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Influence of sizing on rotating detonation combustor performance

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14. ABSTRACT
The main goal of the project was to build and start-up a rocket engine with detonation combustion chamber, as well as to create a test stand for testing the engine and detonation.
Recently, intensive research on the applications of the continuously rotating detonation (CRD) in the propulsion system have been undertaken. It has been demonstrated that it is possible to improve the engine efficiency by 3-7%. The simplest engine utilizing a continuously rotating detonation is the rocket engine. In Rotating Detonation Rocket Engines (RDRE), the fuel and the oxidizer are injected into a cylindrical detonation chamber, and the rotating detonation continuously propagates as long as the fuel and oxidizer are supplied to the chamber. As a first step the tests were carried out in the shock tube (detonation shock tube) in order to develop the detonation shock measurement methodology and also as a way for protection of piezoelectric pressure sensors (protection against the effects of high temperatures). The research of detonation engine on this stage of project was used to check the influence of combustion chamber geometry (primarily the height of combustion chamber) on engine performance and detonation parameters. The comparative experiments of rocket engine with detonation combustion chamber and deflagration combustion chamber were conducted. A key result was that an introduced channel eccentricity resulted in 100% receptivity of direction of wave propagations. As well, the number of waves depends directly on critical length of detonation cell (lc) and rate of mixture supply.

15. SUBJECT TERMS
combustion, thermodynamic, propulsion, detonation, rocket

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Influence of Sizing on Rotation Detonation Combustor Performance

"Research on application of continuous rotating detonation to rocket engine"

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Abstract:

The possibility of improving the thermodynamic cycle by the application of detonative combustion instead of deflagration was first proposed by Zeldovich. The first stationary spinning detonation was successfully achieved by Voitsekhovskii et al. and the first attempts to develop engine based on the rotating detonation was initiated by Nicholls J.A., et al. Since that time, many different possible ways of implementation of detonative combustion to the propulsion systems were studied [1-2]. But only recently more intensive research on the applications of the continuously rotating detonation (CRD) in the propulsion system was undertaken. It has demonstrated that it is possible to improve the engine efficiency by 3-7%. The simplest engine utilizing a continuously rotating detonation is the rocket engine. In Rotating Detonation Rocket Engines (RDRE), the fuel and the oxidizer are injected into a cylindrical detonation chamber, and the rotating detonation continuously propagates as long as the fuel and oxidizer are supplied to the chamber. In this paper, the research on application of the CRD to rocket engine is presented.

Introduction:

The main goal of the project was to build and start-up the rocket engine with detonation combustion chamber, as well as test stand to testing the engine and detonation.
As a first step the tests were carried out in the shock tube (detonation shock tube) in order to develop the detonation shock measurement methodology and also ways of protection piezoelectric pressure sensors (protection against the effects of high temperatures).
The research of detonation engine on this stage of project was to check the influence of combustion chamber geometry (primarily the height of combustion chamber) on engine performance and detonation parameters. The comparative experiments of rocket engine with detonation combustion chamber and deflagration combustion chamber were conducted.

Mixtures used in experiments

In experiments two mixtures were used- Hydrogen- air and Methane-Oxygen. Available detonation cell widths for hydrogen-air and methane-oxygen mixtures which were chosen for current research, are given in figures below. Presented graphs contain results of various experimental studies, and were taken from GALCIT Explosion dynamic Laboratory detonation database [3].

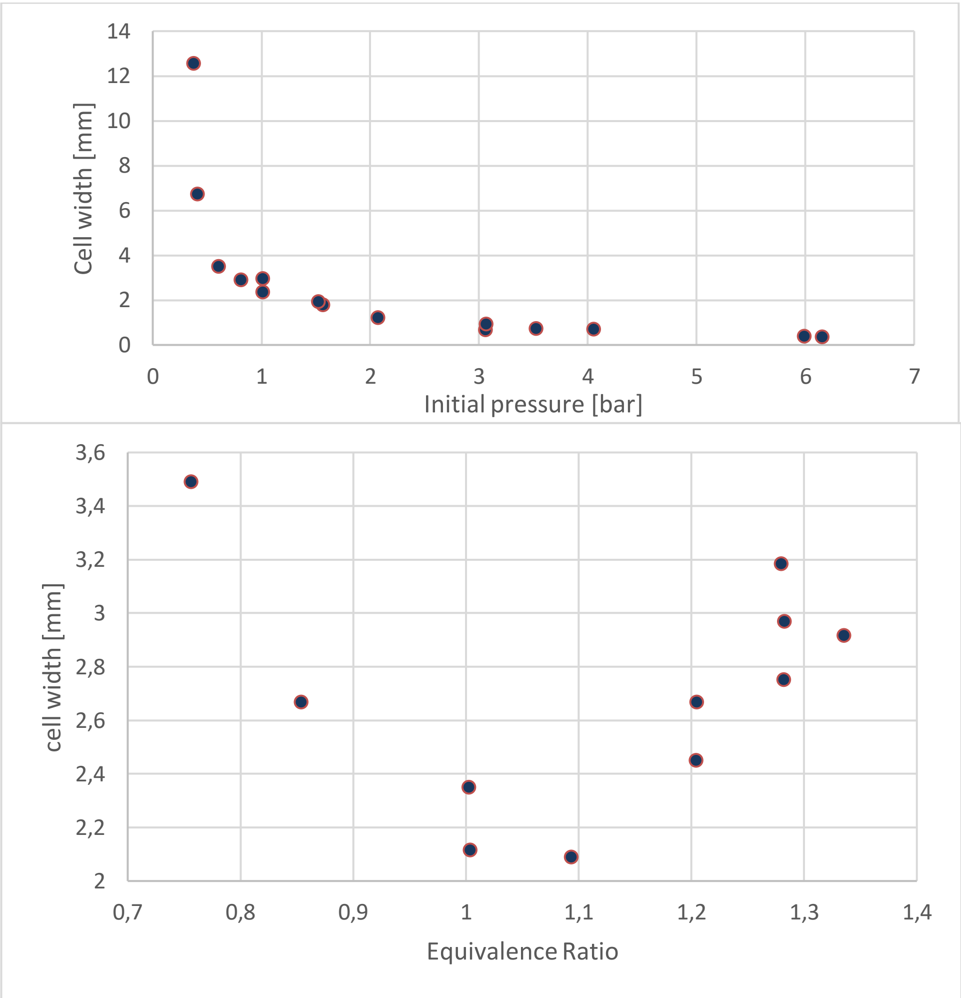
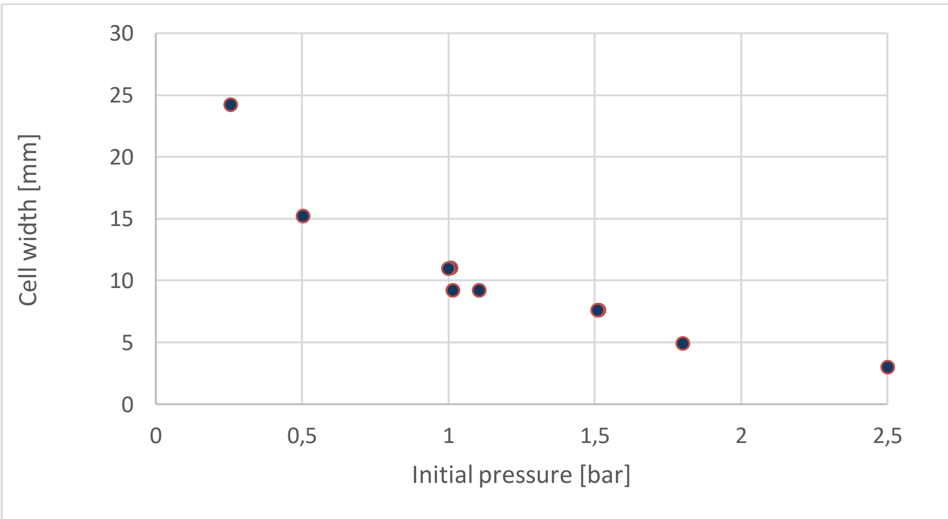


Fig. 1 Cell width for CH_4-O_2 mixture. ER=1 [3]



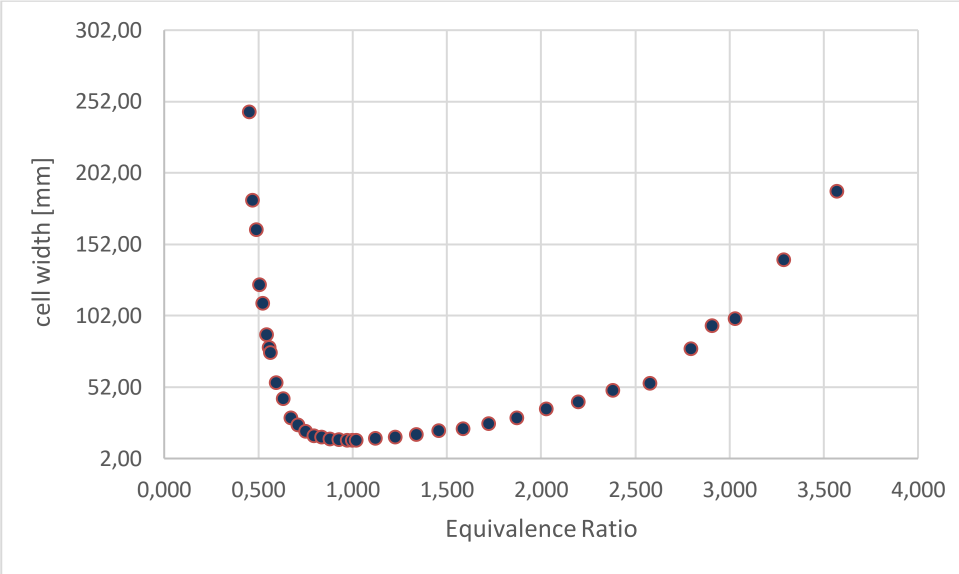


Fig.2. Cell width for H_2-Air mixture. ER=1 [3]

Experiment:

Shock tube

The shock tube research tested the reaction of the pressure sensors to detonation wave. The protective thermal layer of the sensors was also tested, as well as the previously untested sensors.

The shock tube was 1.4m in length, 36mm in diameter. The shock wave was initiated by an ignition spark from a jet engine. The piezoelectric sensors were placed in a manner pictured in Fig.1 The mixtures tested consisted of CH_4 and O_2 (near stoichiometric).The tests were conducted on a closed-end shock tube, as well as on a tube closed off by a thin plastic membrane which burst during each of the trials (imitation of open-end tube).

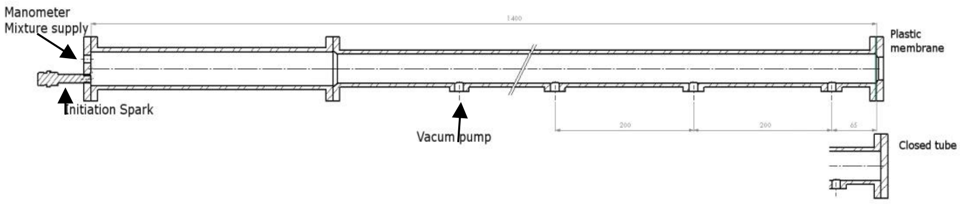


Fig.3. Scheme of the shock tube with piezoelectric sensors.

Construction of the test stand for the rocket engine

Supply system for gaseous oxidizer (Air or Oxygen) and for gaseous fuel (Methane or Hydrogen)

Construction of the supply system allows 6 MPa of storage pressure and has capacity of about 3.5kg of oxidizer and 3.5kg of methane, or 0.45kg of Hydrogen.

Oxidizer supply system	Fuel supply system
-tank 40 l, - Coaxial electrovalve MK/FK 15 to control the oxydizer flow. - 2x pressure sensors - thermocouple K-type in the tank	- Tank 80 l, - Electrovalve 2/2 - G1/2” 24VDC to control the fuel flow. - 2x pressure sensors - thermocouple K-type in the tank

The mass flow for components of the mixture was calculated on the basis of the pressure and temperature records from the supply system. The mass flow rate was estimated as a difference between the mass in the tank before and after the test, according with the formula below (ideal gas formula):

$$\dot{m} = \frac{m_1 - m_2}{t} \qquad (1)$$

$$m_1 = \frac{p_1 V}{RT_1}; m_2 = \frac{p_2 V}{RT_2} \qquad (2)$$

m, p, T – mass of gas, pressure and temperature in storage tanks.

Measurement system

Lp	Measuring parameters	Range	Sensor
	Oxydizer pressure sensors	0 · 60 [bar]	KOBOLD SEN9601
	Fuel pressure sensors	0 · 60[bar]	KOBOLD SEN9601
	Pressure in combustion chamber	0 ·10 [bar]	KOBOLD SEN9601
	Thermocouple in oxydizer tank	-20 · +100 [·C]	Termocouple type „K" + amplierSCC-TC02
	Thermocouple in fuel tank	-20 ·+100 [·C]	Termocouple type „K" + amplierSCC-TC02
	Fast changing pressure in combustion chamber	0 ·10 [bar]	Piezoelectric sensor Kistler 601CAB or Kistler 603 CAB + ampliferKISTLERtyp 5018A1000
	Dynamometer	0 ·500 [N]	KMM-500

Other elements of the measurement system

Central unit - PC
Measurement card NI-PCI-6259 - equipped with a fast analog-digital converter
Measurement card NI USB-6366- for fast acquisition of electrical signals and two-way communication using LabView software.
Terminal SCC-68

Initiation system

Charging of the capacitor with a high voltage power supply (2kV voltage) with an additional manual charging switch (charging signaled by high voltage probe, full charge corresponds to the voltage of about 26mV) and a light bulb indicating discharge, the bulb being lit indicates the discharge of the capacitor. For ignition a spark plug of the K-15 jet engine was used (from the engine start system).

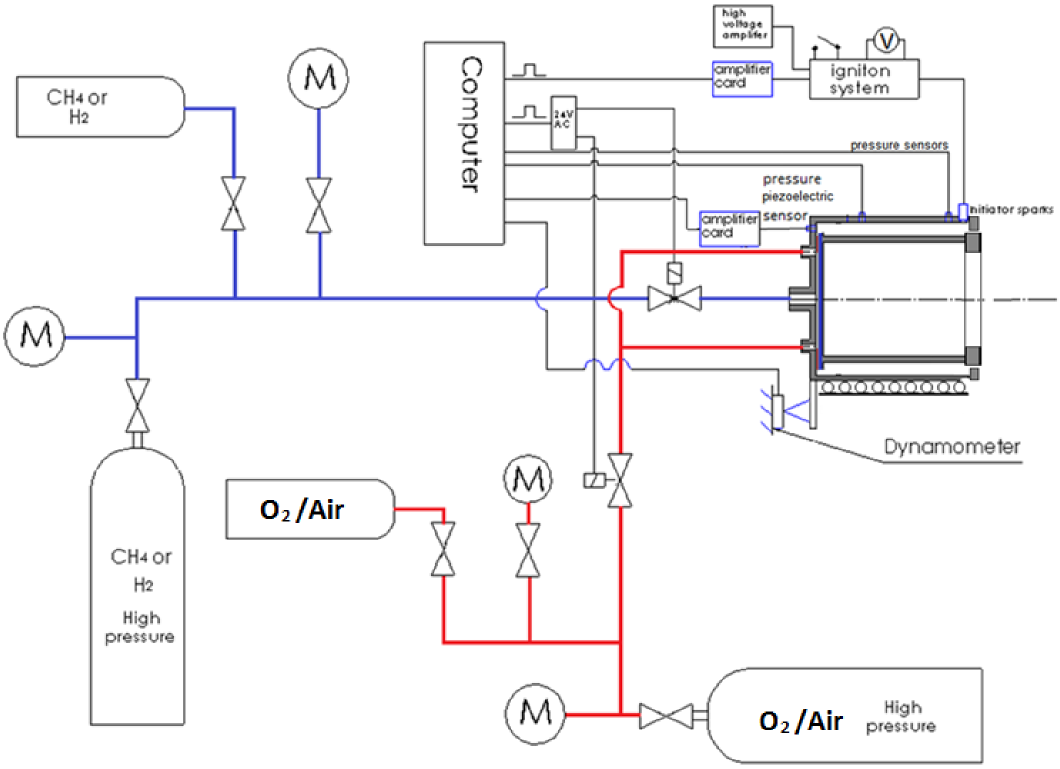


Fig.4. Scheme of the rocket engine test stand

Results, Discussion, Plans for Next Option Period:

Research on detonation wave parameters in the shock tube

The mixtures tested in the shock tube consisted of CH_4 and O_2 (near stoichiometric).
The tests were conducted on a closed-end shock tube, as well as on a tube closed off by a thin plastic membrane which burst during each of the trials (imitation of open-end tube).
Also conducted were tests with no protective sensor layer, in order to check sensor functioning, reactions to the shock wave, and the time of propagation delay.

The test results are presented below.

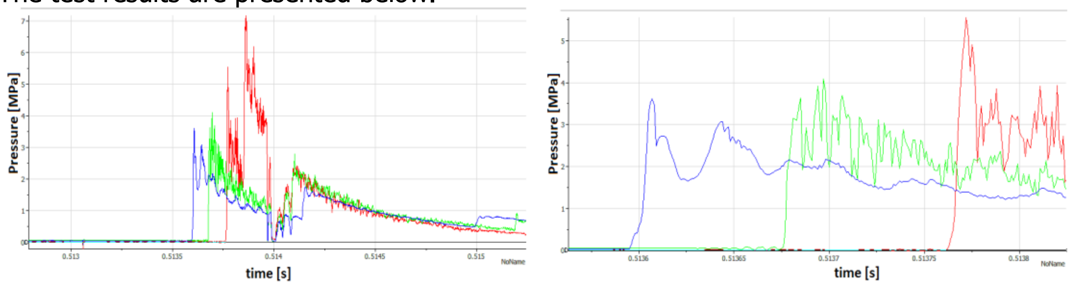


Fig.5. Pressure records for closed shock tube. The speed of the detonation wave-2381 m/s. Pressure sensors with protective layer (the 4-th peak, the highest one – deflected wave).

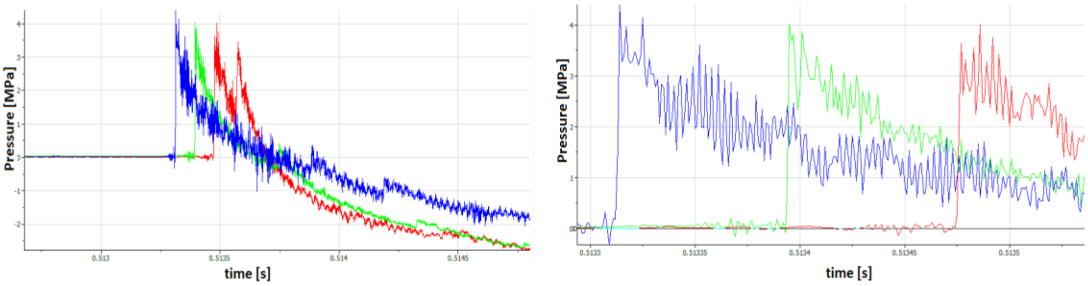


Fig.6. Pressure records for shock tube with plastic membrane. Pressure sensors without protective layer. The speed of the detonation wave- 2436m/s

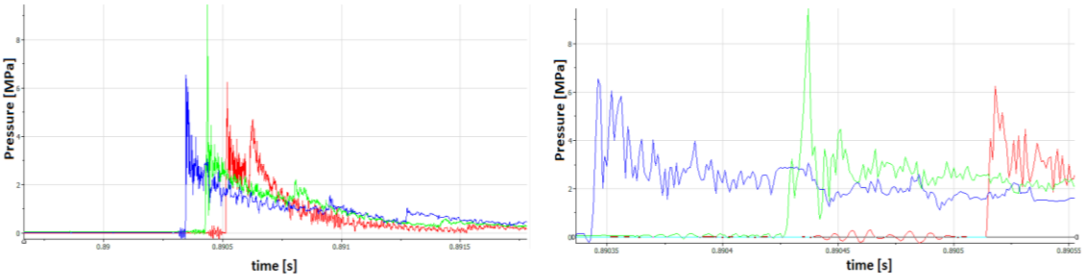


Fig.7. Pressure records for shock tube with plastic membrane. Pressure sensors with protective layer The speed of the detonation wave- 2340m/s

During tests with shock tube the protective layer influence was tested. As a protective layer, the rubber silicon cylinder was used. Height of this cylinder was about 2.5mm. This protection layer was choose after tests with several other options, as the best (with the lower level of inaccuracy).

The influence of the protective layer on the sensors is clearly visible. The layer causes slower signal propagation and as a result, the shape of the recorded waves resembles an acoustic wave more than a detonation wave. Other inaccuracy is too high or too low peaks (Fig. 5. and Fig. 7.). The reason is a mass of silicon layer and not perfectly connection of sensor and and layer.

First tests with rotating detonation in rocket engine

The first test were conducted using a mixture of H_2/AIR and methane/O_2 in a chamber of 200mm in diameter (Fig.18.). The chamber wasn't choked. The height of the chamber was 8mm.

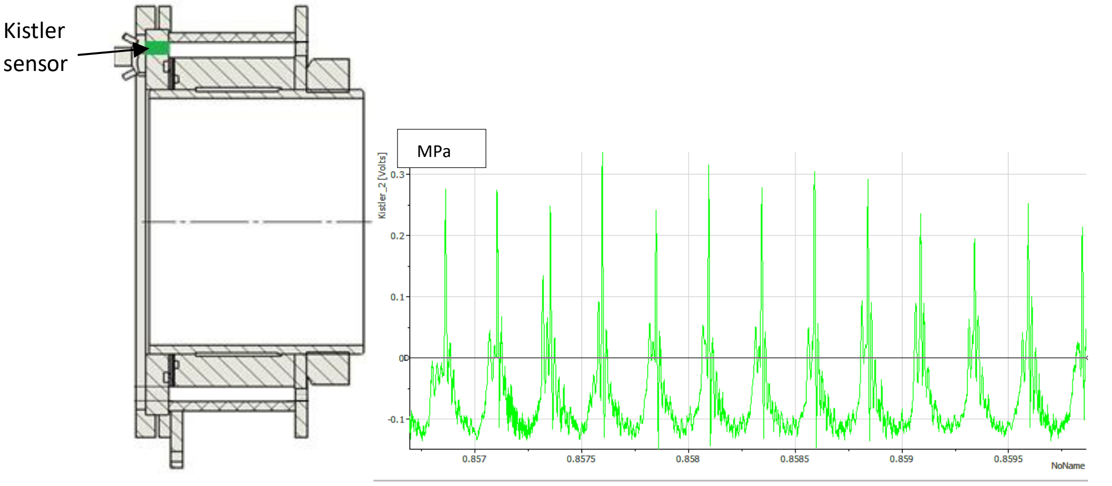


Fig.8. Configuration of pressure Kistler sensor placement and exemplary pressure in detonation wave records for the H_2/Air mixture.

For the same engine and sensor configuration research with methane- oxygen mixture were conducted.

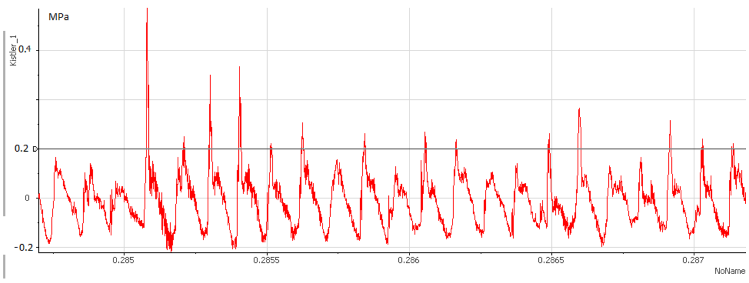


Fig.9. The exemplary pressure records of Kistler sensor for a CH_4/O_2 mixture.

In order to check the direction of detonation waves in the combustion chamber, a test stand with 3 piezoelectric pressure sensors placed unevenly on the perimeter of the ring combustion chamber was built (Fig.10). This setting of the sensors makes it possible to unambiguously determine the direction of the waves, their number and speed.
For an unchoked combustion chamber classic detonation combustion was easily achieved.
The pressure peaks reached a few bars for the mixture of CH_4 and O_2, with the average pressure being slightly higher than the atmospheric one. The Specific impulse of this engine mode is about 400 m/s.

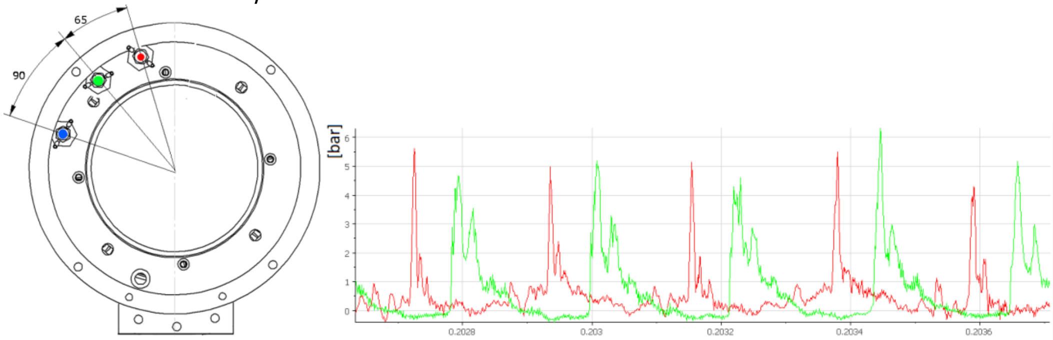


Fig. 10. Configuration of pressure sensor placement. In this configuration 2 waves of 1300 m/s in speed were identified

There were also conducted research with a transparent outer wall of combustion chamber (PC) in order to have a closer look at the waves, and to compare the vision with the sensor responses.

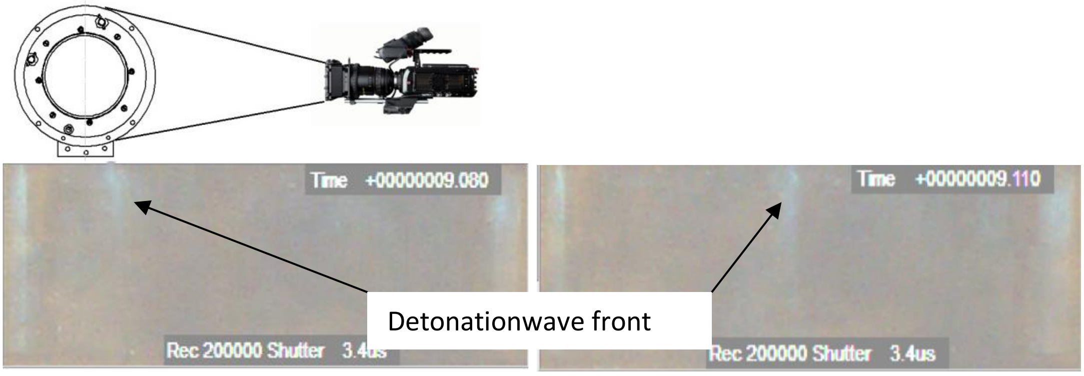


Fig.11. Screenshots from high speed record of the shock-wave motion. The camera was positioned relative to the combustion chamber.

The tests of an engine with a 150mm diameter.

The designed and built engine was equipped with an impinging injector.

The engine elements were made of aluminum alloy, as they must be easy to replace, which facilitates testing the impact of the geometric parameters on the engine performance. The engine was equipped with an AEROSPIKE nozzle (not optimized) made of aluminum alloy. The whole construction was placed on linear bearing table(HIWIN H25H), which was fitted with a dynamometer enabling thrust measuring.

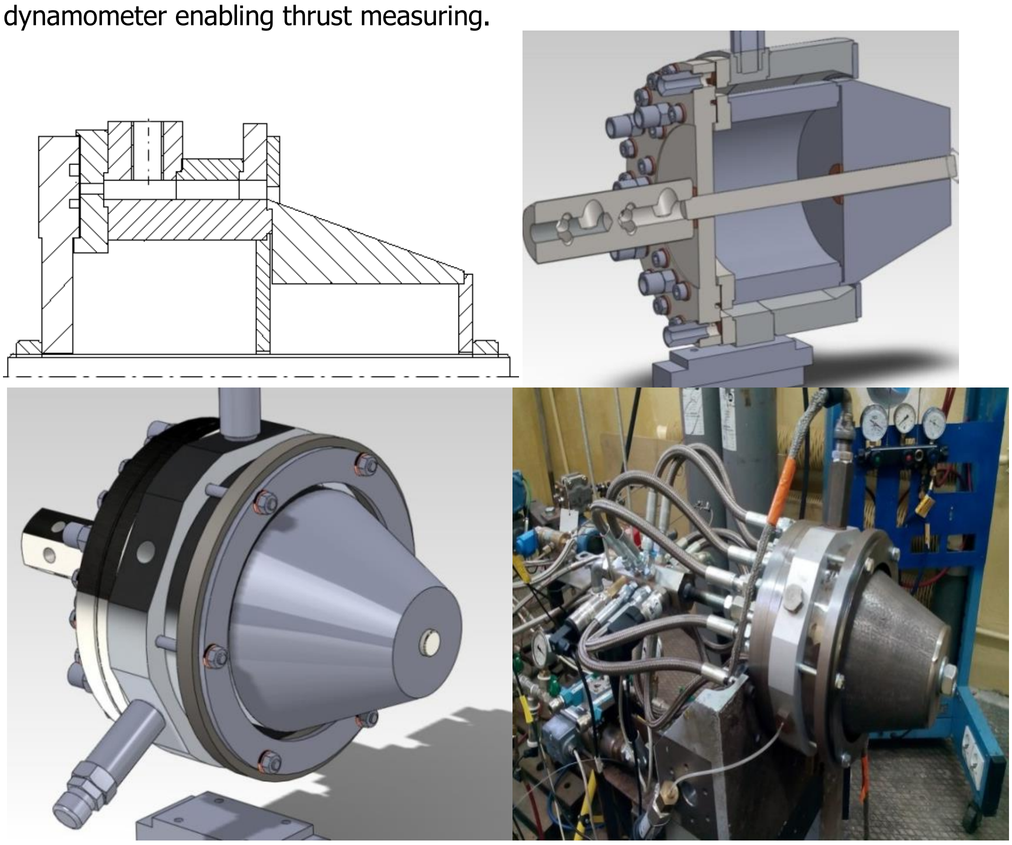


Fig. 12. Design of 150mm engine

Testing the stand.
At first, the stand was tested for leakproofness, flow efficiency of supply systems, and the functioning of the measuring system. Testing of the O2/CH4 mixtures
A number of tests were conducted, testing:
- Injector efficiency
- The impact of the mixture composition
- The influence of the chamber pressure on the specific impulse

Injector efficiency

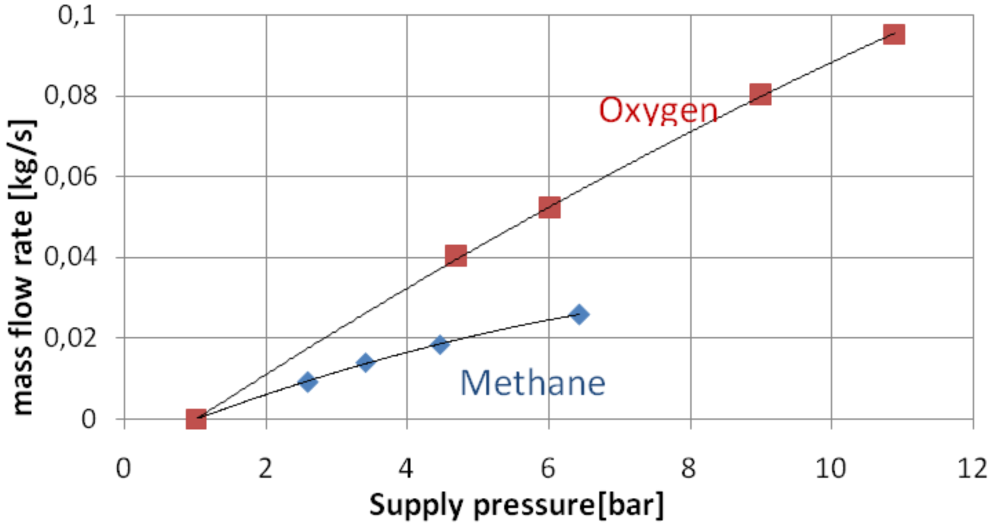


Fig. 13. Injector efficiency

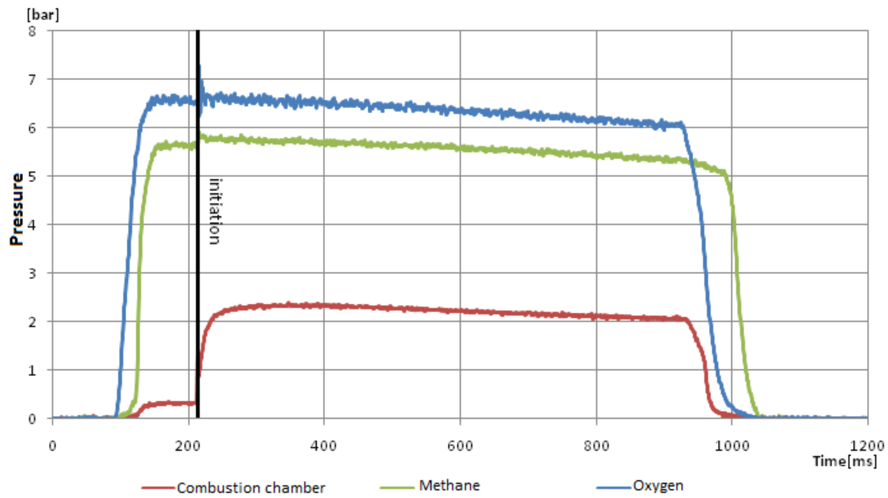


Fig. 14. Records of oxygen, methane and combustion pressures during the experiment

The influence of the parameters on engine performance was determined using the concept of specific impulse

$$I_{sp} = \frac{F}{\dot{m}}\left[\frac{m}{s}\right] \qquad (3)$$

Where
Isp –Specific impulse
F- Thrust [N]
$\dot{m}$ -mass flow rate [kg/s]

The impact of the mixture composition

The influence of the equivalence ratio on Specific Impulse was conducted for two pressures in combustion chamber.

ϕ – equivalence ratio

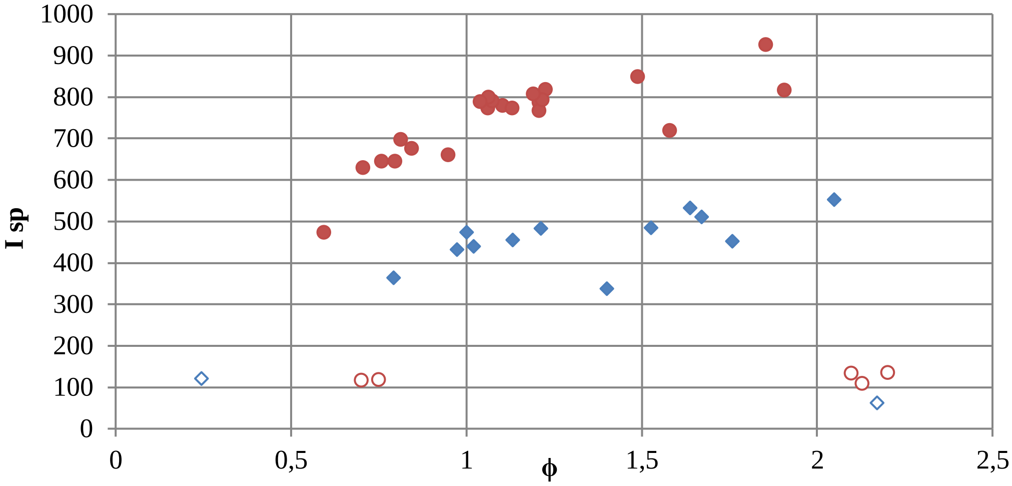


Fig.15. The influence of the equivalence ratio on Specific Impulse for 0.35 MPa (red) and 0.2MPa (blue) pressure in combustion chamber. Blank points- no combustion or combustion outside the chamber.

The influence of the chamber pressure on the specific impulse

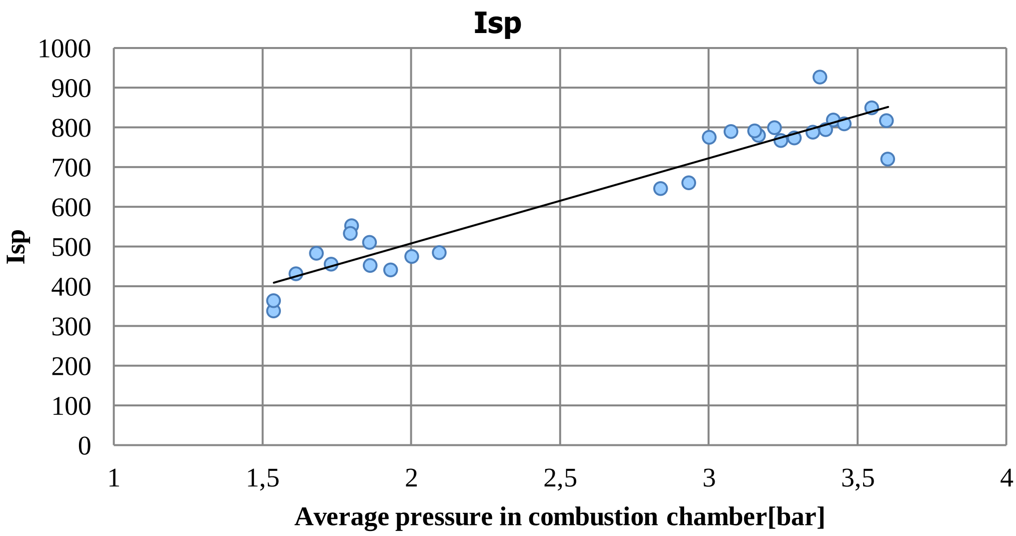


Fig.16. The influence of the chamber pressure on the specific impulse in 150mm engine.

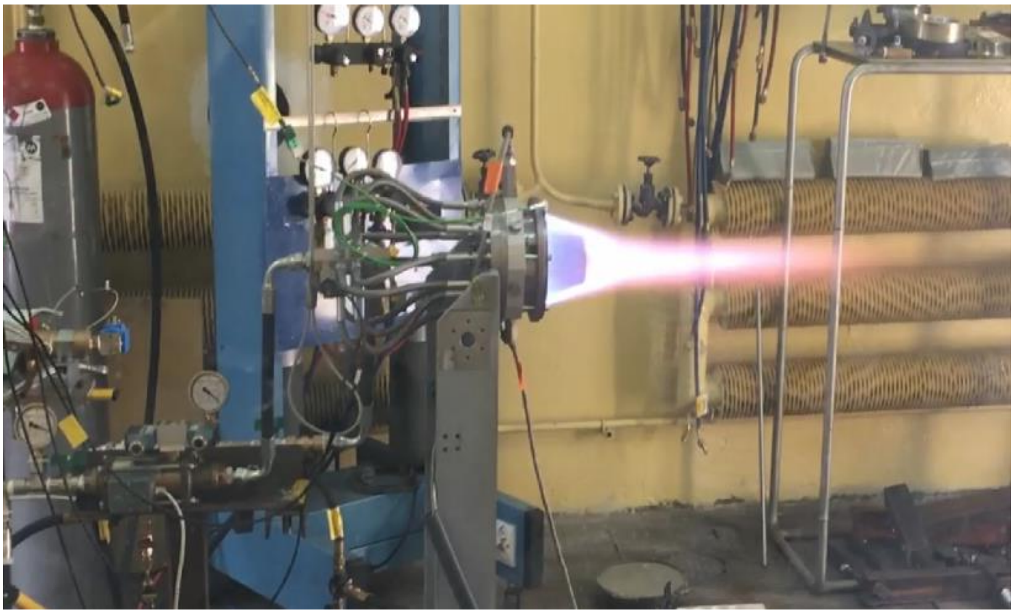


Fig. 17 Test of the 150 mm rocket engine

Rocket engine with 200mm in diameter

The rocket engine was built in such a way as to make easier the replacement of individual elements and introducing changes in the geometry.

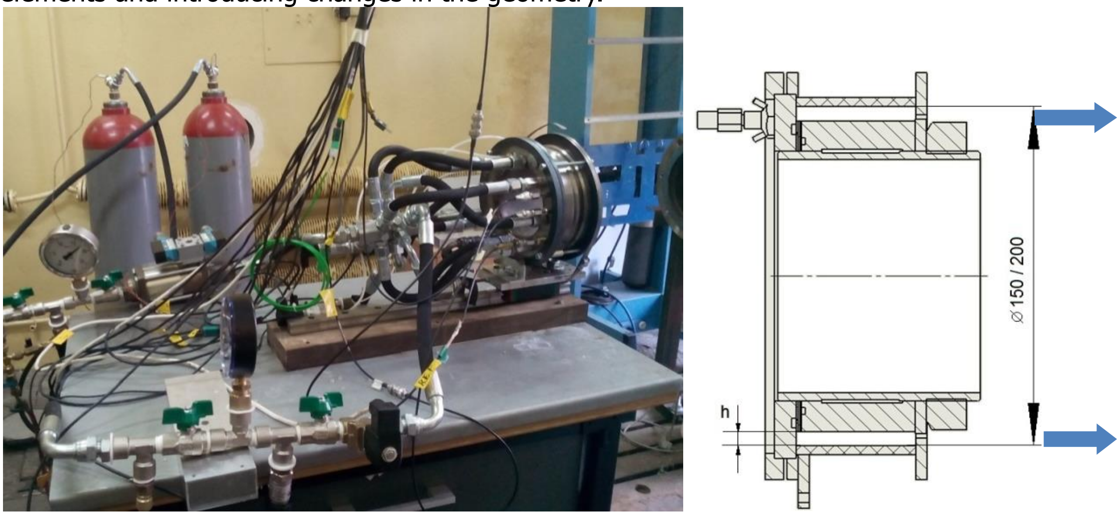


Fig.18. Design of the rocket engine

The design aimed to make easier the changing of the geometrical height of the combustion chamber. This engine has an interchangable outer wall. This enables testing engines of up to 16mm in chamber height which leads to deflagration combustion mode. It's also possible to test the influence of the chamber height, as well as to use a transparent outer wall.

Tests of the 200mm engine

Tests conducted with 200mm Engine:
- tests with deflagration mode
- influence of the height of the combustion chamber
- influence of mixture composition
- tests with a transparent outer wall
- attempting to direct the detonation wave.

Tests with deflagration mode

The height of the chamber was increased to 16mm, which slowed down the mixture and prevented detonation from happening. Test with deflagration mode were conducted for the mixture CH_4/O_2.

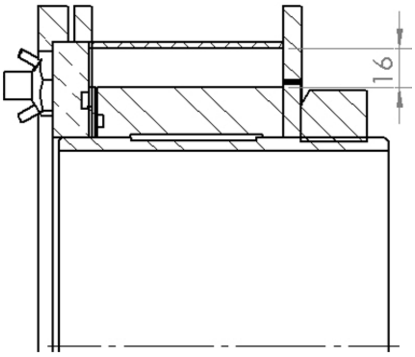


Fig. 19. Scheme of rocket engine with deflagration mode

The difference in the Kistler records in deflagration and detonation mode.

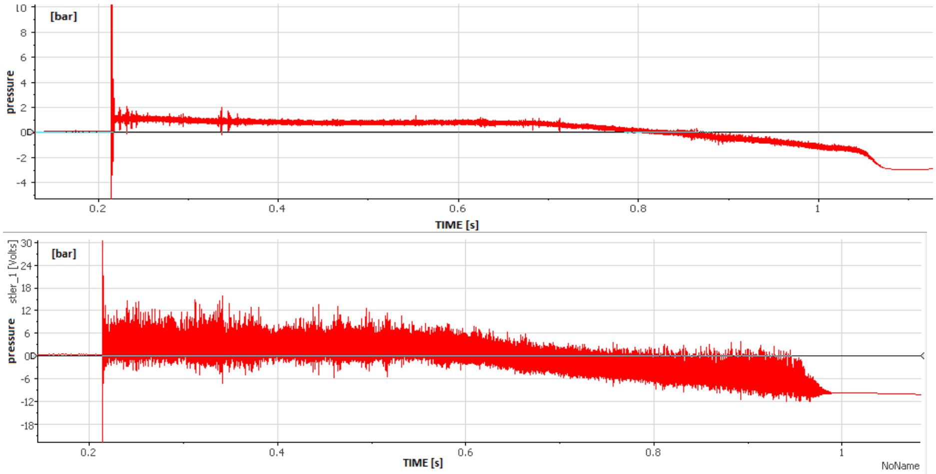


Fig.20. Deflagration mode pressure record (above) in compare to detonation mode (below)

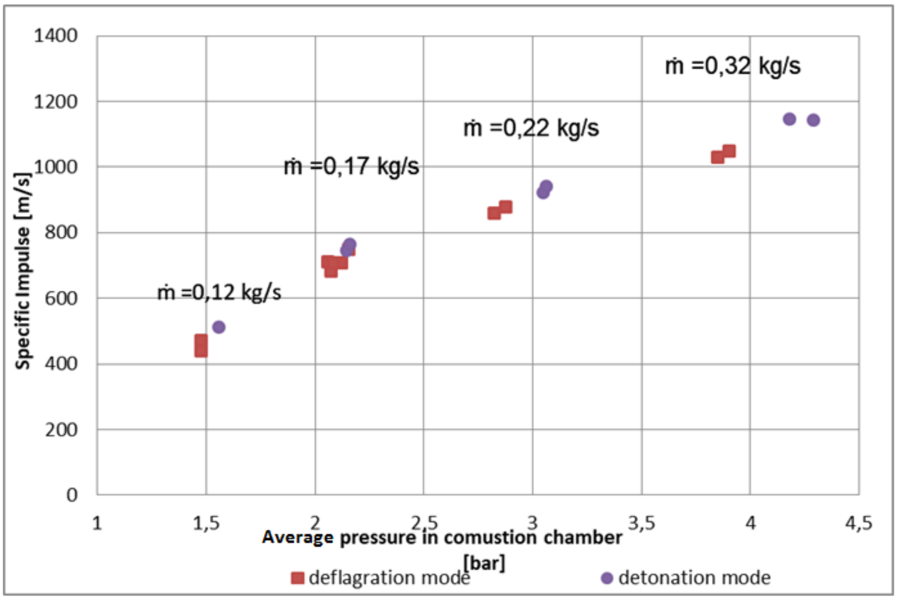


Fig. 21. The comparison of specific impulse obtained for 2 combustion modes.

The increase in Isp is caused by an increase in the average pressure in the combustion chamber for detonation mode, with the same mixture parameters. The advantage in impulse for detonation mode is about 7-8% comparing to deflagration mode.

Influence of the height of the combustion chamber

Tests of different heights of the channel. The tested heights of the combustion channel included 2.5mm, 3mm, 4mm, 6mm, 8mm.
For the channel of 4, 6, 8 mm test with nozzle of 2mm slit were conducted.

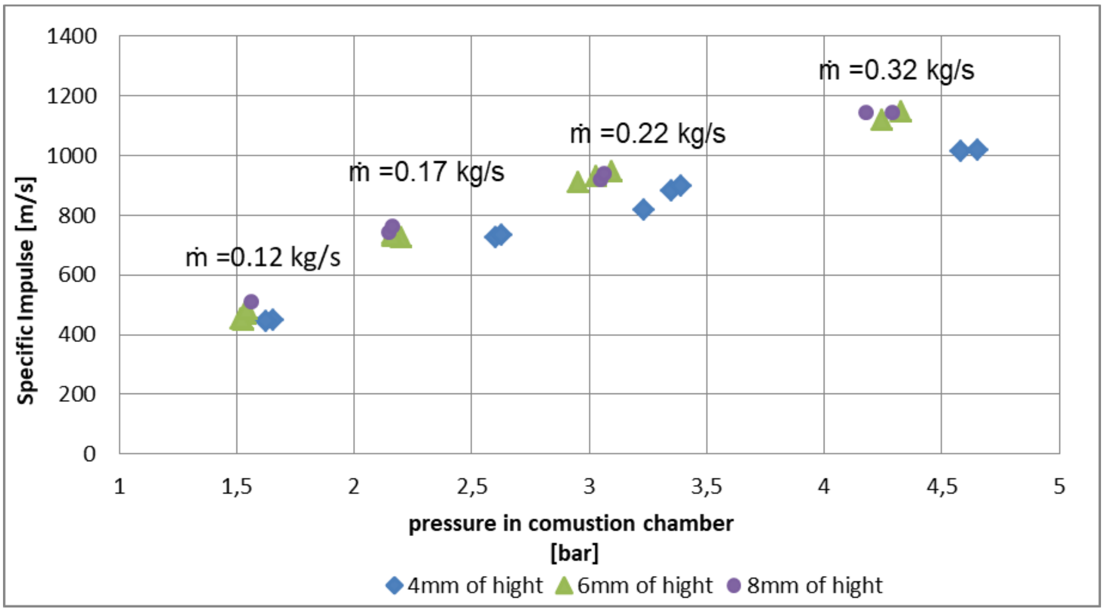
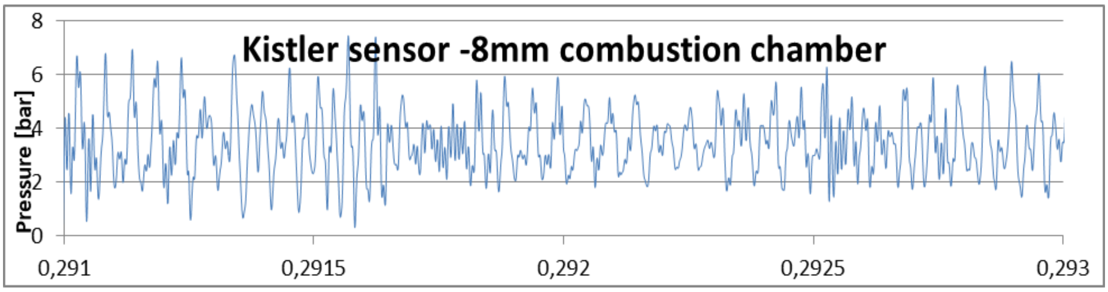


Fig.22 Comparison between 3 height of detonation combustion chamber

Read-outs from piezoelectric sensors show the structure of the waves. For a narrow combustion chamber the pressure read-outs are more chaotic, and some peaks are very high (Fig.23.) . Due to this fact average pressure is higher in case of narrow combustion chamber.



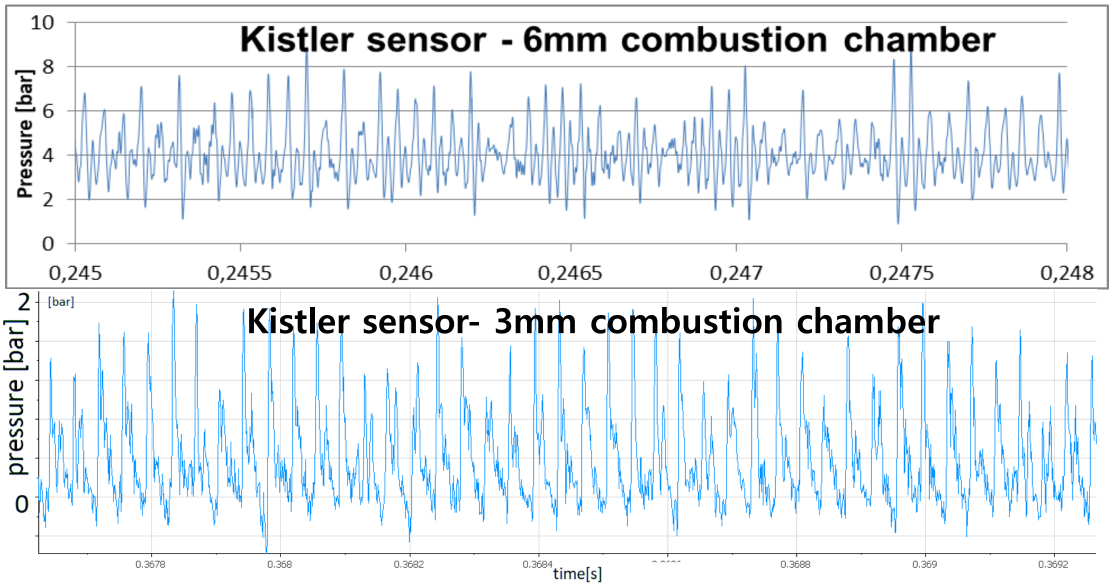


Fig.23. Read-outs from piezoelectric sensors for 3 different height of combustion chamber.

For a different nozzle - 1.5mm slit - tests were conducted with a 2.5 and 3 mm channel height. Due to a difference in choking, it is impossible to compare the results with previous tests.

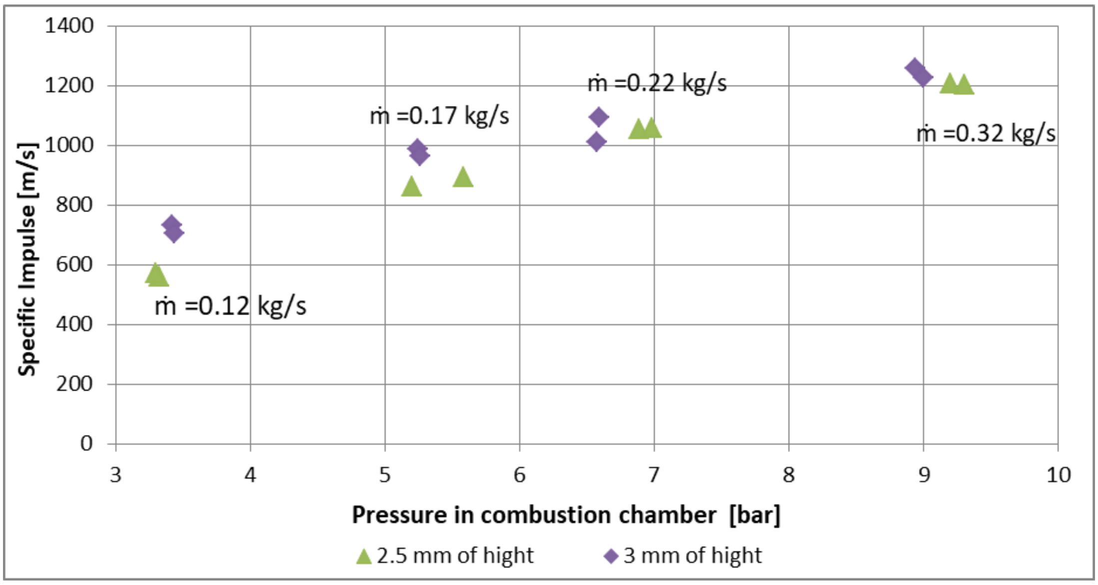


Fig. 24. Comparison between 2 other height of detonation combustion chamber with 1.5mm slit nozzle.

High engine choking and height of the combustion chamber downsizing have caused an increase in the average pressure in the chamber. The high pressure of combustion does not always contribute to a high Specific Impulse (Fig 24.and Fig 22.). Nevertheless, the nature of the combustion was more chaotic. The peaks reached beyond 20 bars for the CH_4/O_2 mixture. However, the number of the wave and their direction became difficult to assess (Fig.25) . Carrying out combustion in a narrow chamber causes the waves to be serially reflected off the walls. Additionally, acoustic waves appear. The pressure plot is very chaotic. High-speed recordings of the research on 8mm combustion chamber channel, as well as with 80% choking showed a large number of detonation and acoustic waves. However, engine performance improved significantly. For the configuration with the engine with a simple slit nozzle, the Isp reached 1300m/s for the CH_4/O_2 mixture(Fig.24.) in compared to 400m/s for unchoked engine.

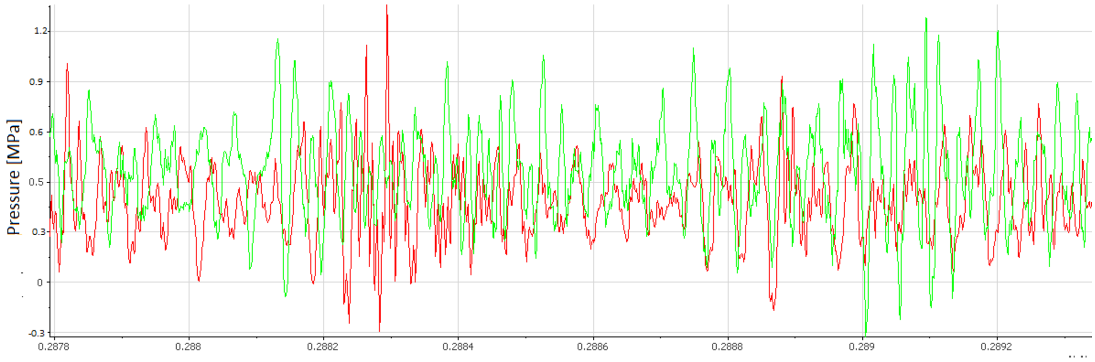


Fig.25. Read-outs from the piezoelectric sensors for a narrow combustion chamber with a high level of choking.

Influence of mixture parameter

The influence of mixture was conducted with this same geometrical parameters and this same mass flow rate.

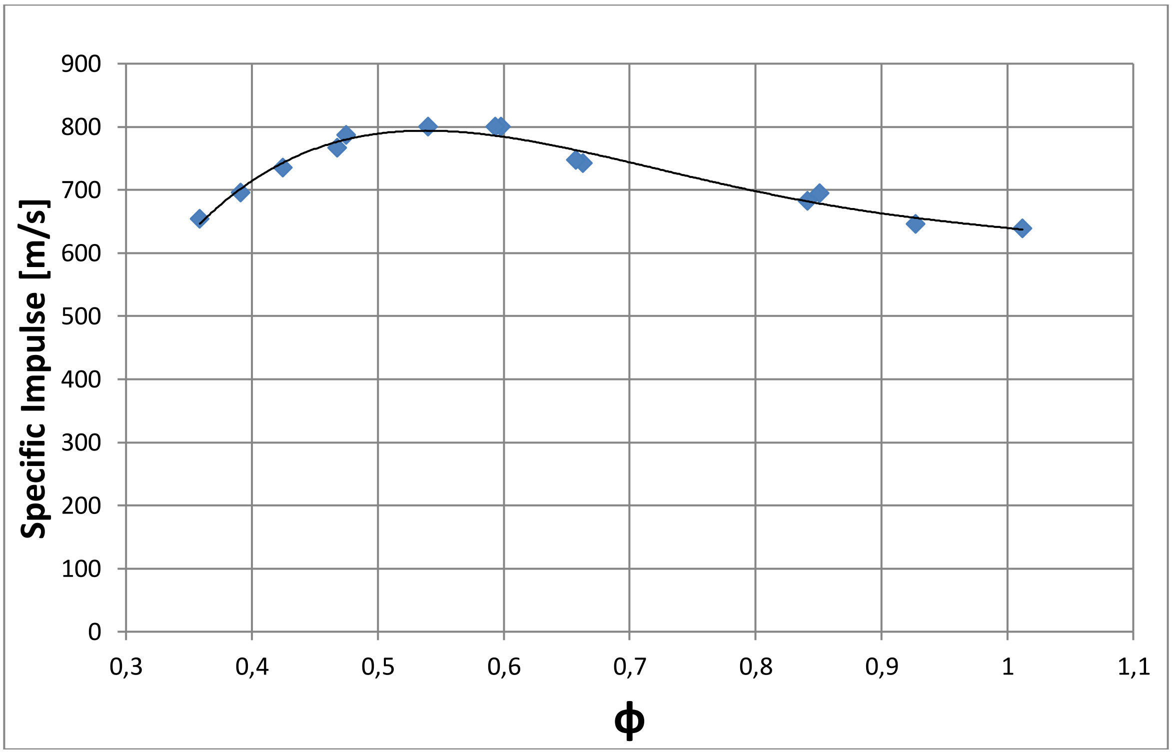


Fig. 26. Influence of equivalence ratio

Parameters of engine:
Engine with 200 mm of outside diameter;
Mixture of oxygen/ methane;
Mass flow rates: 0.17kg/s
Choking (A_{IN}/A): 0.25
The best engine performance was obtained for methane/oxygen mixture of about 0.5- 0.6 equivalent ratio.

Influence of combustion chamber diameter

Three combustion chambers have been built to check the effect of diameter on the engine parameters.
This same length (45mm) and height (3mm) of detonation channel has been applied.
The tests were made for a simple slit nozzle with contraction ratio (A_{NOZ}/A_{RDE}) of 0.667.

Combustion chambers with 200mm, 150mm and 100mm have been made and tested with gaseous methane-oxygen mixture.

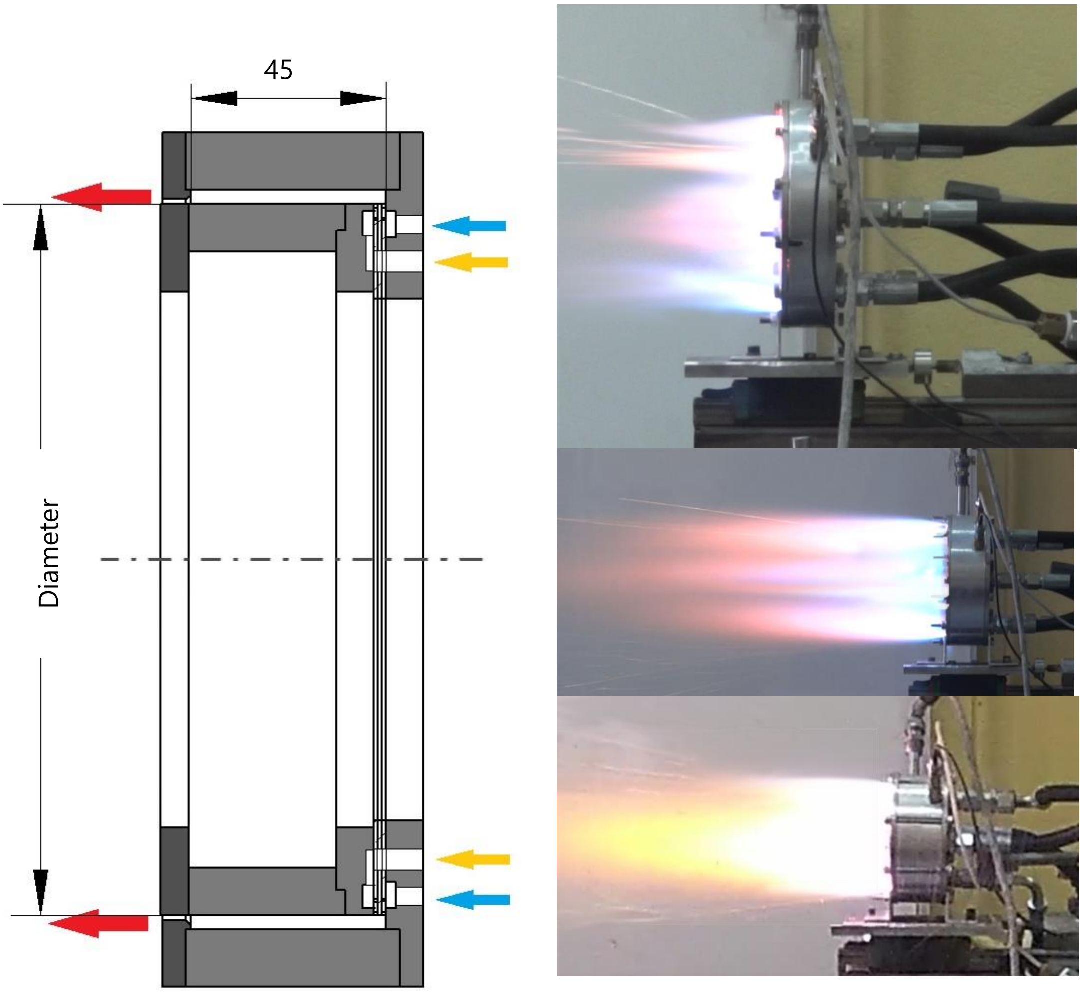


Fig. 27. Combustion chamber with 100mm, 150mm and 200mm diameter.

The results for different mass flow ratio are presented below (Fig. 28 and Fig. 29). To compare combustion chamber with different diameters, mass flow ratio was selected in proportion to the perimeter.

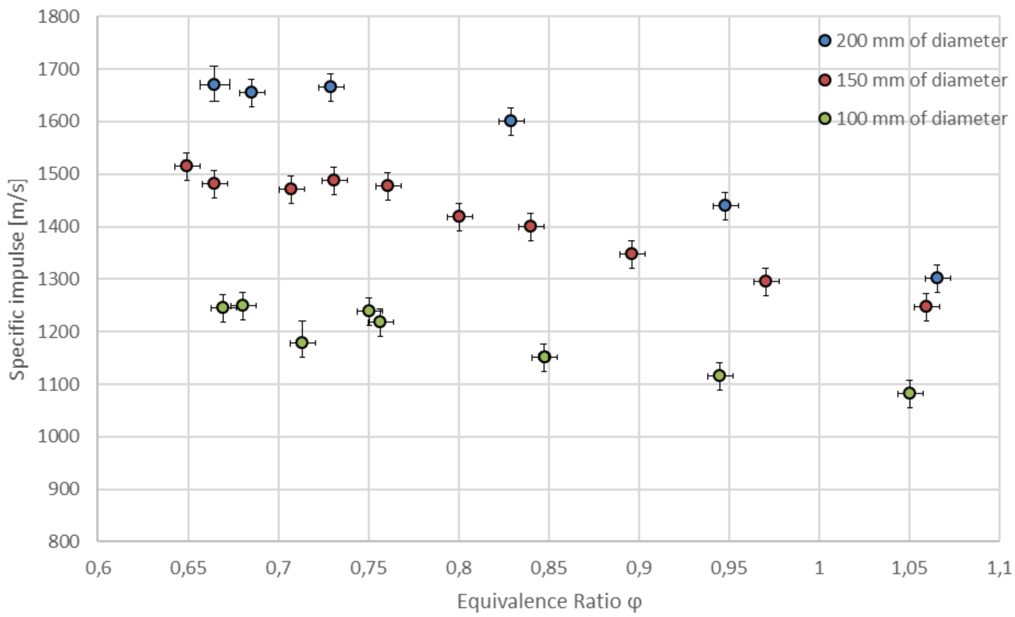


Fig. 28. Measured Specific Impulse (Isp) shown as a function of equivalence ratio. Mass fluxes ($\dot{m}_{mix}/A_{RDE}$) of 160 kg/sec/m^2.

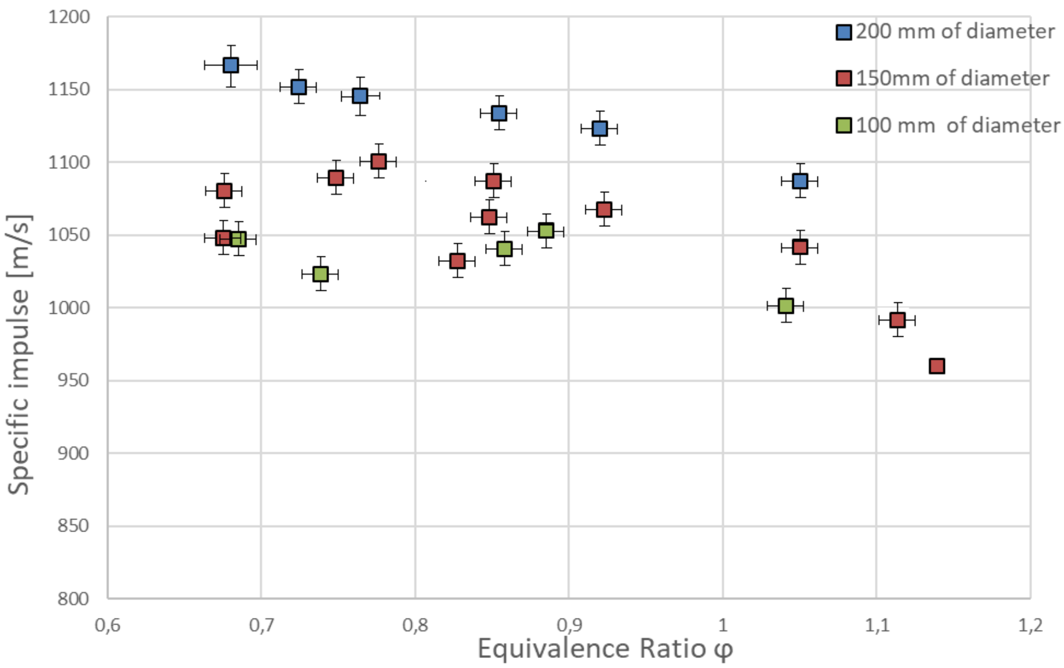


Fig. 29. Measured Specific Impulse (Isp) shown as a function of equivalence ratio. Mass fluxes ($\dot{m}_{mix}/A_{RDE}$) of 115 kg/sec/m^2.

Influence of combustion chamber length

The influence of length was checked with 150mm combustion chamber diameter. Height of the detonation channel was 3mm. Simple slit nozzle with contraction ratio (A_{NOZ}/A_{RDE}) of 0.667 was also used in the tests. The tests were conducted with oxygen/methane mixture for three chamber lengths: 60mm, 45mm and 30mm.

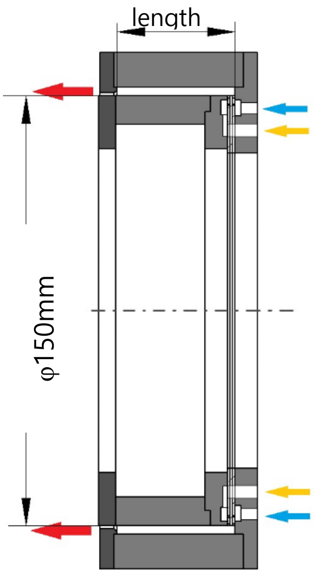


Fig. 30.Combustion chamber with 60mm ,45mm and 30mm of length.

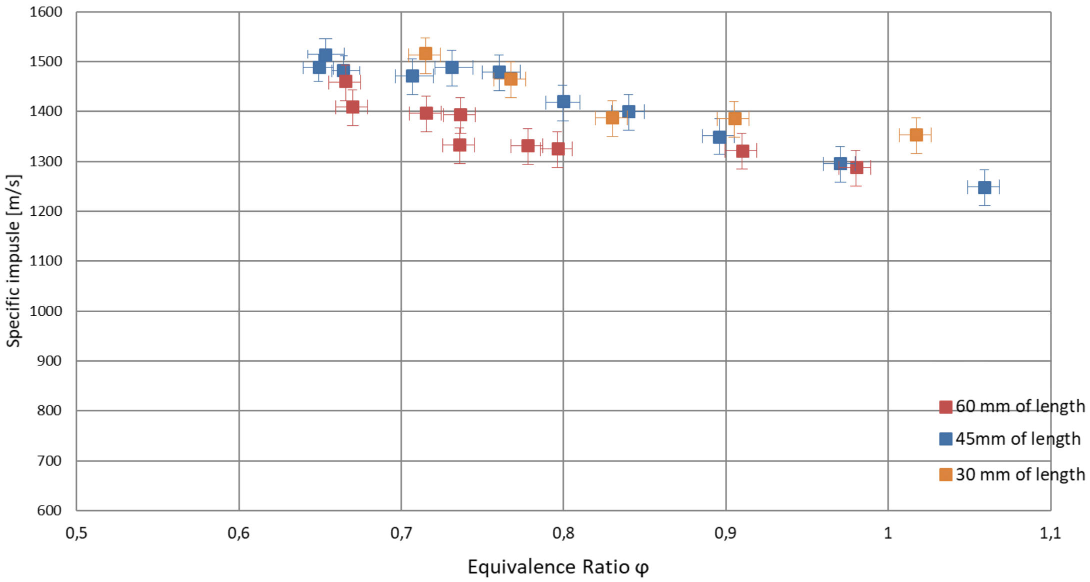


Fig. 31. Measured Specific Impulse (Isp) shown as a function of equivalence ratio. Mass flow ratio 0.225kg/s.

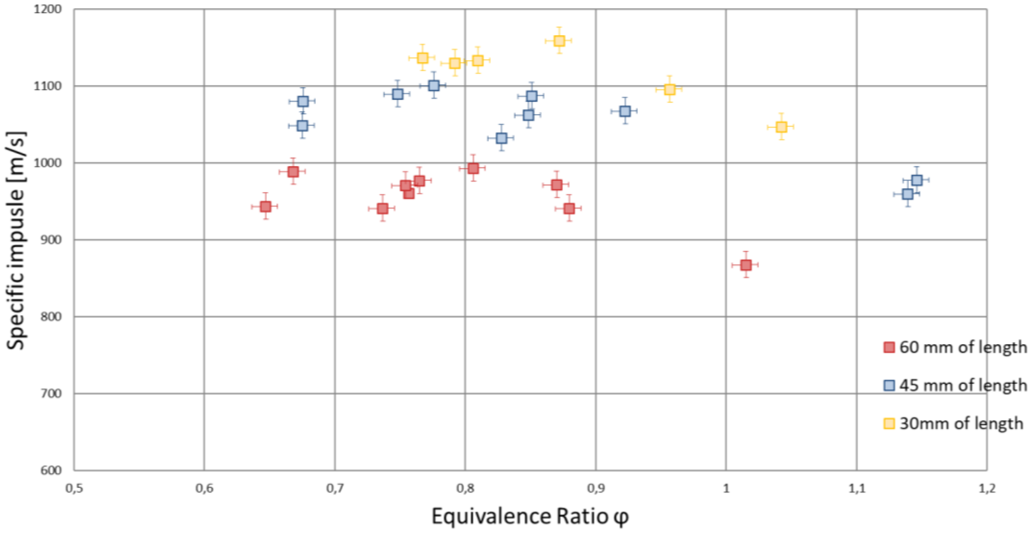


Fig. 32. Measured Specific Impulse (Isp) shown as a function of equivalence ratio. Mass flow ratio 0.15kg/s.

Tests with transparent outer Wall

Tests with a transparent outer wall were conducted with a 200mm engine. This was done in order to create a video footage of the combustion process.

Fig. 33. A record of the shock waves . Arrows indicate the position of the pressure sensors. The camera's position relative to combustion chamber is visible.

Parameters of the test:
Mass flow= 0.11kg/s
O/F = 0.85
Choking – 60%
As was mentioned before, the choking of the chamber results in a chaotic plot. Clearer plots are available for an unchoked engine.

Direction of the wave

One of the problems in development of rotating detonation engines is the problem of detonation waves direction. Detonation propagating in such engines looks as follows: after the initiation usually two or more waves in opposite directions appear, after some time the number of waves is reduced until the waves remain rotating in one direction. During such an attempt, the waves direction often changes.

It has still not been confirmed whether the direction of the wave causes the torque to rotate the engine [4-5]. This is important for rockets with a detonation engine design perspective point of view . The additional torque on a rocket would have to be taken into account. An even number of engines should be introduced (in which the directions of moments cancel each other out), or otherwise correct the flight path of the rocket.

Another reason why it is worth directing the wave is the problem of connecting the rotating detonation combustion chamber with a turbine engine. Knowledge of detonation direction in the turbine engine is crucial for the optimal design of the first stage of the turbine vanes in the engine [6-7].

Since the detonation wave itself does not carry mass, its direction is considered insignificant. In a real process, the detonation wave swirls the combustion products slightly in the direction of detonation, which raises the following questions:

1) Does the swirl transfer torque to the engine?
2) How big is this effect?
3) Is it possible to control the direction of wave motion and how?
4) How much does the swirl reduce engine performance?

This research deals with the problem of wave direction control and attempts to design a combustion chamber with a pre-determined direction.

The problem of wave direction control is addressed in the article by Knowlen and Kurosaka [8], where the wave direction was triggered by the sequential initiation of 12 spark plugs placed evenly around the circumference of the ring combustion chamber. Another attempt was to place the initiator together with the pre-initiator pipetangentially to the combustion chamber channel. It has been reported that this solution does not bring the expected effect.

Experiments were carried out with hydrogen-air mixtures, Four possible solutions: A) Wedged-shaped outer wall, B) Synchronized initiators, C) The use of aluminum foil to block one direction, D) Eccentric chamber.

A. **Wedged-shaped combustion chamber**.

The first attempt to direct the wave was an adoption of the surface cut out into the shape of a series of unidirectional wedges, as seen in Fig.34- "wedged wall". (in photo the wall seems to be conical but it is just parallax)

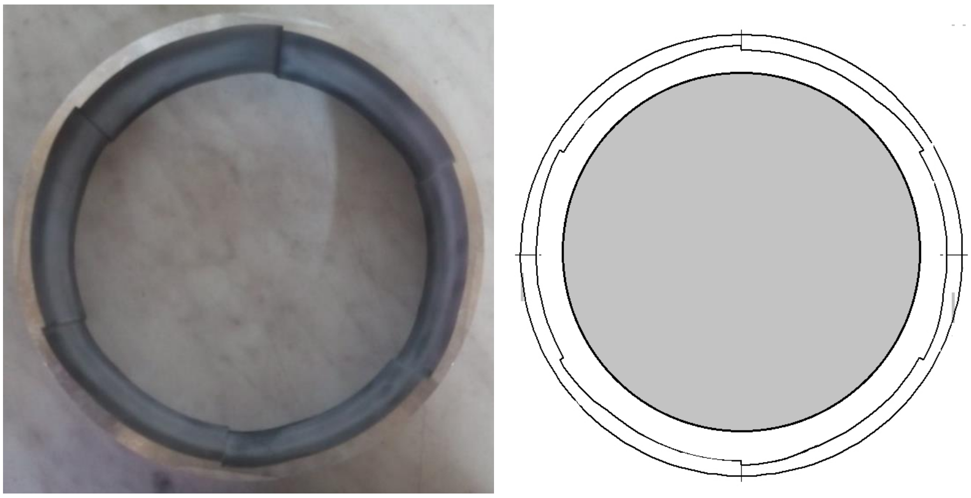


Fig. 34. Wedged surface in outer wall.

The first experiment results with CH_4/O_2 mixture with choking nozzle was difficult to define the influence of the "wedged wall" on the direction of the detonation wave gyration.

In the next stage the mixture was change in to Air/H_2 and the combustion chamber was completely unchoked.

For combustion chamber without "wedged wall" the direction of shock wave gyration was counter clockwise (Looking in the axial direction of flow) for all experiment (4 tests were conducted for this same mixture parameters and geometry of the combustion chamber) (Fig. 28.).

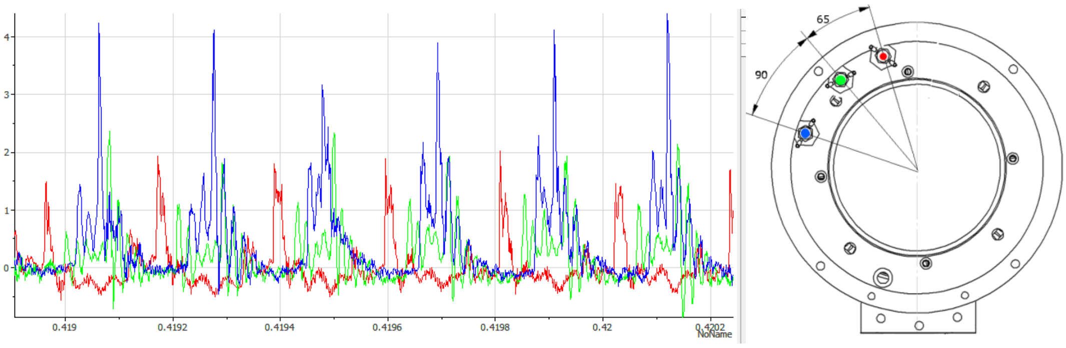


Fig. 35. Read-outs of piezoelectric sensors in combustion chamber without "wedged wall". In all cases two detonation waves with 1250m/s-1300m/s speed and counter clockwise rotating appears.

After using the wedge chamber (configuration Fig 36.) the nature of combustion was much more chaotic (Fig. 37). Detonation disappears and appears. The direction of the appeared waves was random. Sometimes there were 4 spinning waves - 2 in opposite directions

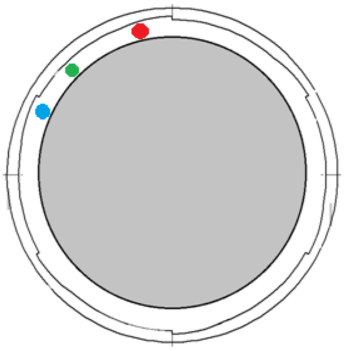


Fig.36. The "wedges wall" with the piezoelectric sensors placement.

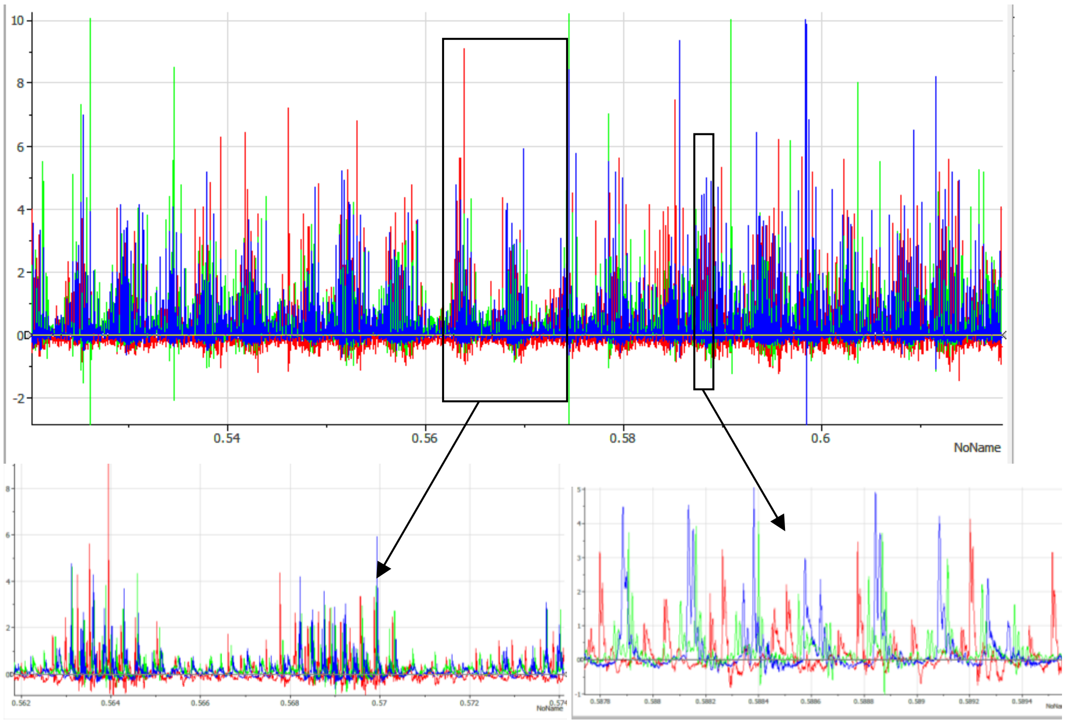


Fig. 37. Read-outs of piezoelectric sensors in combustion chamber with "wedged wall".

Outer wall of the engine was inverted 180 deg to reverse wedge direction (Fig 38).

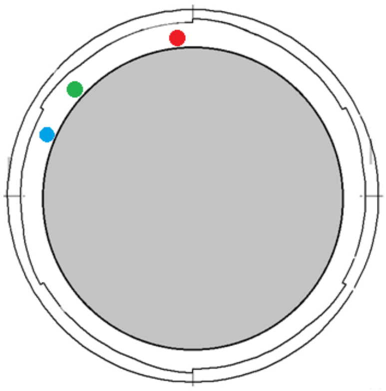


Fig. 38. *The "wedges wall" with the piezoelectric sensors placement.*

After reversing the outer wall the waveform has changed a bit. After approx. 0.75- 0.8s, the number and direction of the waves were stabilized (Fig.39.). Three tests were conducted in this configuration. In all cases, after the process was stabilized, there were 2 waves to the right and 2 waves to the left. It was possible to see more predominant waves in clockwise direction (Fig. 39.).

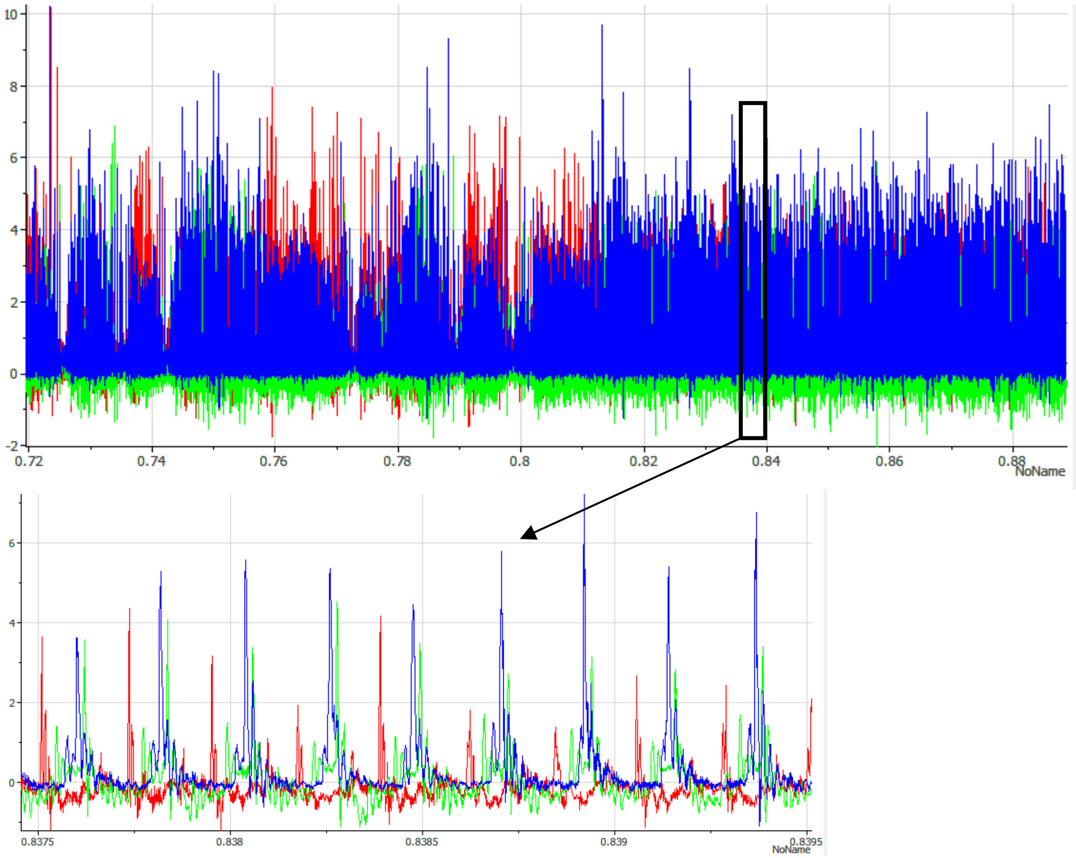


Fig. 39. Read-outs of piezoelectric sensors in combustion chamber with "wedged wall".

During expeiments with this solution a lot of additional waves occured, the direction changes took place dozens of times during our experiments. We considered this solution to be non-prospective

B. Synchronized initiators

One of the idea was to use synchronized initiators. In this study, car spark plugs were used as initiators.
The initiators were placed asymmetrically on the outer casing of the chamber. The assumption was to check whether the unsymmetrical initiations would achieve detonation in one direction (Fig. 40).

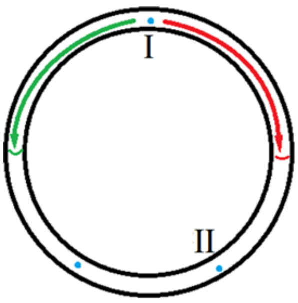


Fig.40. Location of the initiators in during experiments with synchronized spark-plugs.

The time of the waveform between initiators is about 0.12 ms. Synchronization of the initiators took place before the actual experiment, by recording spark plug discharges with a high speed camera. The recording speed of the camera was 100 000 fps . It allowed to synchronize sparks with the accuracy of 0.01 ms.

Two scenarios are considered (colours according to Fig. 40):

- The red wave from initiator I is degraded by the wave from initiator II. During this time, the green wave have such a high speed and strength that it persist and become the dominant wave.
- The red wave from initiator I is amplified by the wave from initiator II. During this time, the green wave is too weak to persist and disappears.

The results of several experiments are presented in Figure 3 in a form of recordingsof pressure changes obtained with piezoelectric sensors.

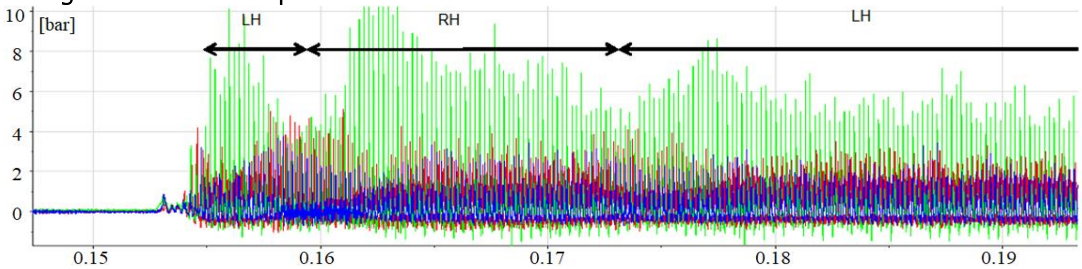
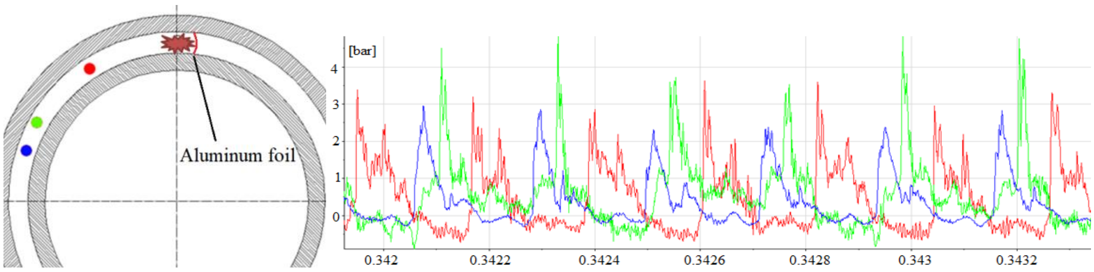


Fig.41. Pressure record in the chamber with synchronized initiators. Changing of wave direction during of experiments- left hand (LH) and right hand (RH).

As the results show in this solution, it was difficult to check the influence of the method on wave direction, because more than one initiation resulted in a large number of waves at the beginning of the process. After the process was determined in the next phase of the experiment, some waves expired and kept propagating in one direction. Moreover, the direction seems to be accidental. It is assumed that the initiators may not have been exactly synchronized with each other. In subsequent experiments, spark electrodes can change the distance between them, as a result of high temperature, and thus the moment of discharge. At present, it is difficult to unambiguously reject this idea based on the lack of possibility to confirm the synchronization of the initiators.

C. The use of aluminum foil to block one direction.

In this solution, a rectangular piece of aluminum foil was placed right next to the initiator (Fig. 42.). Out of the two symmetrical waves initiated by the initiator, one was reduced and the other continued the process of detonation, finally giving the direction throughout the experiment. The aluminum foil element was blown out of the chamber at the beginning of the experiment. This solution had a repeatability of 80%. Detonation induced in one direction continued until the end of the experiments (Fig.43.).



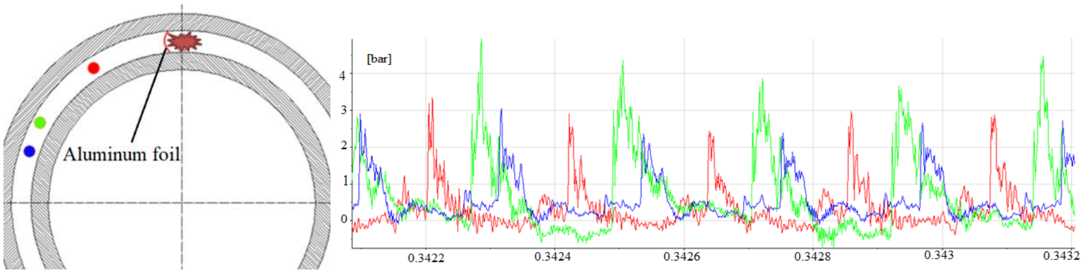


Fig. 12. RDE chamber with aluminum foil, with clockwise direction of wave motion (above), and counter clock direction of wave motion (below).

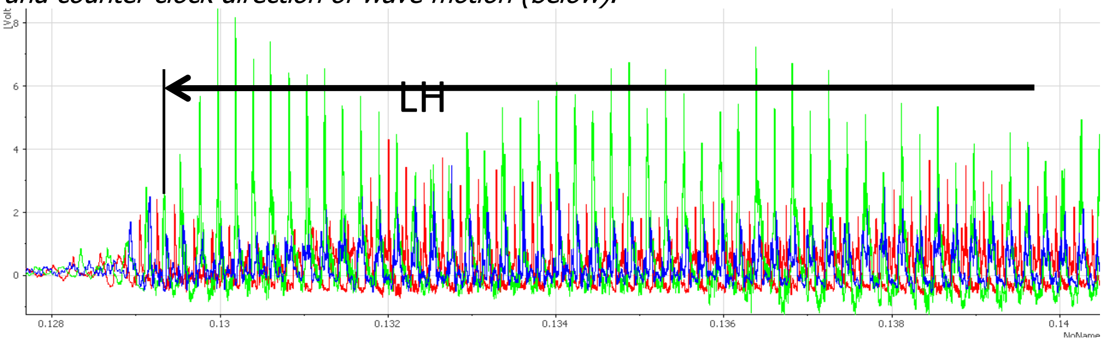


Fig. 43. Direction of process sustained during whole experiment.

D. Eccentric chamber

Simple numerical calculations of the wave passage through the wedge shaped channel were carried out in FLUENT. The channel has dimensions and initial conditions shown in Fig. 44 Numerical calculations were conducted for stoichiometric hydrogen-air mixture using Navier-Stokes equations and one step chemical reaction. Based on the results (Fig.5) it was found that the DDT process propagates first in the extended channel (diffuser) direction. Moreover, wave passing through the confusor slows down and accelerates through the diffuser (Fig. 7).

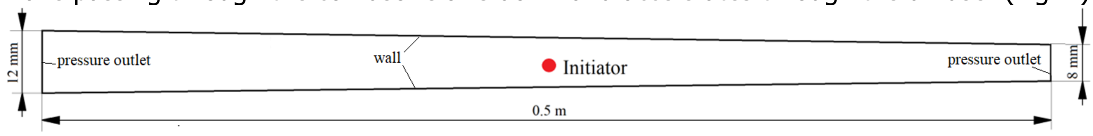


Fig. 44. Dimensions of wedge-shaped channel. Initiator is in the middle of the channel.

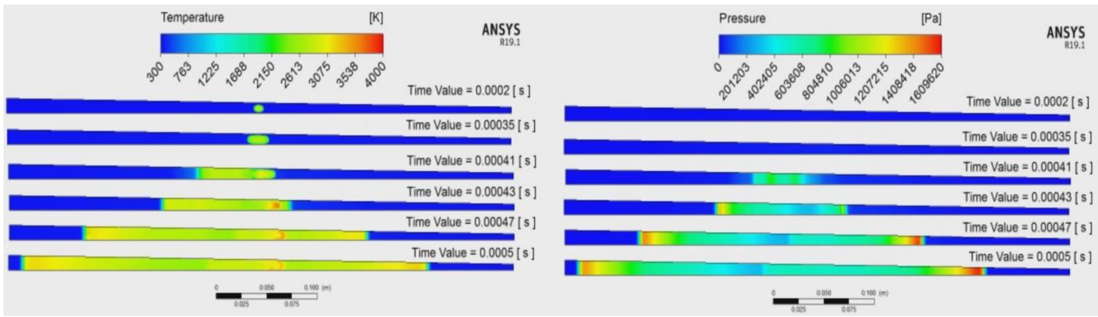


Fig. 45.Numerical calculations results of wave propagation in wedge-shaped channel.

Collision of two waves weakens the slower wave. This phenomenon can be used to direct the detonation wave in the chamber.

The chamber is annular with variable height, which is obtained in such a way that the center of the inner ring is eccentrically shifted in relation to the outer ring by a certain distance "X". The numerical calculations are simplified, however, allow the mechanism of wave propagation to be noticed.

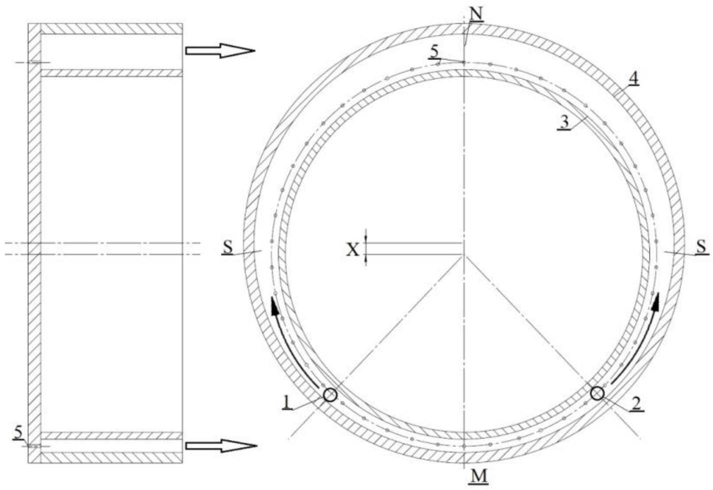


Fig. 46. Detonation Chamber with Eccentric channel.

The detonation initiator is placed at a certain distance from the minimum and the maximum height of the chamber.

Several dozens of experiments were carried out by initiating initiator 1 or initiator 2. Initializing the process with the initiator No. 1 (Fig.46) causes the wave to be generated in the clockwise direction (Fig.47), and the initiation of the initiator No. 2 process causes the dominant, counter clockwise direction of the wave (waves) to be determined (Fig. 48.). The minimum measured dimension "X" at which solution works was 0.3 mm. Entering a smaller dimension was associated with geometry measurement problems. The average height of annular combustion chamber was 7mm.

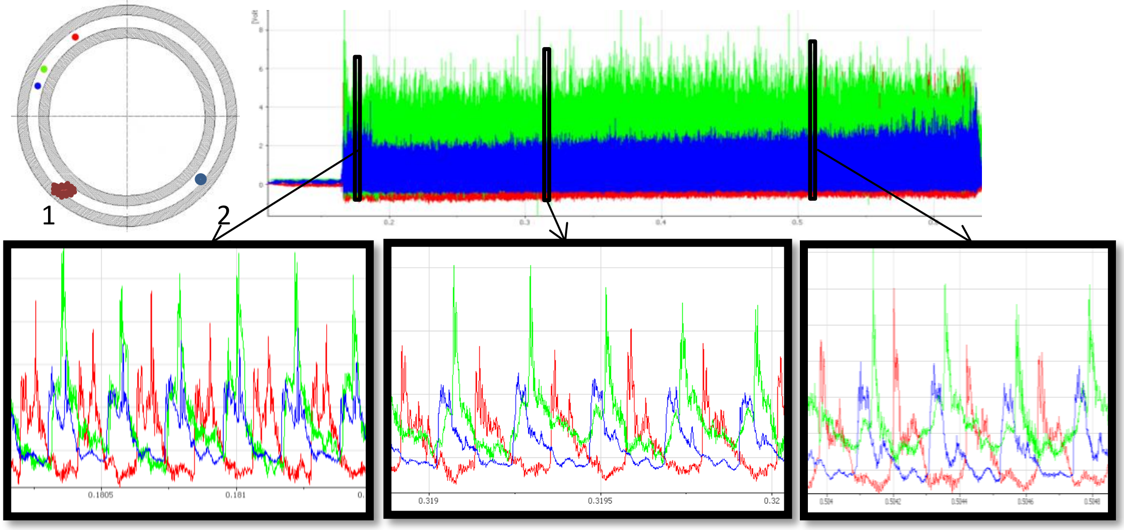


Fig.47. The example of an experiment with the use of the No. 1 initiator.

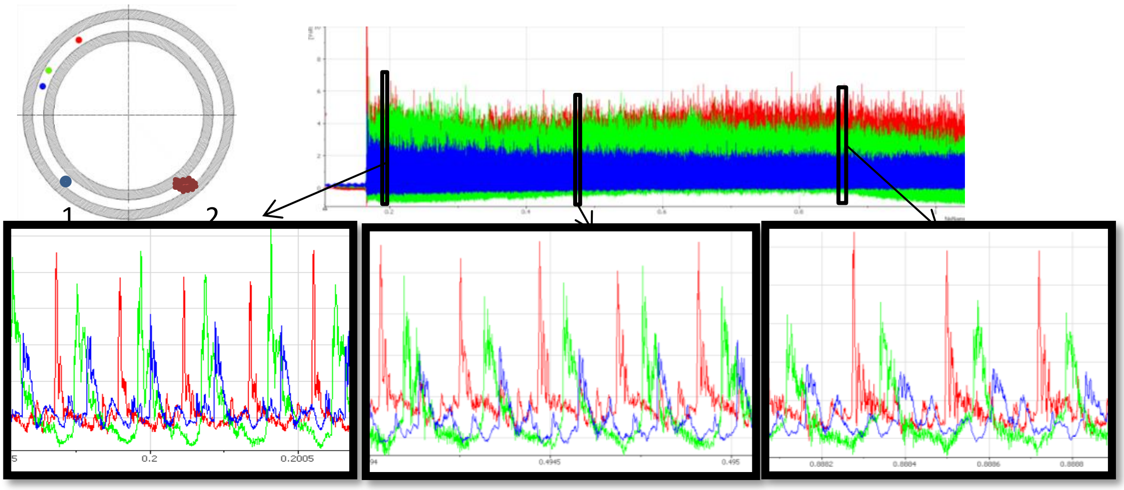


Fig. 48. The example of an experiment with the use of the No. 2 initiator.

Number of waves

In RDE engine, one or more waves usually move in a ring chamber. The number of wavelengths that are determined in the process is not accidental. In [9] a simple dependence on the number of waves in the detonation process in the RDE is derived.

The number of wavelengths is the quotient of the cycle time of the detonation wave in the cylindrical combustion chamber (t_r) by the time of filling with the fresh mixture necessary to detonate the volume (t_{mf}).

$W = t_r/t_{mf}$ (4)

$t_r = \pi d/u_D$, (5)

where d-diameter of the combustion chamber, u_D- speed of detonation,

$t_{mf} = V_{cr}/\dot{V}_{mix}$ (6)

$V_{cr} = \frac{\pi(d_o{}^2 - d_i{}^2)}{4} * l_c$; (7)

where d_o and d_i are the outer and inner diameter of the combustion chamber, l_c- critical length of the fresh mixture.

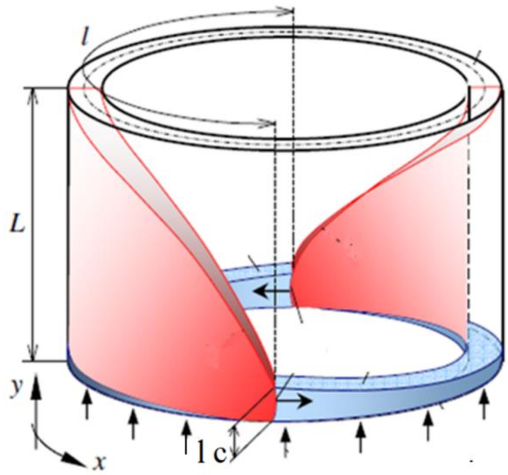


Fig. 49. Diagram of combustion chamber with fresh mixture.

The size l_c is in fact the depth of the fresh mixture penetrates the combustion chamber before the detonation wave reaches it.

$\dot{V}_{mix} = \frac{\dot{m}_{mix}}{\rho_{mix}}$; where m_{mix} and ρ_{mix} are the mass output of the mixture and its density.

After transformations, the formula takes the form:

$W = \frac{2\dot{V}_{mix}}{l_c\ h\ u_D}$ (8)

Knowing all the parameters it is easy to calculate the number of detonation waves for the cylindrical chamber. If "W" is equal to 1, 2, 3 ... If "W" is equal to 1, 2, 3 ... n, then one, two, three or "n" number of detonation waves propagating in one direction will be observed in the chamber.

A typical example of a single-wave detonation pressure recording is shown in Fig. 3.

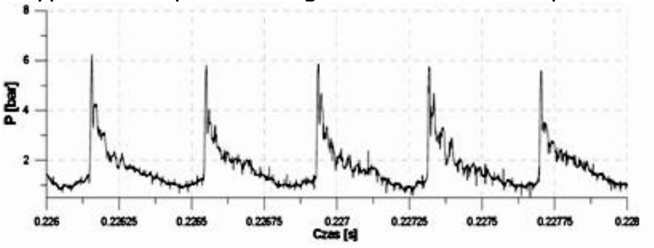


Fig.50. Stabling rotating detonation.

If "W" is slightly smaller than one, an unstable detonation will be observed first. In this case, after one rotation of the detonation wave in a cylindrical chamber, the fresh mixture will not be able to feel sufficient volume of the chamber, and the detonation will begin to disintegrate (and thus spread at a lower speed). Lower propagation velocities will prolong the explosion time of the detonation wave and thus more fresh mixture will be delivered to the chamber, while detonation will accelerate and the process will be repeated over and over again, creating a form of "galloping rotational detonation". Typical examples of such a process are shown in 51.

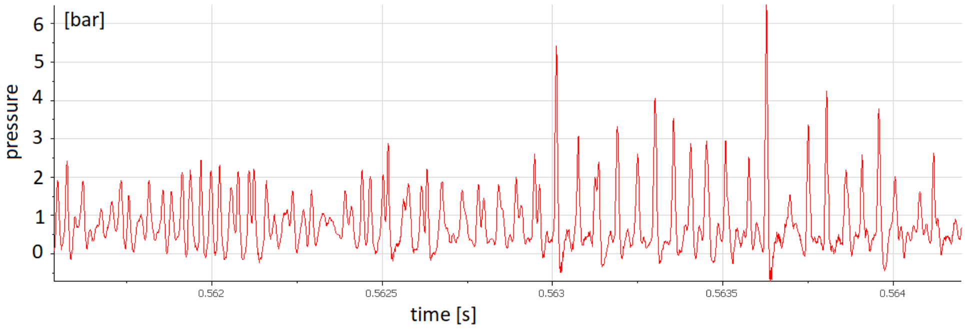


Fig. 51. Unstable (galloping) rotating detonation

The mechanism of such "galloping rotational detonation" differs from classical galloping detonation, but the behavior of the front wave speed is very similar. If "W" is much smaller than 1, the spinning detonation will fail and the deflagration combustion will occur.

The only uncertain parameter to be used for this calculation is lc. The critical length of this zone will depend on many parameters, but will basically depend on the initial pressure and temperature,

the composition of the mixture and its homogeneity (or non-ideal mixing of fuel and oxidant) and channel geometry.

In this experimental work the parameter was examined in detail.

Tests were carried out in the combustion chamber for the hydrogen-air mixture and methane-oxygen mixture at different compositions of the mixture and mean pressure in the chamber (this was achieved by modification of the outlet nozzle from the chamber).

Experiments were carried out using at least one piezoelectric pressure sensor. Records of pressure waveforms are shown in Fig52.

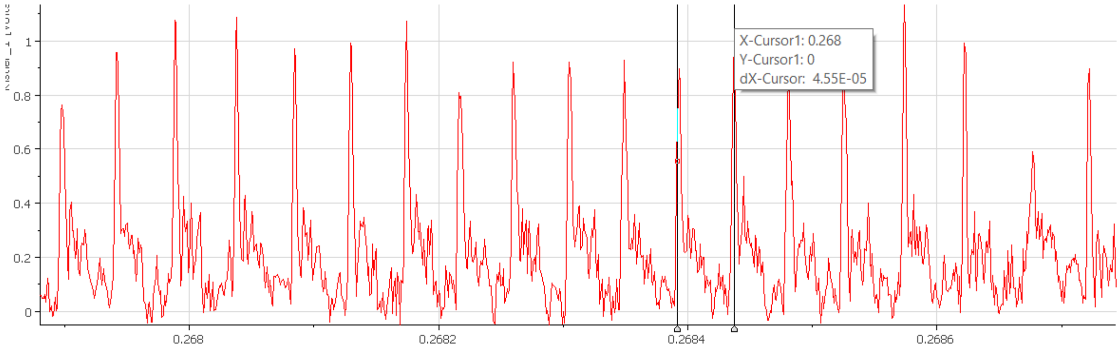


Fig. 52 Fragment of the pressure record in the combustion chamber for piezoelectric sensor. Methane-oxygen mixture, equivalence ratio=0.9

Looking at the records from the sensor you can observe pressure peaks sequentially. The time between peaks (hereinafter referred to as t_{bp}) is similar from the moment of stabilization of the detonation process in the engine until the end of the experiment. By measuring this time we can answer the following questions:

- What is the speed of detonation? (knowing the circumference of the combustion chamber)
- What is the number of waves in the process? (knowing the estimated CJ speed under given conditions)

It is also possible to determine what the size of *lc* in the process is.

$l_c = v_{axis} * t_{bp}$, (9)

i.e. axial speed of fresh mixture in the chamber * time of fresh mixture inflow (before fresh mixture is consumed by the next wave).

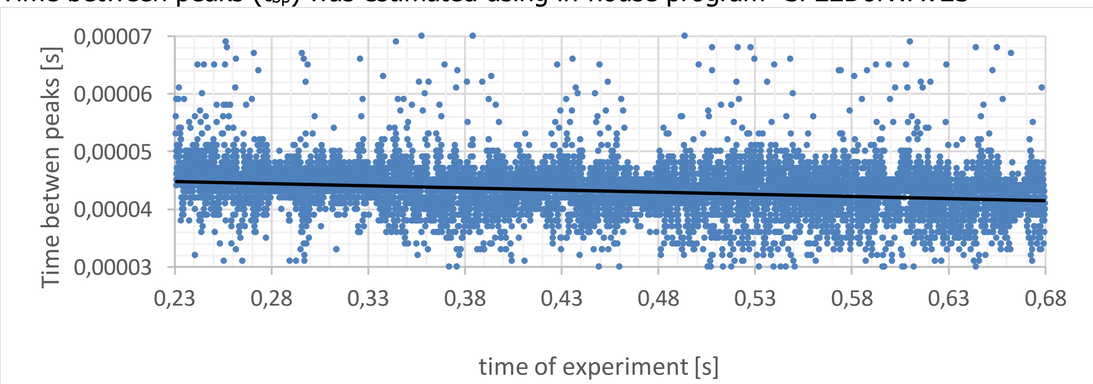
$v_{axis} = \frac{\dot{m}_{mix}}{\rho_{mix} * A_{RDE}}$ (10), where $\dot{m}_{mix}$ is the mass output of the mixture and ρ_{mix} its density and A_{RDE} is the geometric front surface of the detonation combustion chamber .

Ultimately:

$$l_c = \frac{\dot{m}_{mix}}{\rho_{mix} * A_{RDE}} * t_{bp} \quad (11)$$

For the case from Fig. 52.

The test was conducted for average pressure in combustion chamber: 1.94bar,
Mass flow ratio for mixture- 0.14 kg/s.
Equivalence ratio- 0.9
Density of the mixture ρ_{mix}- 2.198/m^3 (for temperature of fresh mixture- 300K)
Axial speed of fresh mixture- v_{mix}- 44,5m/s
A_{RDE}-(150mm* п*3mm) 0.001414m^2
Time between peaks (t_{bp}) was estimated using in-house program "SPEEDofWAVES"



t_{bp}= 4.55E-04s, it means, that **l_c=1,96 mm**

Dozens of experiments were conducted for different pressure in combustion chamber and different mixtures.

The results were compared with detonation database [3]. Caltech database presents the width of detonation cell.

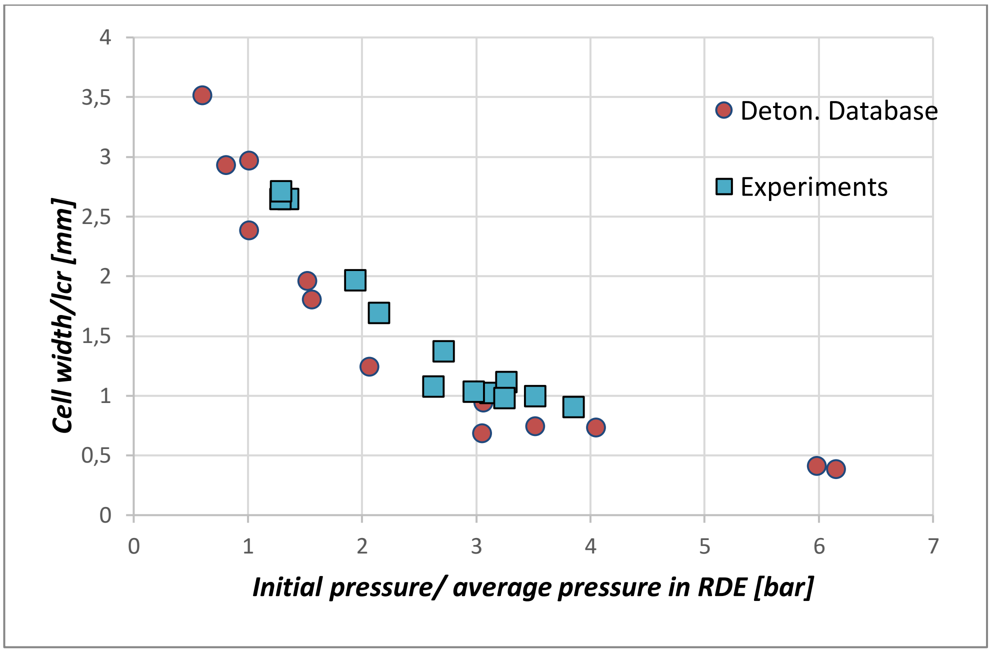


Fig.53. Results of Lcr received in experiments for CH_4-O_2 mixture, and CH_4-O_2 mixture cell size from Detonation Database [3].

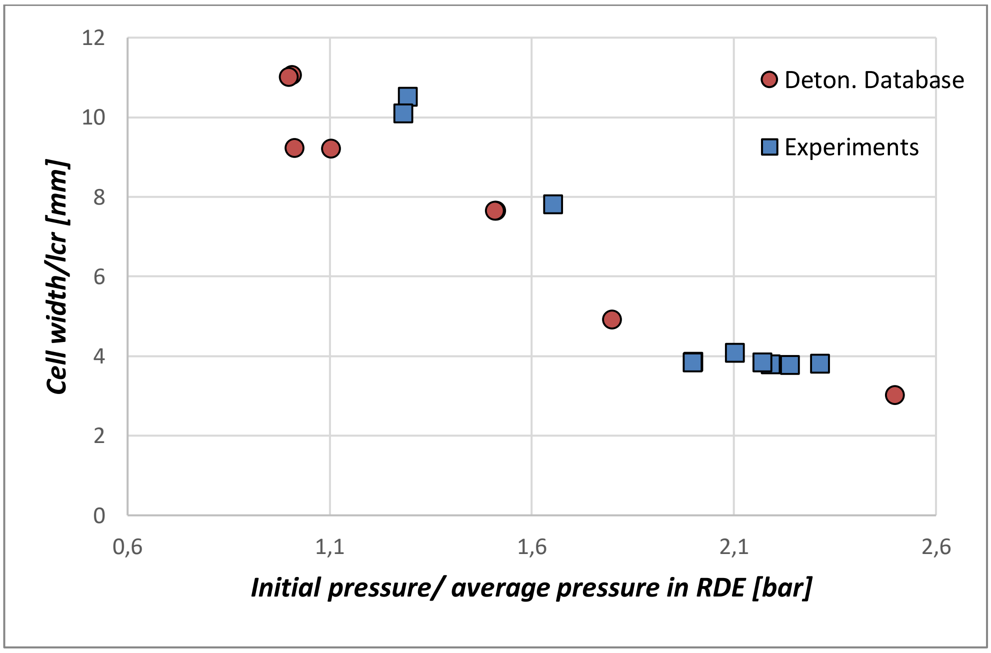


Fig.54. Results of *lcr* received in experiments for H_2-Air mixture, and H_2-Air mixture cell size from Detonation Database [3].

The results show the correlation between detonation cell size and critical length of fresh mixture (*lcr*). Lcr is little bigger than cell size in this same condition. For obtain a specific number of waves, conditions for a particular cell size should be provided.
In the future experiments it is necessary to check the temperature of fresh mixture right next to the injector, for more accurate results of fresh mixture density.

The main conclusions

1. During first part of the project two engines with chamber diameters of 150mm and 200mm were built and tested.
2. Extensive research was carried out for gaseous methane-oxygen mixtures with different initial pressure and mixture composition.
3. It was found that for optimum configuration, 7-8% higher Specific Impulse (Isp) was recorded for detonation combustion as compared to deflagration mode.
4. The best engine performances were for mixture of methane/oxygen of equivalent ratio close to 0.6.
5. For engine configuration with a simple slit nozzle, the Isp reached 1300m/s.
6. Performance improves for larger size engine. Engine with the chamber diameter of 200mm has Isp about 5% higher than the engine with chamber diameter of 150mm.
7. For an unchoked combustion chamber classic detonation combustion was easily achieved.
8. High engine choking and downsizing the height of the combustion chamber caused an increase in the average pressure in the chamber,
9. The protective layer influence signal from the piezoelectric sensors.
10. Combustion chamber with wedged shape
11. Synchronized initiators was not able to control directions waves propagations,
12. Imposing aluminum foil next to initiator allows direction control in 80% of experiments, but is not practical.
13. Solution with Wedge-shaped channel for determine waves direction is non perspective.
14. Introduced channel eccentricity resulted in 100% receptivity of direction of wave propagations
15. The number of waves depends directly on critical length of detonation cell (lc) and rate of mixture supply.
16. Critical length (lc) depends directly on cell size (uniform mixture) under specific conditions.

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List of Publications and any Significant Collaborations that resulted from your AOARD supported project:

In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:
a) papers published in peer-reviewed journals,
b) papers published in peer-reviewed conference proceedings,
Michal Kawalec, Piotr Wolański; Research of the Rocket Engine with Detonation Chamber; 26th International Colloquium on the Dynamics of Explosions and Reactive Systems; July 30, 2017 - August 16, 2017; Boston.

c) papers published in non-peer-reviewed journals and conference proceedings,
Michał Kawalec, Piotr Wolański; Influence of the Mixture Parameters on Performance of Rotating Detonation Rocket Engine; International Constant Volume and Detonation Combustion Workshop – ICVDCW 2017; Poitiers.

d) conference presentations without papers,
e) manuscripts submitted but not yet published, and
f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

Attachments: Publications a), b) and c) listed above if possible.

1. Patent applitation: P.425491 ,,Detonacyjna komora spalania o ustalonlonym kierunku wirowania" [Detonation combustion chamber with settled direction of rotation]

Important Note: If the work has been adequately described in refereed publications, submit an abstract as described above and refer the reader to your above List of Publications for details. If a full report needs to be written, then submission of a final report that is very similar to a full length journal article will be sufficient in most cases. This document may be as long or as short as needed to give a fair account of the work performed during the period of performance. There will be variation depending on the scope of the work.