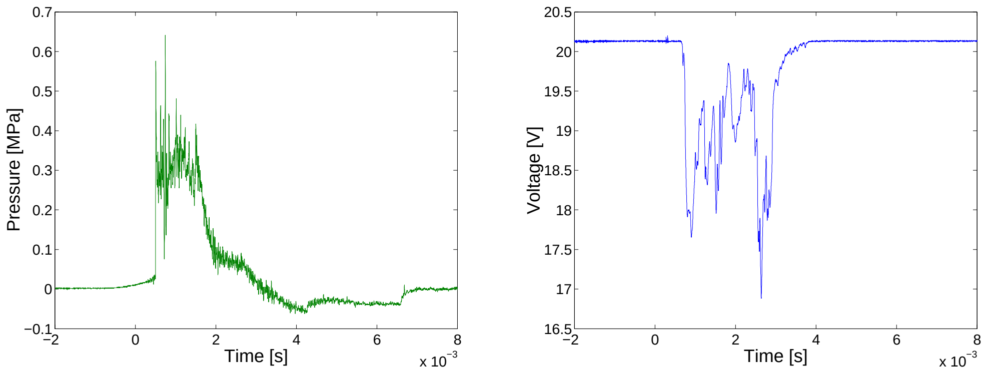


Figure 22: The pressure, and the voltage over the spark plug, at location G9.

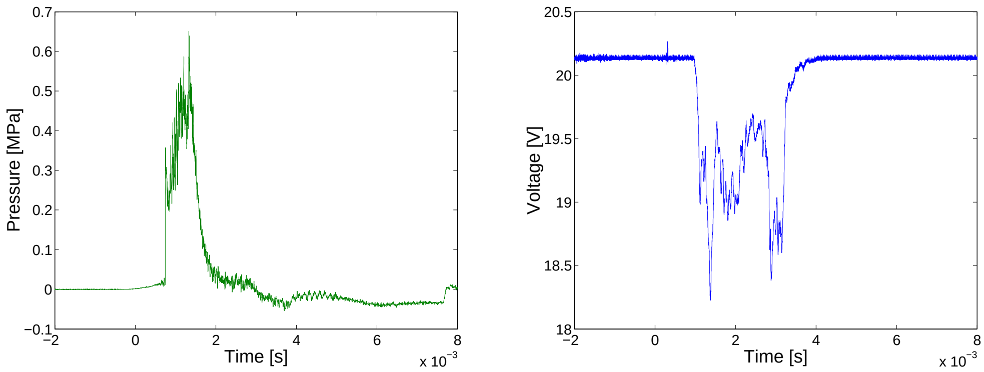


Figure 23: The pressure, and the voltage over the spark plug, at location G11.

Whether or not it is a detonation can be decided by both the pressure level and by the speed of the combustion complex. The speed of the combustion wave is calculated by taking the distance between the given locations, which are known, and divide it by the time. The time can be read both from the figures over the pressure and the ones over the voltage. The calculated speed, when the time is taken from the pressure figures, becomes about 440 m/s between G3 and G5, 920 m/s between G5 and G9, and 1000 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 830 m/s, 920 m/s and 1000 m/s.

To see if the rise occur at the same time for both the pressure sensor and the spark plug the signals, at the same location, are shown in the same figure (where the voltage is flipped). This is shown for the four different locations (G3, G5, G9 and G11) in Figure 24. In this figure the pressure always rises some time before the voltage drops. This depends on the fact that when there is no successful transition to detonation there is a separation between the shock wave and the combustion complex. On the other hand, when there is a successful transition, the shock wave and the combustion complex travel together.

Before the first measuring point, G3, the shock wave has run away from the combustion complex. After that, up to measure point G9, the combustion wave travels faster and gets closer to the shock wave but between G9 and G11 the shock wave runs away again. Hence, there is no successful transition to detonation.

At lower speeds it is very difficult to determine an exact value for the speed. Especially for the pressure signal it is difficult to decide when the shock wave reaches the pressure sensor. Is it at the very beginning of the pressure rise or at some special value of the pressure? I decided to use the time at which the signals first begin to rise, or drop, in my calculations.

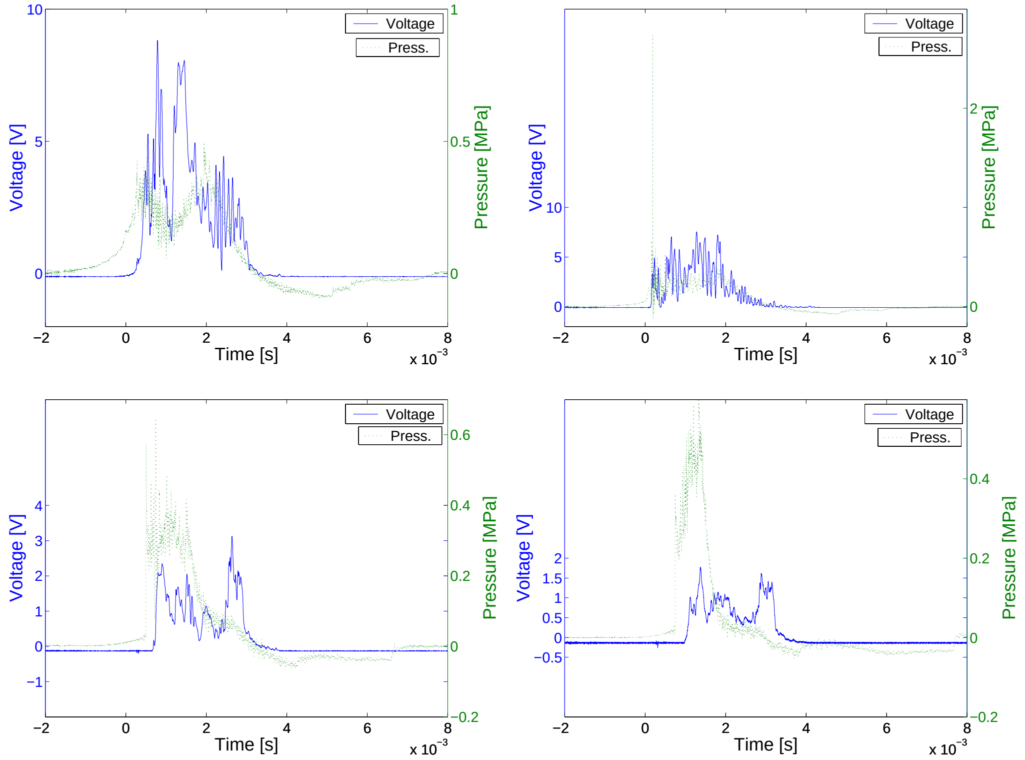


Figure 24: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

8% of oxygen gas

With a mixture containing 8% of oxygen gas there is a deflagration to detonation transition (DDT). In Figure 25 - Figure 28 the signal over the spark plug is compared to the pressure signal, at the given locations.

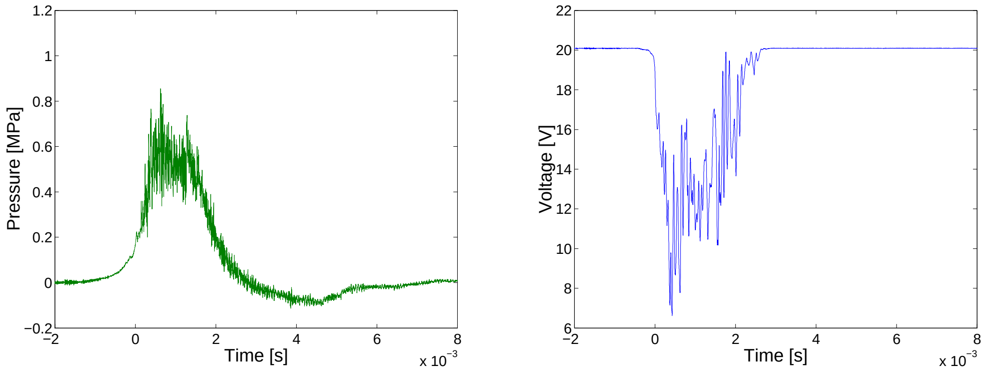


Figure 25: The pressure, and the voltage over the spark plug, at location G3.

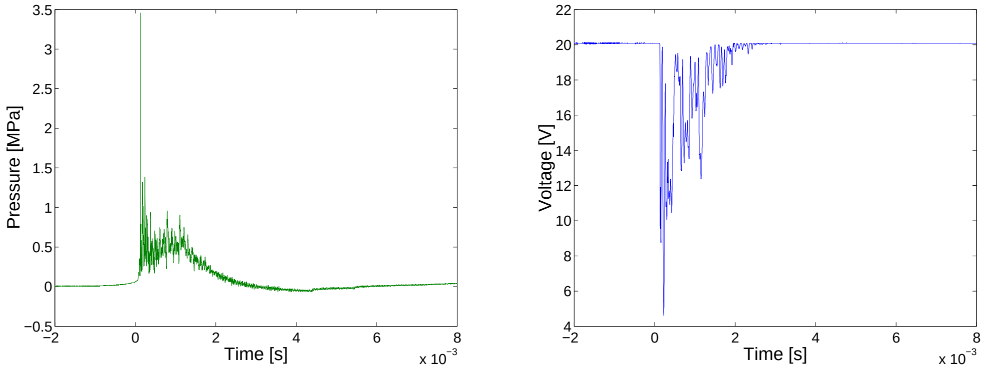


Figure 26: The pressure and the voltage over the spark plug at location G5.

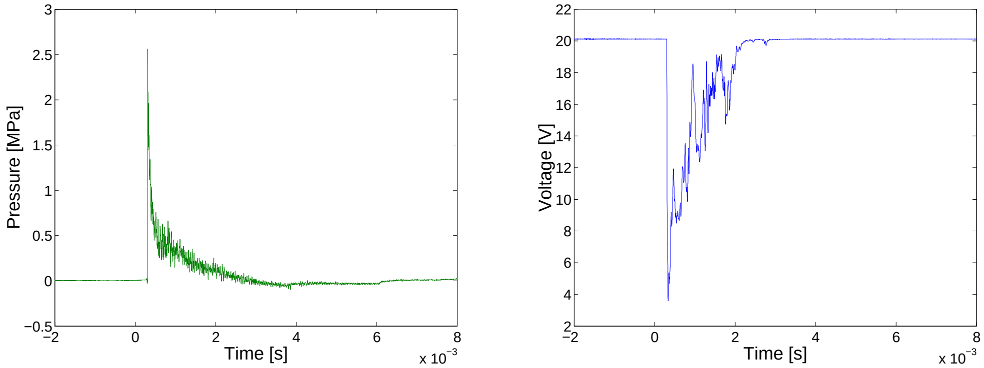


Figure 27: The pressure, and the voltage over the spark plug, at location G9.

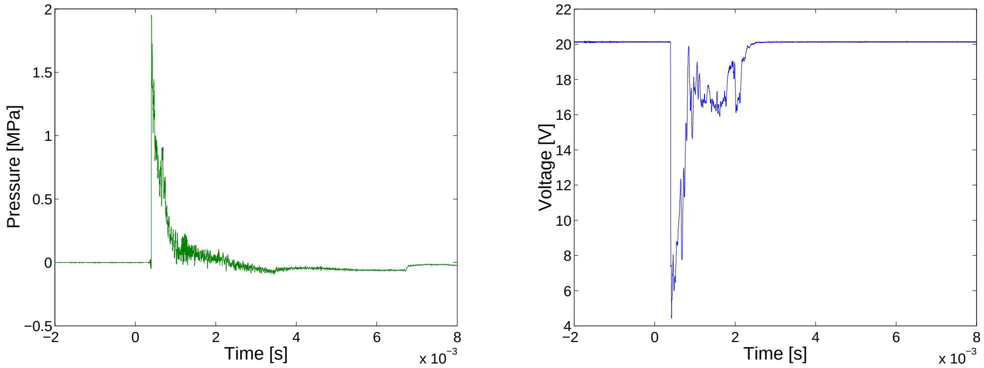


Figure 28: The pressure, and the voltage over the spark plug, at location G11.

The calculated speeds in this case, when the time is taken from the pressure figures, become about 290 m/s between G3 and G5, 450 m/s between G5 and G9, and 1800 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 400 m/s, 1500 m/s and 1800 m/s.

In Figure 29 the signals from the same location are shown in the same figure to see the difference in time. The two first figures show, as the ones for 4% of oxygen gas, that the pressure rises a little bit before the voltage drops. As the speeds gets closer to detonation speed the differences decrease. This again gives that before G3, the shock wave has run away from the combustion complex and after that the combustion wave travels faster and gets closer to the shock wave. In this case it even catches up with the shock wave at location G11. So between G9 and G11 there is a transition to detonation.

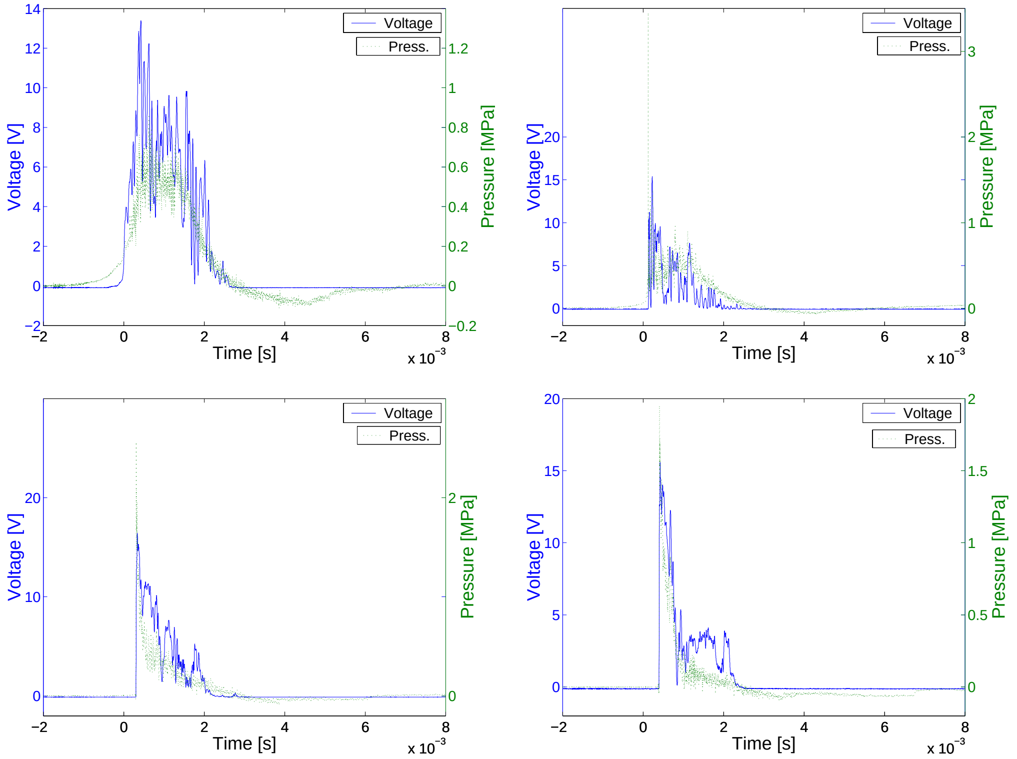


Figure 29: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

14% of oxygen gas

With a mixture containing 14% of oxygen gas there is also a deflagration to detonation transition (DDT). In Figure 30 - Figure 33 the signal over the spark plug is compared to the pressure signal, at the different locations.

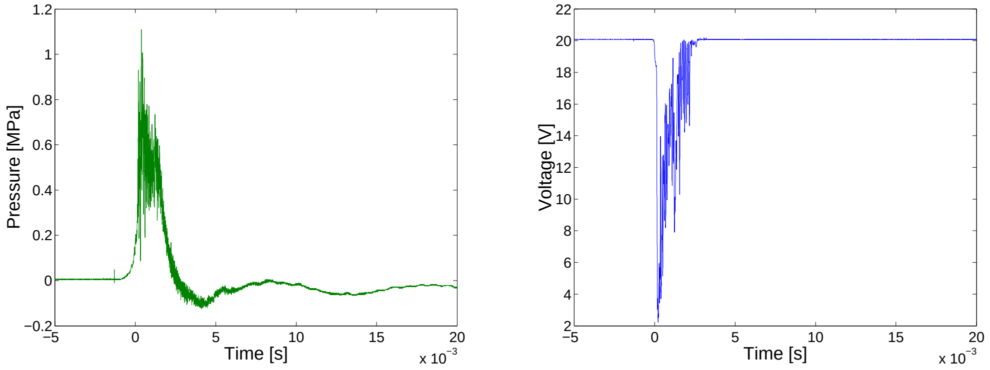


Figure 30: The pressure, and the voltage over the spark plug, at location G3.

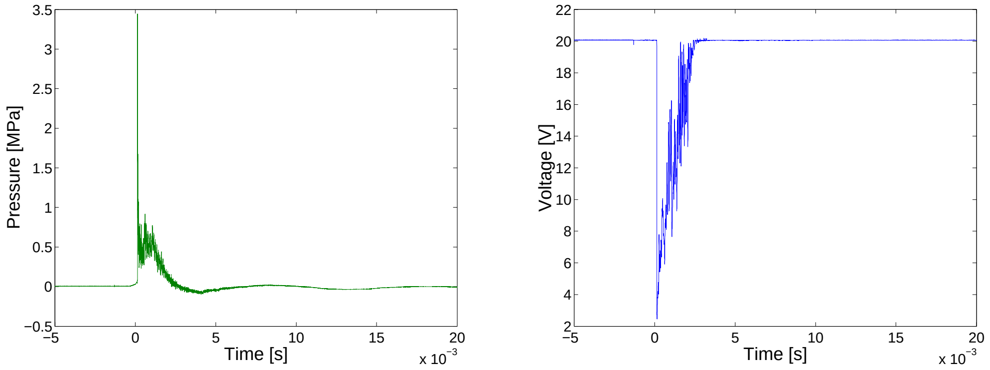


Figure 31: The pressure, and the voltage over the spark plug, at location G5.

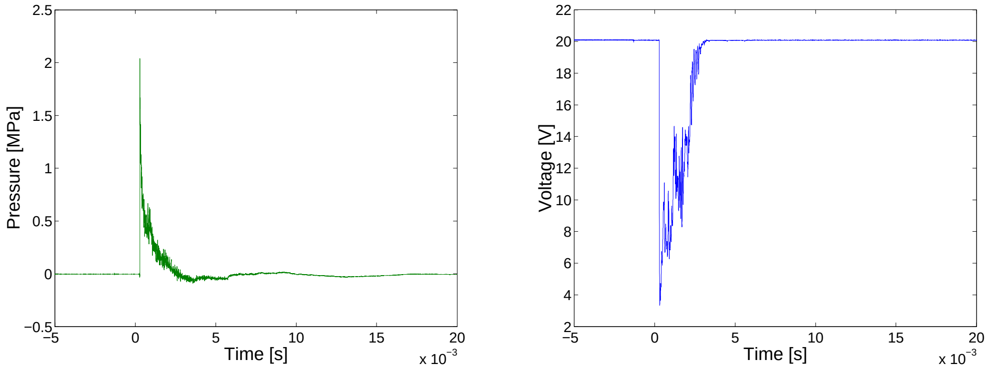


Figure 32: The pressure, and the voltage over the spark plug, at location G9.

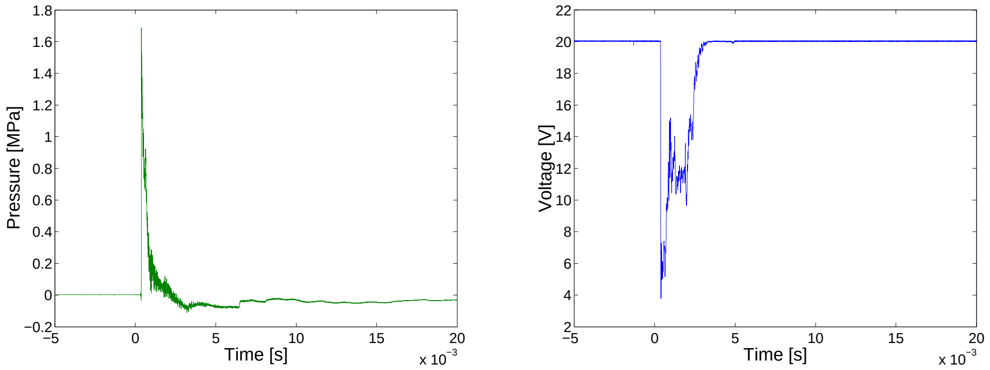


Figure 33: The pressure, and the voltage over the spark plug, at location G11.

Now the calculated speeds, when the time is taken from the pressure figures, becomes about 420 m/s between G3 and G5, 1200 m/s between G5 and G9, and 1800 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 950 m/s, 1800 m/s and 1800 m/s.

Figure 34 shows the signals at the same location in the same figure. In the two first figures the pressure rises a little bit before the voltage drops but in the second two they rise at the same time. In this case the shock wave just separates a little bit before G3 and already at location G9 the combustion wave catches up with the shock wave. The transition to detonation therefore occurs somewhere between G5 and G9.

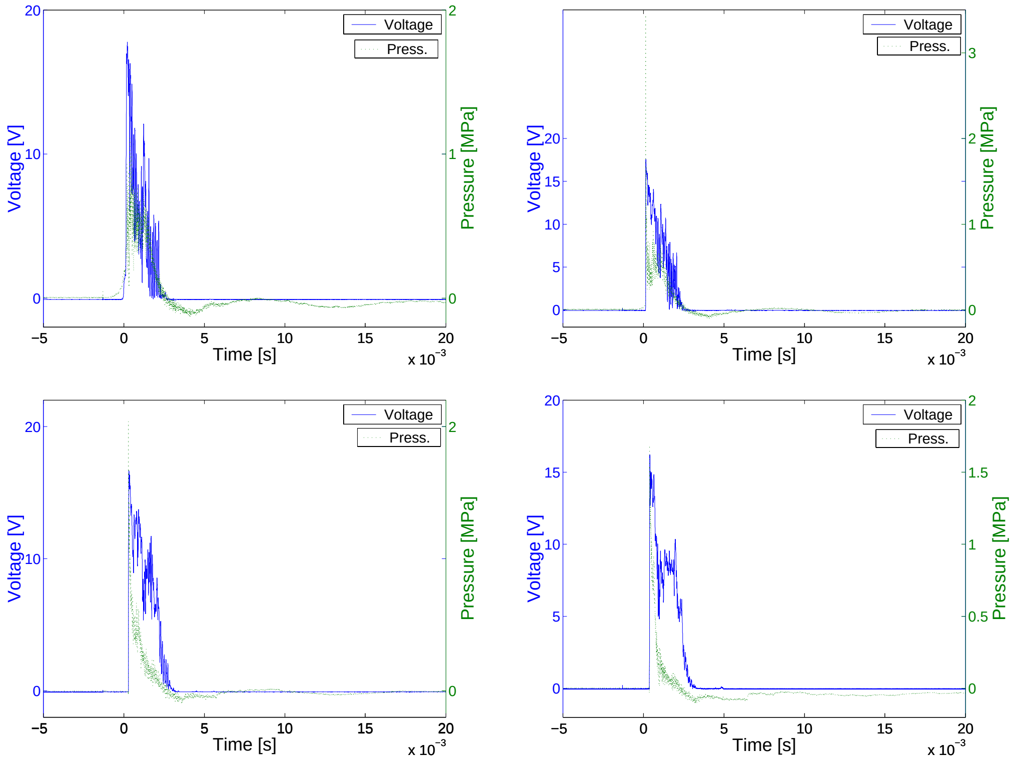


Figure 34: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

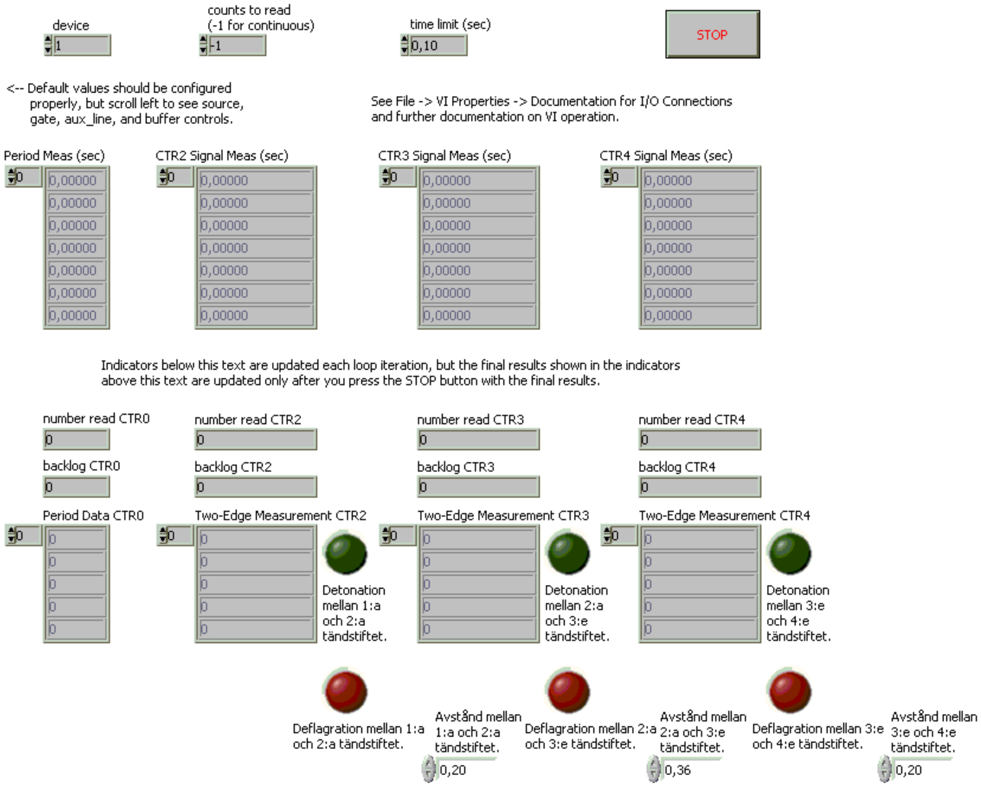
Speed of the combustion wave

		Speed between G3 and G5 (m/s)	Speed between G5 and G9 (m/s)	Speed between G9 and G11 (m/s)
4% of oxygen gas	*looking at the pressure*	440	920	1000
	looking at the voltage	830	920	1200
8% of oxygen gas	*looking at the pressure*	290	450	1800
	looking at the voltage	400	1500	1800
14% of oxygen gas	*looking at the pressure*	420	1200	1800
	looking at the voltage	950	1800	1800

Table 4: The speed of the combustion wave between the different locations.

LabVIEW interface

When the program is running there are two buttons, a red one for speeds below detonation speed and a green one for detonation speeds, which lights up depending on the speed of the combustion wave. An example of how it may look is shown in Figure 35.



device: 1

counts to read (-1 for continuous): -1

time limit (sec): 0,10

<-- Default values should be configured properly, but scroll left to see source, gate, aux_line, and buffer controls.

See File -> VI Properties -> Documentation for I/O Connections and further documentation on VI operation.

Indicators below this text are updated each loop iteration, but the final results shown in the indicators above this text are updated only after you press the STOP button with the final results.

Avstånd mellan 1:a och 2:a tändstiftet.: 0,20

Avstånd mellan 2:a och 3:e tändstiftet.: 0,36

Avstånd mellan 3:e och 4:e tändstiftet.: 0,20

Figure 35: The LabVIEW interface.

Conclusions

In this work it has been shown that there is a good correspondence between the appearance of the pressure and the voltage drop. If there is a sharp rise in pressure there is also a sharp drop in voltage. Though for the cases when there is no successful transition to detonation, the pressure rise and the voltage drop do not occur at the same time. The shock wave separates and travels ahead of the zone where the combustion takes place. Consequently, there will be a time difference between the events recorded by the pressure sensors and the spark plugs. However, in the case of a successful transition to detonation the two measuring devices will detect the same event.

In almost all the cases the combustion complex traveled faster than the shock wave. This may seem strange since when there is no successful transition it its the shock wave that travels ahead of the combustion zone. The explanation is that this happens before the first point of measuring so the figures show how the combustion wave catches up with the shock wave.

The results for the speed of the combustion wave are only approximate. It is very difficult to determine when the shock wave and the combustion complex reach the measuring point at lower speeds since the rise is very slow, which makes it almost impossible to determine when it starts.

Conclusively, using spark plugs instead of pressure sensors to verify detonations is an equally good, and always cheaper, alternative. The difference from pressure sensors is that spark plugs record the combustion wave instead of the pressure wave.

References

Tegnér J., *“The Pulse Detonation Engine”*, Swedish Journal of Military Technology, no. 4, 2001

6601/6602 User Manual, www.ni.com

Bosch, *Tändstift – Teknisk Information*, Bosch, 1982

Appendix 1

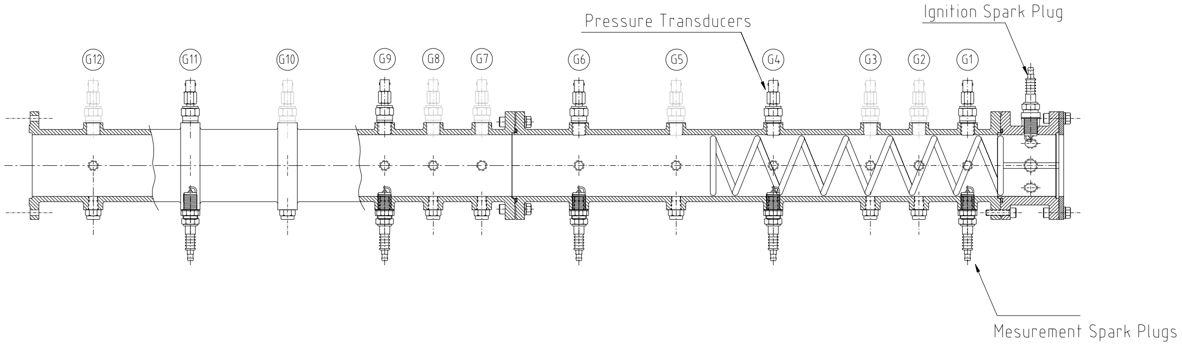


Figure 36: The PDE with pressure sensors, spiral (used to enhance the transition from flame to detonation) and spark plugs.

The Pulse Detonation Engine (PDE) has several attractive features:

- High thermodynamic efficiency, and hence a high specific impulse.
- The principle of the engine is simple, and the engine therefore has the potential of being significantly less complex than a turbojet engine to produce (and hence less expensive).
- Applicable for a wide range of velocities.
- Not limited to circular geometries, and the PDE should therefore be relatively easy to incorporate inside the structure of the aircraft.
- Can be used both in rocket- and in air breathing mode, and it would be possible to design an engine which uses the oxygen from the surrounding air while travelling at lower altitudes and uses oxygen carried on board while reaching higher altitudes.

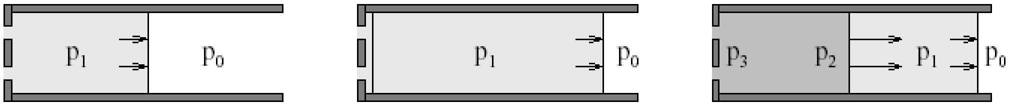
The performance advantages and the expected low cost of the PDE makes it possible to use in many applications which are today powered by other types of engines (e.g., turbojets, ram jets and rockets). Examples of applications are missiles – especially if there is a demand for an extended range – and space vehicles. Furthermore, if the noise of the engine can be reduced the PDE could even be an alternative in manned aircrafts.

One example of a PDE is shown in the figure above. This particular engine operates on hydrogen and air and is capable of reaching frequencies up to 40 Hz. The experimental set-up basically consists of a straight tube (in this case with a length of about one meter) in which hydrogen and air is injected, and ignited by an ordinary spark plug. In this experimental engine the pressure sensors are used to find out whether the engine operates successfully in detonative mode, something which can be seen both by the level of the pressure and the speed of propagation of the wave (a detonation in hydrogen air reaches pressures over 20 bar and propagates at around 2000 m/s). Also shown is a spiral, which since it helps to induce turbulence in the flow field is known to make the transition from the flame to a detonation more rapid.

The detonation can be initiated in two ways, as a direct initiation where the detonation is initiated by a very powerful ignitor more or less immediately or as a Deflagration to

Detonation Transition (DDT) where an ordinary flame (i.e., a deflagration) accelerates to a detonation under a much longer time span. Typically hundreds of joules are required to obtain a direct initiation of a detonation in a mixture of the most sensitive hydrocarbons and air which prevents this method to be used in a PDE (if oxygen is used instead of air, these levels are drastically reduced). On the other hand, to ignite an ordinary flame requires reasonable amounts of energy, but the DDT requires lengths of the order of several meters to be completed, making even this method impractical to use in a PDE.

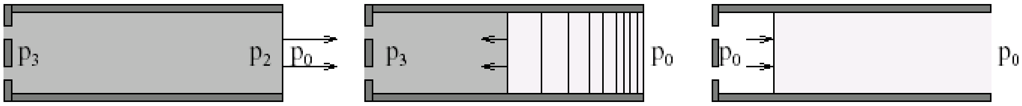
A common method to circumvent these difficulties is to use a pre-detonator – a smaller tube or a fraction of the main chamber filled with a highly detonable mixture (typically the fuel and oxygen instead of air) – in which the detonation can be easily initiated. The detonation from the pre-detonator is then supposed to transmit to the main chamber and initiate the detonation there. The extra component carried on board (e.g., oxygen) for use in the pre-detonator will lower the specific impulse of the engine, and it is important to minimize the amount of this extra component.



1. The engine is filled with fuel–air mixture.

2. Initiation of the detonation.

3. The detonation moves through the engine. The pressure p_3 acts on the front plate and generates thrust.



4. The detonation leaves the engine.

5. Rarefaction waves move in from the exit and gradually lower the pressure at the front plate.

6. Exhaust of the combustion products.

Figure 37: Principle of the engine.

As the name implies the engine operates in pulsating mode, and each pulse can be broken down to a series of events. The performance of the engine is among other things limited by the time each of these events can be completed in, and the thrust can be shown to be proportional to the frequency and the volume of the engine. The events in one cycle are shown schematically in the figure above where p_0 is the ambient pressure, p_1 represents the pressure of the fuel and air mixture, p_2 is the peak pressure of the detonation and p_3 is the plateau pressure acting on the front plate. Briefly the events are the following:

1. The injection of fuel and air (and/or possibly oxygen) into the combustion chamber. For high velocities the air has to be supplied by an air intake. For lower velocities, Ma = 0 – 0.9, a fraction of the fresh air can be supplied by a self-aspirating process, i.e., the over expansion in the engine leads to a reverse flow from the end of the engine.
2. The detonation is initiated in the chamber, either at the closed end or at the open end (in the figure the detonation is initiated at the closed end). Under the assumption that the detonation is initiated directly, closed or open end initiation are equally efficient.
3. The actual combustion, when the detonation propagates through the combustor. It is during this event that the major part of the thrust is produced due to the over pressure at the thrust wall, p_3. The pressure p_3 is substantially lower than the peak pressure of the detonation, p_2.

4. The combustion of one cycle is terminated, but p_3 is still acting on the front plate, generating thrust.
5. Rarefaction waves (a pressure wave which lowers pressure and density of the gas) move in from the exit, and starting with the arrival of the first one the pressure at the front plate is gradually decreased.
6. In the final event of the cycle the hot combustion gases are exhausted from the detonation chamber.

As stated above the thrust of the engine is proportional to the frequency of the engine, and in order to reach acceptable performance levels the indicated cycle has to be repeated at least 50 times per second.

Appendix 2

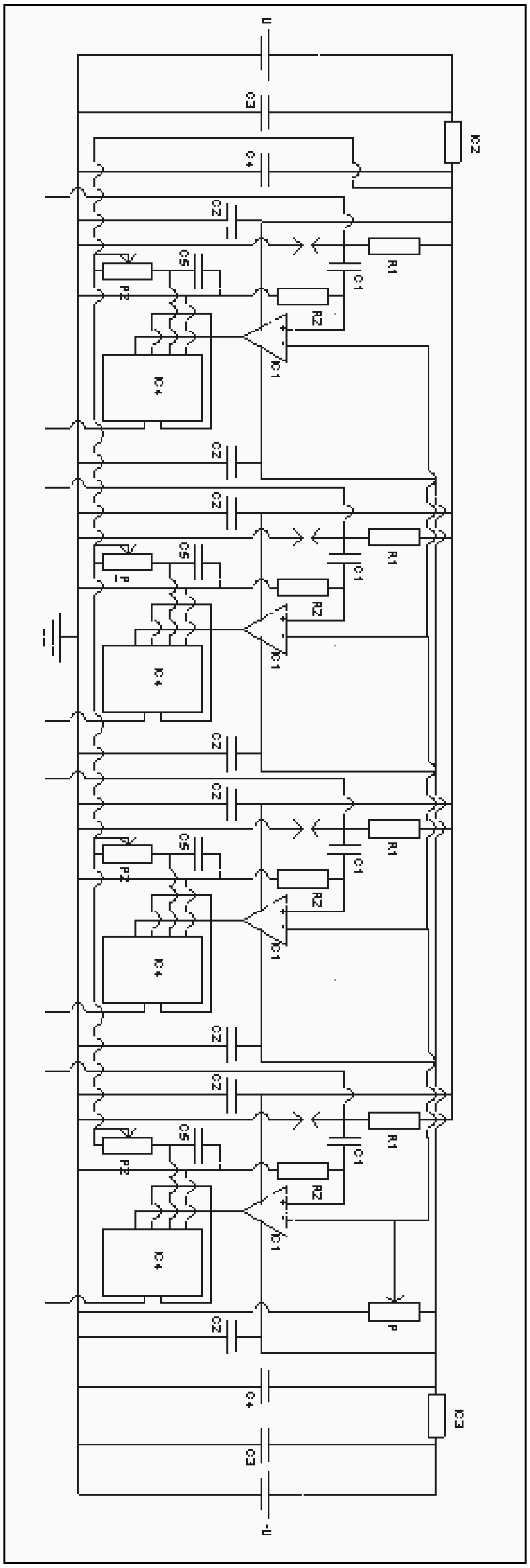


Figure 38: The entire electric circuit.

Appendix 3

Signal comparison (Engine with spiral)

6% of oxygen gas

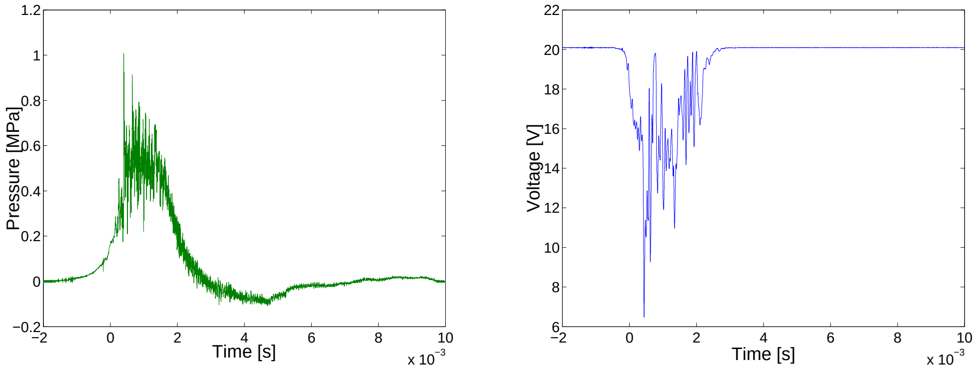


Figure 39: The pressure, and the voltage over the spark plug, at location G3.

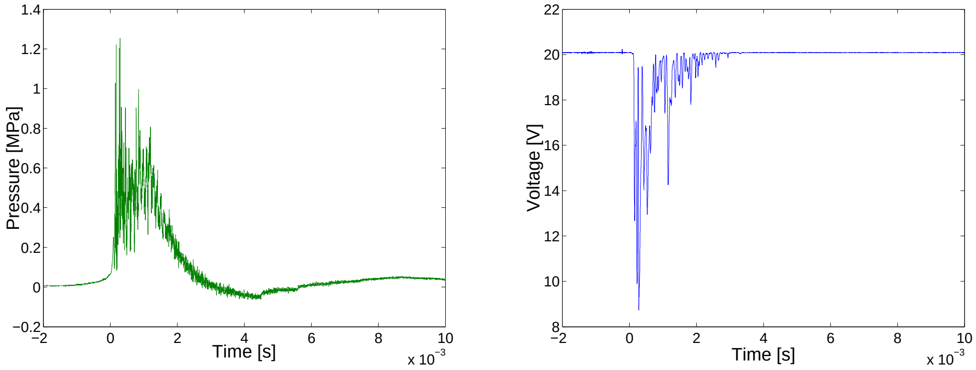


Figure 40: The pressure, and the voltage over the spark plug, at location G5.

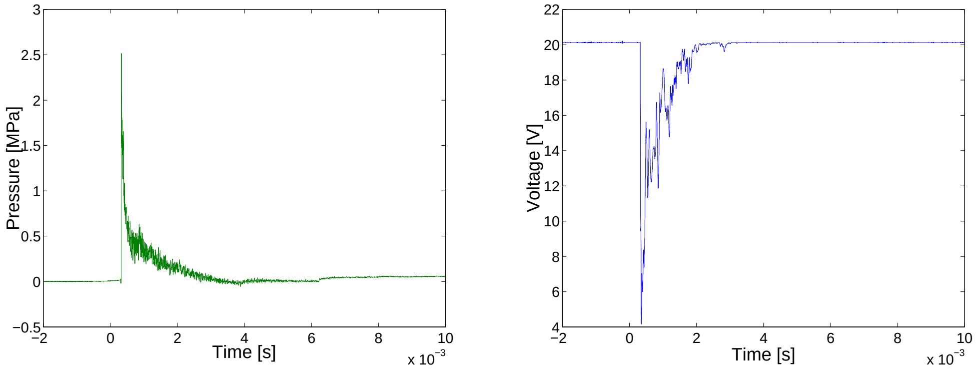


Figure 41: The pressure, and the voltage over the spark plug, at location G9.

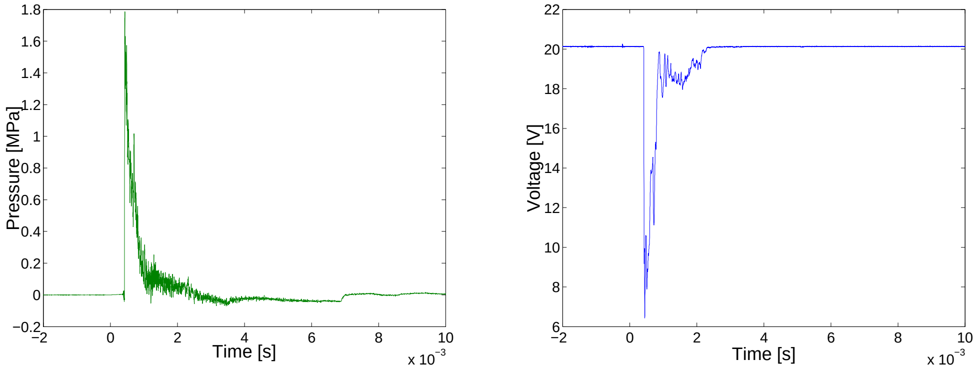


Figure 42: The pressure, and the voltage over the spark plug, at location G11.

The calculated speed, when the time is taken from the pressure figures, becomes about 290 m/s between G3 and G5, 520 m/s between G5 and G9, and 1000 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 500 m/s, 1100 m/s and 1800 m/s.

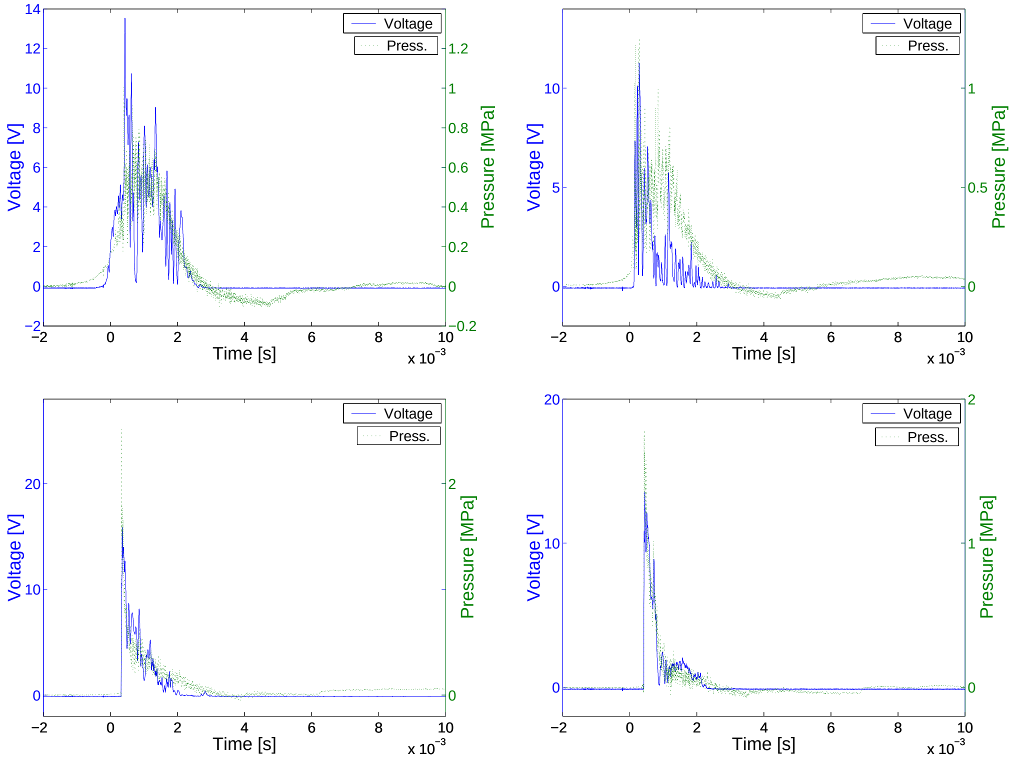


Figure 43: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

Signal comparison (Engine without spiral)

8% of oxygen gas

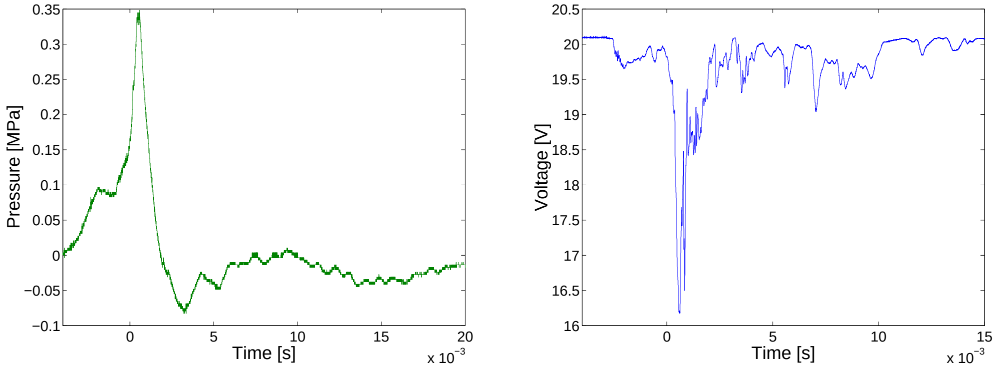


Figure 44: The pressure, and the voltage over the spark plug, at location G3.

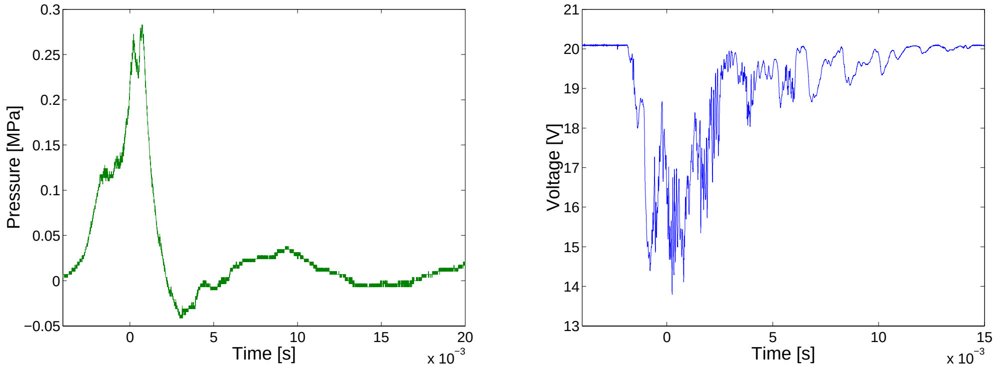


Figure 45: The pressure, and the voltage over the spark plug, at location G5.

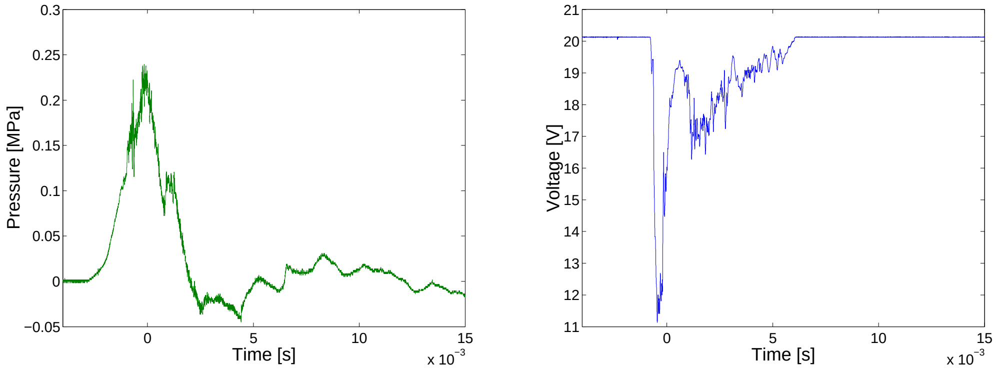


Figure 46: The pressure, and the voltage over the spark plug, at location G9.

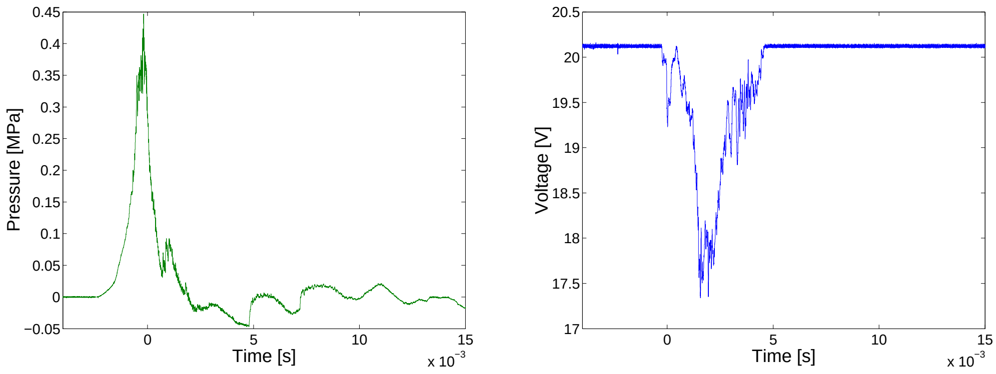


Figure 47: The pressure, and the voltage over the spark plug, at location G11.

The calculated speed, when the time is taken from the pressure figures, becomes about 200 m/s between G3 and G5, 240 m/s between G5 and G9, and 560 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 220 m/s, 280 m/s and 490 m/s.

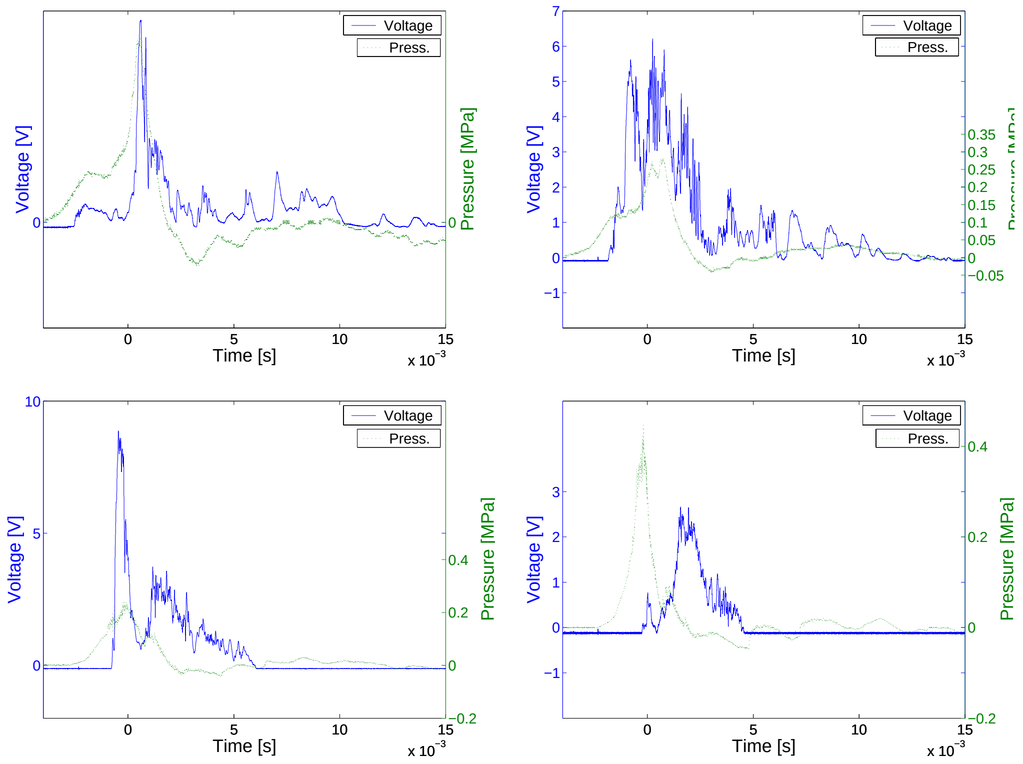


Figure 48: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

14% of oxygen gas

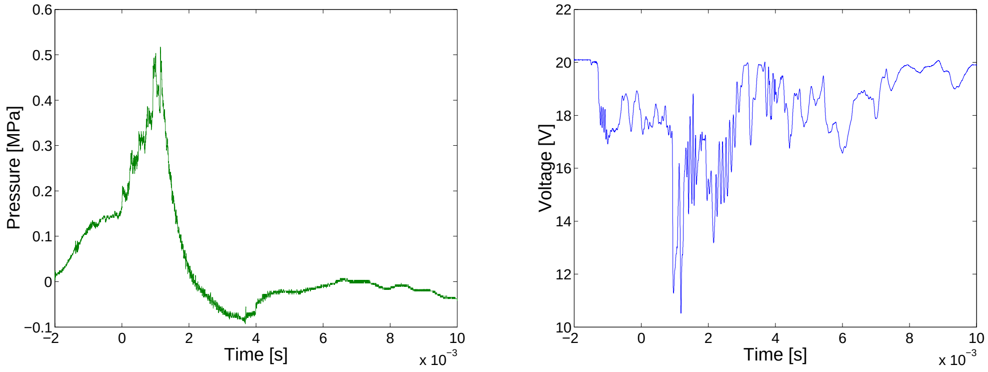


Figure 49: The pressure, and the voltage over the spark plug, at location G3.

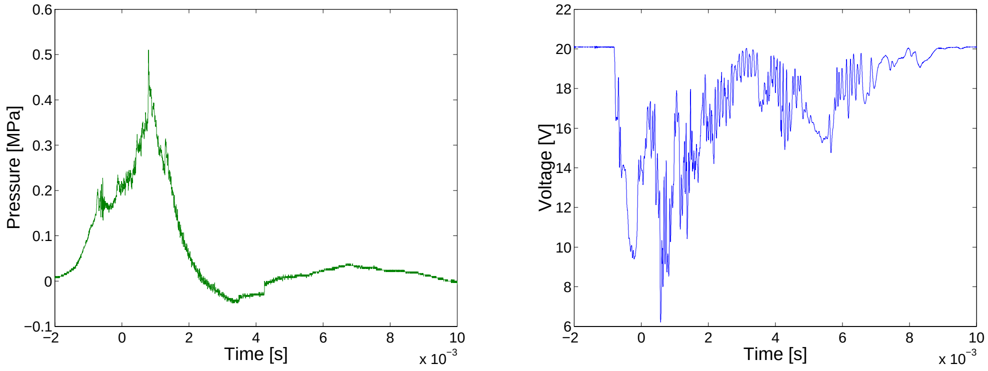


Figure 50: The pressure, and the voltage over the spark plug, at location G5.

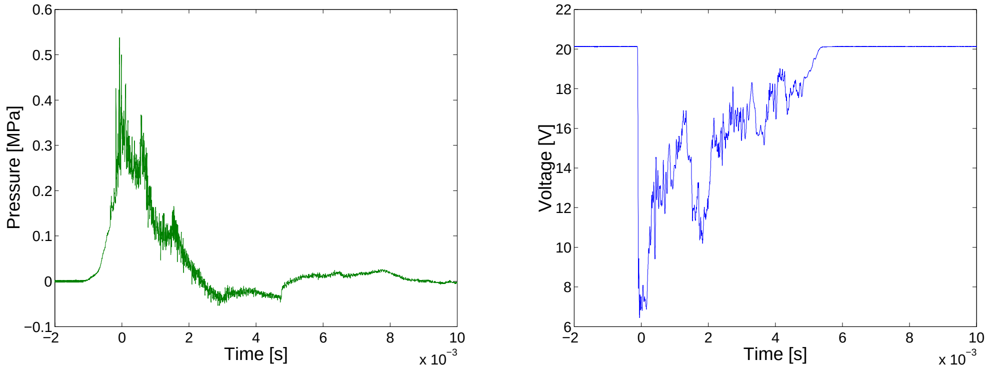


Figure 51: The pressure, and the voltage over the spark plug, at location G9.

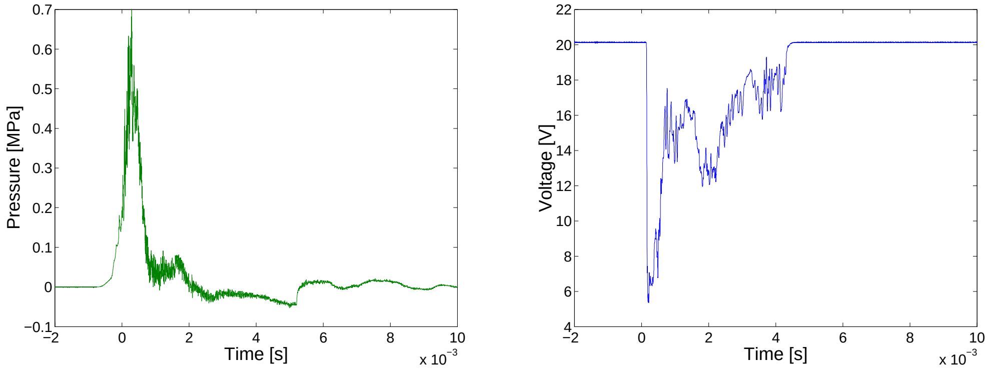


Figure 52: The pressure, and the voltage over the spark plug, at location G11.

The calculated speed, when the time is taken from the pressure figures, becomes about 310 m/s between G3 and G5, 540 m/s between G5 and G9, and 1000 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 390 m/s, 920 m/s and 1800 m/s.

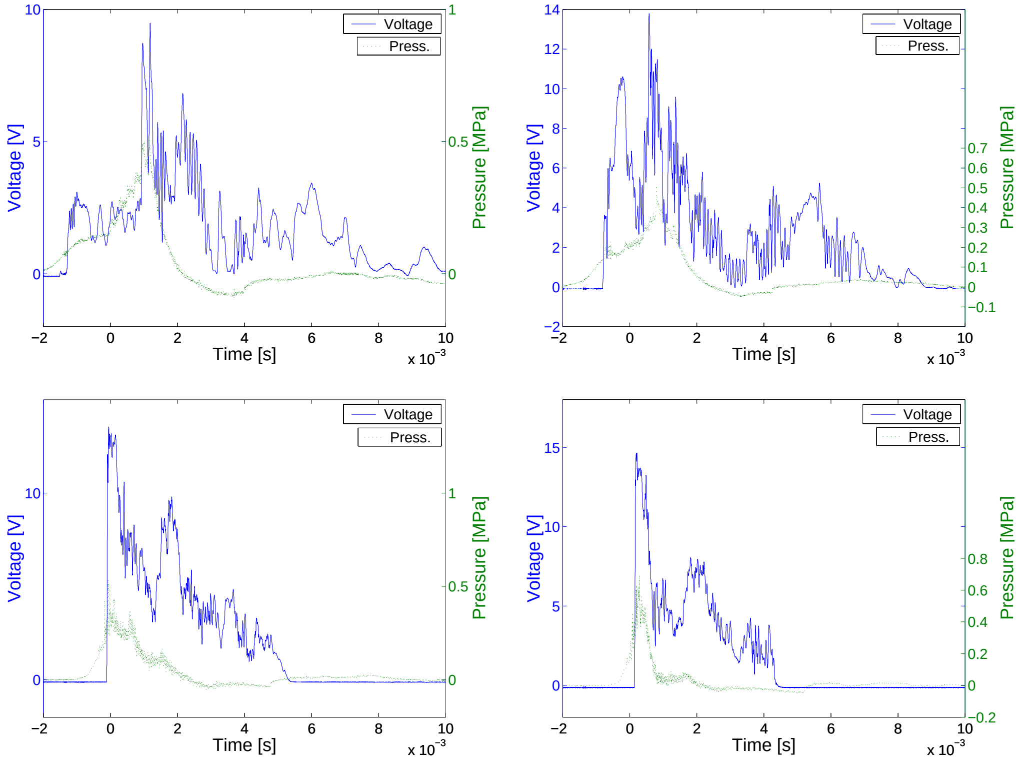


Figure 53: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

20% of oxygen gas

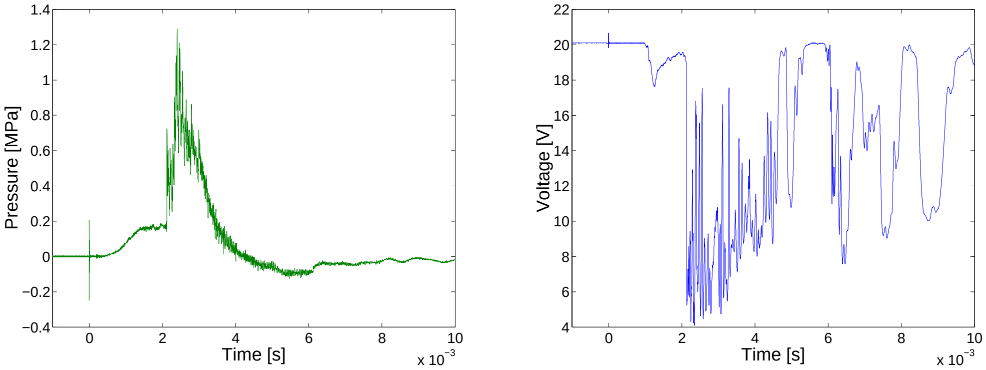


Figure 54: The pressure, and the voltage over the spark plug, at location G3.

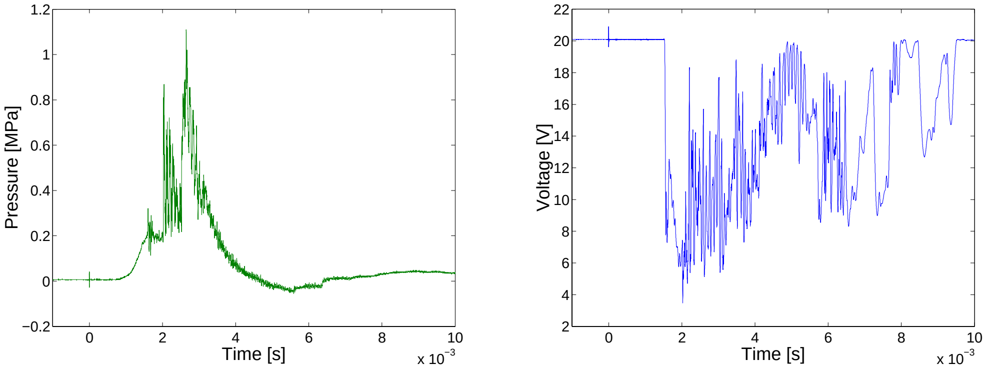


Figure 55: The pressure, and the voltage over the spark plug, at location G5.

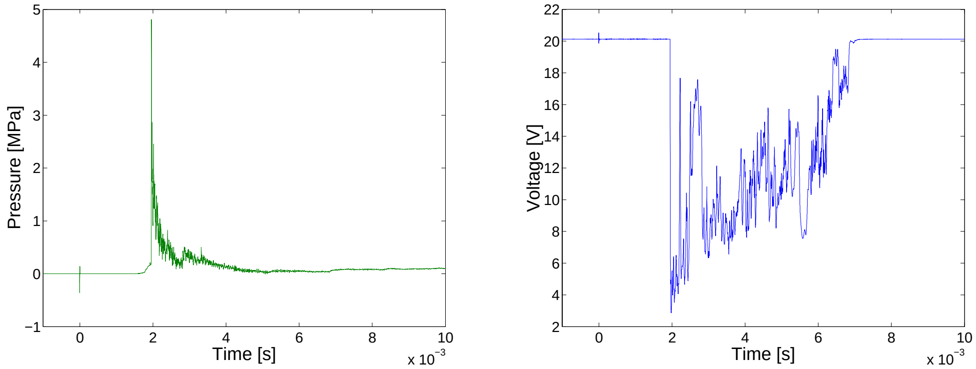


Figure 56: The pressure, and the voltage over the spark plug, at location G9.

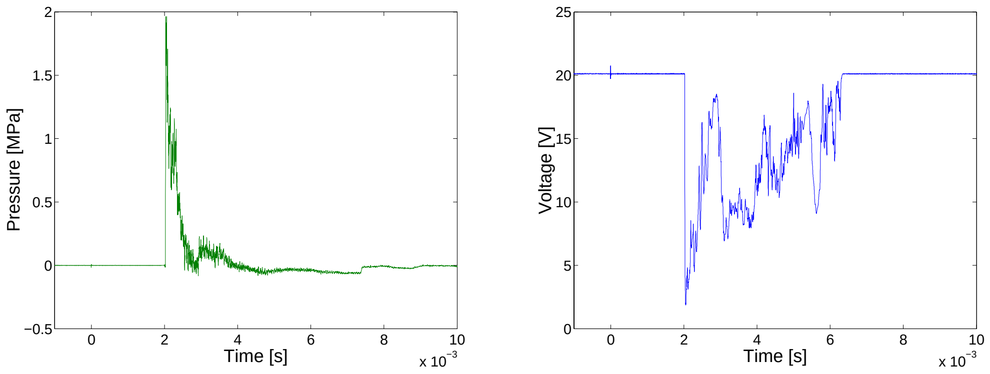


Figure 57: The pressure, and the voltage over the spark plug, at location G11.

The calculated speed, when the time is taken from the pressure figures, becomes about 500 m/s between G3 and G5, 1000 m/s between G5 and G9, and 1800 m/s between G9 and G11. The corresponding speeds when the time is taken from the voltage figures are about 500 m/s, 1200 m/s and 1800 m/s.

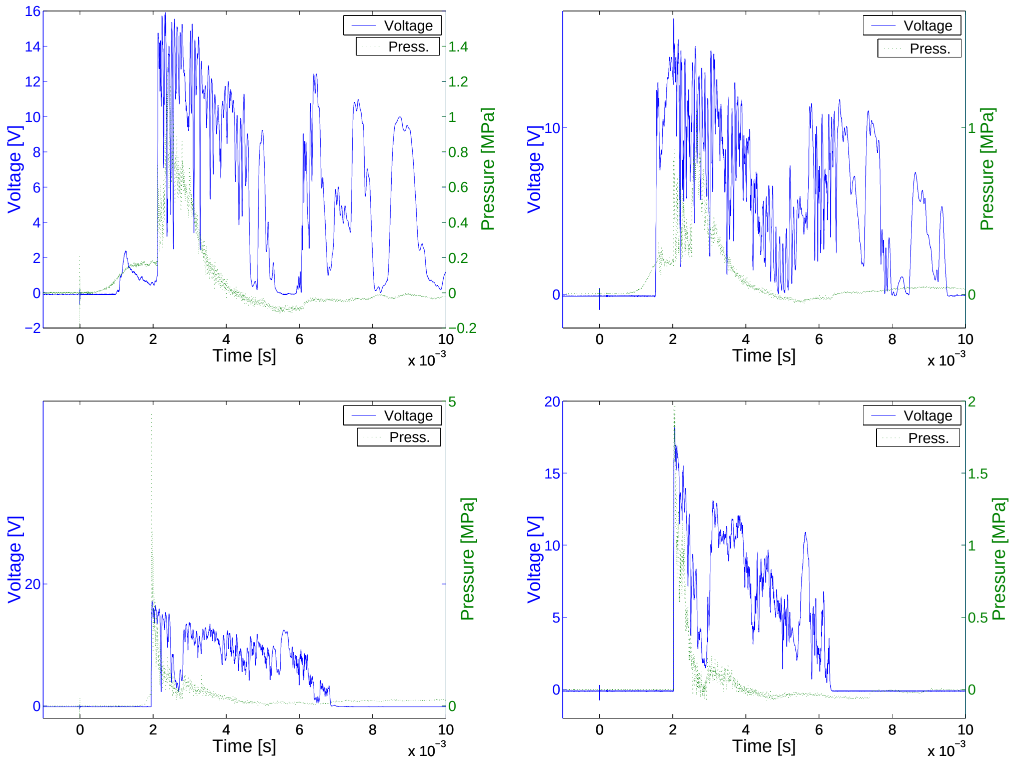


Figure 58: The pressure, and the voltage over the spark plug, shown together in the same figure, at the given locations.

Speed of the combustion wave

		Speed between G3 and G5 (m/s)	**Speed between G5 and G9 (m/s)**	**Speed between G9 and G11 (m/s)**
6% of oxygen gas	*looking at the pressure*	290	520	1000
	looking at the voltage	500	1100	1800
8% of oxygen gas	*looking at the pressure*	200	240	560
	looking at the voltage	220	280	490
14% of oxygen gas	*looking at the pressure*	310	540	1000
	looking at the voltage	390	920	1800
20% of oxygen gas	*looking at the pressure*	500	1000	1800
	looking at the voltage	500	1200	1800

Table 5: The speed between the different locations.