MOBILITY & VEHICLE MECHANICS

https://doi.org/10.24874/mvm.2023.49.03.01
UDC: 621.43.041.4:662.769.2

INFLUENCE OF HYDROGEN INJECTION AND IGNITION PARAMETERS ON THE COMBUSTION PROCESS IN THE IC ENGINE

Miroslav Petrović [1], Aleksandar Davinić[2], Nadica Stojanović[3], Ivan Grujić[4]*

Received in August 2023 *Revised in September 2023* *Accepted in October 2023*

RESEARCH ARTICLE

ABSTRACT: Given that the trend of using vehicles has been increasing in recent decades, and as oil reserves are limited and environmental requirements are increasing, there is nothing left but to look for alternative solutions as a replacement for oil derivatives. Alternatives are electric vehicles and hybrid vehicles, but internal combustion engines (IC) should not be written off, alternative fuels such as liquefied petroleum gas (LPG) and compressed natural gas (CNG) are used for spark ignition (SI) engines. There is another alternative fuel for IC engines that is still being tested for use in vehicles, and that is hydrogen (H_2). There are still not many published results on hydrogen as a propellant. This paper will present the results of experimental research on the IC engine with hydrogen as a propellant, and the results refer to the parameters of injection and ignition as well as the combustion process, the research was carried out in the Laboratory for IC engines at the Faculty of Engineering, University of Kragujevac.

KEY WORDS: *alternative fuels, hydrogen, internal combustion engine, injection and ignition parameters*

[1]*Miroslav Petrović, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac,Serbia, petrovickg95@gmail.com, -, (*Corresponding author)*
[2]*Aleksandar Davinić, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac,Serbia, davinic@kg.ac.rs, https://orcid.org/0009-0002-0260-3430*
[3]*Nadica Stojanović, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac,Serbia, nadica.stojanovic@kg.ac.rs, https://orcid.org/0000-0002-4199-0587*
[4]*Ivan Grujić, University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34000 Kragujevac, Serbia, ivan.grujic@kg.ac.rs, https://orcid.org/0000-0003-0572-1205*

UTICAJ PARAMETARA UBRIZGAVANJA I PALJENJA VODONIKA NA PROCES SAGOREVANJA U MOTORU SUS

REZIME: S obzirom da se poslednjih decenija trend upotrtebe vozila povećava, a kako su rezerve nafte ograničene i ekološki zahtevi sve veći, ne preostaje ništa drugo nego da se traže alternativna rešenja kao zamena naftnih derivata. Alternativa su električna vozila i hibridna vozila, ali motore sa unutrašnjim sagorevanjem (SUS) nikako ne treba otpisivati, za OTO motore u upotrebi su alternativna goriva kao što su tečni naftni gas (TNG) i komprimovani prirodni gas (KPG). Postoji još jedno alternativno gorivo za motore SUS koje je još uvek u fazi ispitivanja za primenu na vozilima, a to je vodonik (H_2). O vodoniku kao pogonskom gorivu, još uvek nema mnogo objavljenih rezultata. Ovaj rad će prikazati rezultate dobijene eksperimentalnim istraživanjem na motoru SUS sa vodonikom kao pogonskim gorivom, a rezultati se odnose na parameter ubrizgavanja i paljenja kao i process sagorevanja, istraživanja su vršena u Laboratoriji za motore SUS na Fakultetu inženjerskih nauka Univerziteta u Kragujevcu.

KLJUČNE REČI: *alternativna goriva, vodonik, motor SUS, parametri ubrizgavanja i paljenja*

INFLUENCE OF HYDROGEN INJECTION AND IGNITION PARAMETERS ON THE COMBUSTION PROCESS IN THE IC ENGINE

Miroslav Petrovic, Aleksandar Davinic, Nadica Stojanovic, Ivan Grujic

INTRODUCTION

The key process in the IC engine is the combustion process, the output characteristics of the engine depend on it. The area where most work is done when it comes to engine and fuel development is the optimization of the combustion process flow. The main difference between SI and compress ignition (CI) engines is the way the work process is carried out. The difference in the work processes is reflected in: the way the mixture is formed, the way the mixture is ignited and the regulation of the load. The mixture in the SI engine is formed immediately before entering the cylinder, so that the fresh working material is largely homogenized and consists of fuel vapor and air, and when entering the cylinder it mixes with a small amount of residual combustion products. The ignition of the mixture is carried out forcibly by a foreign ignition source at a precisely determined moment, while the regulation of the load is carried out by changing the amount of fresh working material.

In the SI engine, combustion can be divided into three stages, and these three stages are shown in Figure 1.

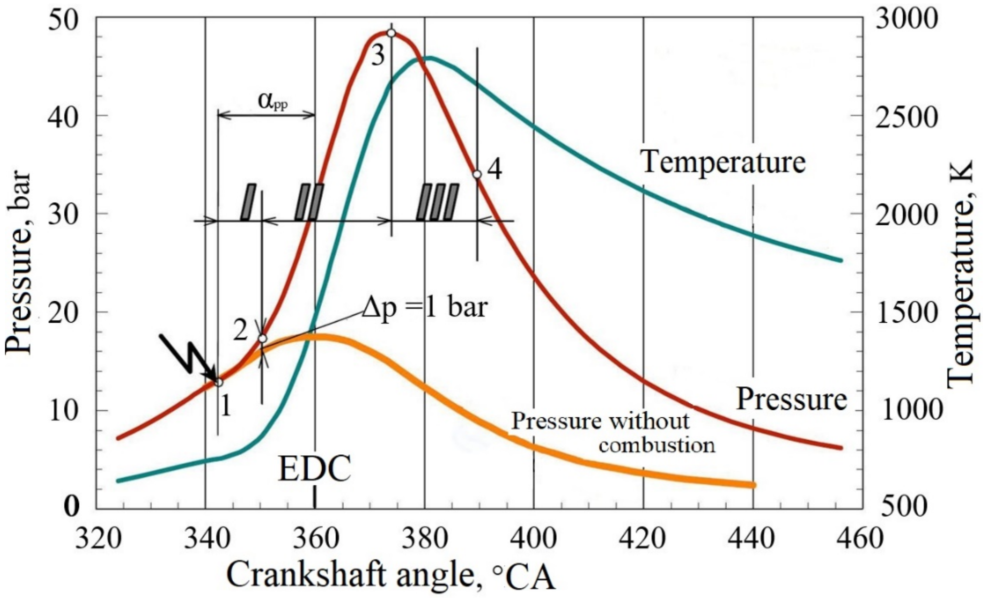


Figure 1. Stages of combustion in SI engines, [1]

The first stage is called the latent combustion period and lasts from the moment the mixture is ignited, by means of a spark between the electrodes of the spark plug, until the pressure increases by 1 bar due to combustion compared to the pressure without combustion. The second stage represents the period of the basic phase of combustion, it lasts until the pressure in the cylinder reaches its maximum value, and during it the turbulent flame has passed the entire volume of the cylinder. The third stage is the burning process.

In the case of CI

engines, the main difference compared to auto engines is reflected in the combustion process, its characteristics are: the operation of the engine with an inhomogeneous mixture, a short time for the formation of the mixture, the combustion process begins before the entire amount of fuel is injected, during one part of the combustion process at the same time both injection and combustion take place. The combustion process in a CI engine is divided into four stages, which is shown in Figure 2.

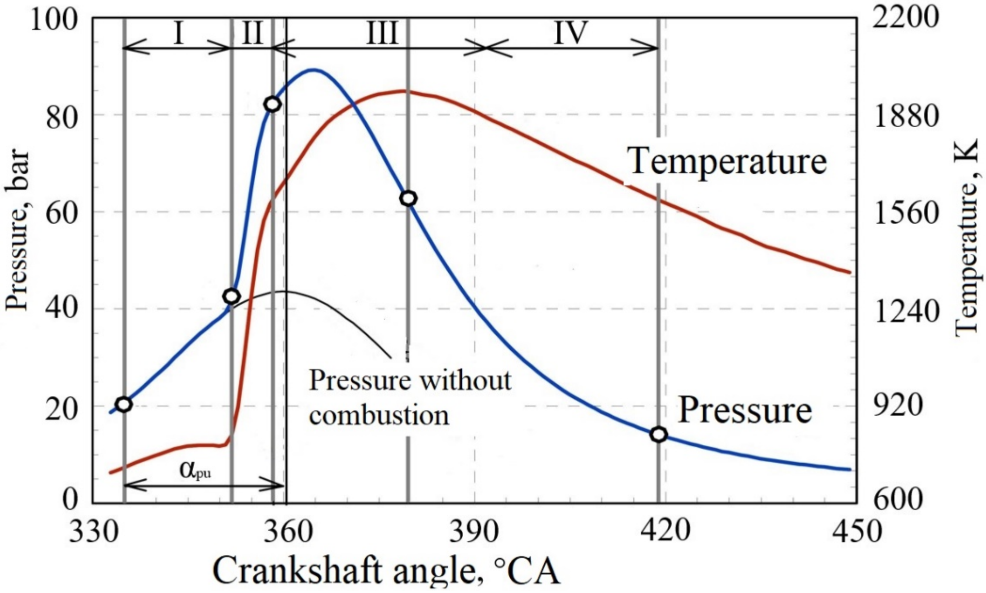


Figure 2. Stages of combustion in CI engines, [1]

The angle of the crankshaft at which the injection starts is called the pre-injection angle, after the start of the injection the physical and chemical preparations for combustion begin, this represents the first stage called the induction period [1]. The second stage consists of a period of uncontrolled combustion, during which rapid combustion occurs, resulting in a large increase in pressure, the tolerance limit for the degree of pressure increase is about 10 bar·$°CA^{-1}$. The third stage is the stage of regulated combustion where the law of heat release is proportional to the law of injection. The last or fourth stage of the combustion process is combustion. In this phase, combustion takes place slowly and this phase is extended to the beat of expansion.

The basic variants of IC engines such as SI and CI engines use fuels of fossil origin, i.e. oil derivatives obtained by refining crude oil. As oil is extracted in large quantities, and its production takes a very long time, it is certain that at some point it will disappear. Combustion of fossil fuels releases combustion products that are harmful to human health and the environment. For this reason, the European Union introduced Euro norms, with the aim of protecting the environment. Given that the requirements for environmental protection are constantly increasing, at some point even the latest Euro standards will not be able to satisfy them. Due to all of the above, alternative solutions are being worked on. There are two types of alternative solutions, alternative drive and alternative fuel. Given that there are a very large number of vehicles in the world with conventional engines, the development of an alternative fuel for use on them stands out as a better solution, and hydrogen stands out as the most promising alternative fuel.

1. OVERVIEW OF RESEARCH IN THE WORLD

Hydrogen is often mentioned as the fuel of the future. There is some research into the application of hydrogen in auto or CI engines. By adding hydrogen, as an additive, in conventional CI engines, harmful emissions of carbon-containing gases are reduced [3], because the chemical composition of hydrogen does not contain carbon. However, due to its high energy, hydrogen raises the maximum temperatures during combustion, which directly affects the increase of nitrogen oxides (NOx) [3, 4], but it can also affect the reduction of nitrogen oxides as follows [5, 6]:

- exhaust gas recirculation (EGR);

- by adding hydrogen as an additive in the amount of 3.9% of the energy value.

In the case of adding 3.9% of hydrogen, a reduction of 5.5% of nitrogen oxides is achieved [6]. Hydrogen-powered internal combustion engines can operate on a very lean mixture thanks to the wide range of flammability and the high flame speed of the hydrogen-air mixture. A lean mixture reduces the emission of nitrogen oxides and increases the efficiency of the engine. Therefore, the hydrogen engine can operate without or with low damping, which reduces pumping losses and increases efficiency. The first research into the use of hydrogen as a fuel for IC engines indicates that hydrogen is a much better fuel for auto engines. The reason for this is the high self-ignition temperature, which is around 848 K [7]. Using hydrogen as an additive, but in this case with a gasoline engine, also achieves a reduction of toxic components that have carbon in their composition [8]. However, gasoline engines can very easily be modified to run with hydrogen as the only fuel injected into the intake manifold. The biggest problem is the possibility of the flame returning due to the formation of explosive gas (HHO), which ignites very easily. Comparing the performance of the engine when hydrogen or ethanol are added as an additive to gasoline is very difficult [9]. In order to achieve similar or better results with some of the fuels, different pre-ignition angle settings are needed, as well as an accurate calculation of the mixture composition coefficient for the corresponding fuel. Adjusting the preignition angle is critical because of the different burning rates from fuel to fuel.

S. Zanforlin and S. Frigo [10], as part of their research, realized an experimental engine for working with hydrogen as the only fuel. The experimental engine was realized with an unconventional system of two-stage direct injection of hydrogen into the engine cylinder with a low pressure of 6 bar. The system is based on the concept of hydrogen dosing in an intermediate chamber that is separate from the hydrogen inlet valve to the engine. Dosing hydrogen into the intermediate chamber is provided by an electric injector, which can be kept open during the entire engine cycle, so a commercial electric injector for CPG can deliver the required amount of hydrogen even at low pressure. Dosing into the cylinder is done by mechanically starting the injection valve, which, thanks to the sufficient flow section, can be opened for a short time. The injection of hydrogen into the cylinder starts when the intake valves are closed to avoid back-ignition. The layout of the experimental engine from this research is given in Figure 3.

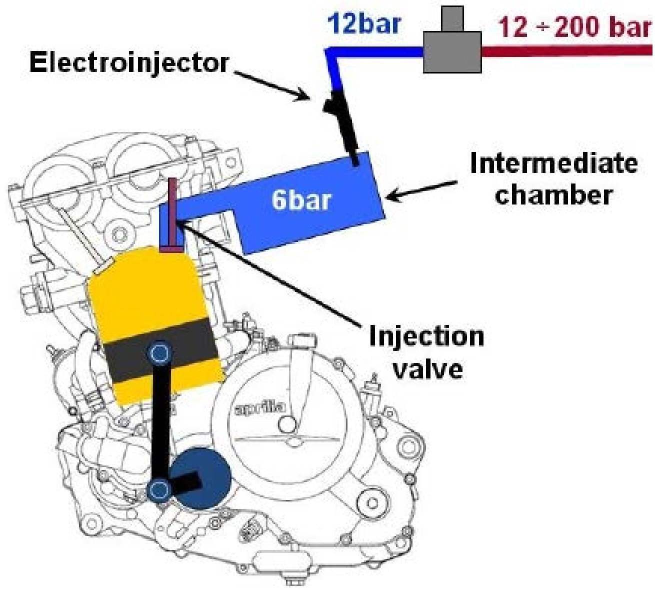


Figure 3. Experimental engine with two-stage direct hydrogen injection, [10]

In short, it can be said that the solution, the sketch of which is shown in Figure 3, combines a system characterized by a constant hydrogen flow rate and a variable opening duration (the first step - an electric injector) with a system characterized by a variable hydrogen flow and a constant angular duration (the second step is a valve for engine injection). The essence of the system is that there are always equalized gas flows through the electric valve and through the mechanical injection valve on the engine, which is controlled by the electric injector. In addition to reducing exhaust emissions, hydrogen is considered an interesting fuel from another aspect. Namely, it is known that hydrogen has a significantly higher burning speed compared to other fuels. Therefore, it is considered that the combustion speed will contribute to the combustion at an almost constant volume, thus increasing the efficiency [11, 12]. However, the high speed of combustion is accompanied by a large increase in pressure, as well as an increase in temperature, which, in addition to the mechanical load, also causes an increase in the emission of nitrogen oxides. By adding a small amount of hydrogen to conventional fuels, emissions are improved [13], but more serious changes in emissions require larger amounts or complete replacement of conventional fuel with hydrogen. This approach often causes a significant increase in nitrogen oxides at the expense of the reduction of other harmful components, as well as the occurrence of detonating combustion. In some research, the injection of water along with hydrogen was considered in order to reduce the combustion speed and thus the emission of nitrogen oxides. It was established that adding water reduces the concentration of nitrogen oxides and detonations do not occur, but this approach is also limited as it has a bad effect on the indicator level of usefulness [14-16]. In addition to water, the concentration of nitrogen oxides in an engine where hydrogen has been used as an additive can be reduced by adding water vapor. By using 30% of hydrogen as fuel, from the total volume of fuel, in CI engines and adding 20% of water vapor, the concentration of nitrogen oxides in relation to when using conventional fuel decreases by 22.1%, and the effective power increases by 22.8% [17].

2. EXPERIMENTAL RESEARCH

A successful engine start was achieved with an injection time of 12ms, by dividing the injection into two portions, the injection start of 30% of the total injection time was set at 344°CA, during intake, and the remaining 70% of the total injection was set at 30°CA before EDC. With this type of injection, a large pressure drop occurred when the engine was started, but with an increase in the number of revolutions, the operation of the engine became more stable. The engine is started with an active decompressor until the first signs of combustion appear, otherwise there will be premature ignition and rotation of the engine direction. To avoid this phenomenon during tarting, an electric starter with a higher starting speed should be used.

2.1 Examination of the method of hydrogen injection

After successfully starting the engine, it was concluded that the engine could fully operate without damping. A certain instability, i.e. lack of ignition, was also observed. During operation, a metallic sound was registered, which appeared every time there was a misfire. The metallic sound was found to be coming from the 200 L silencer tank, which is used to allow airflow measurement. It was discovered that there is actually an explosion in the intake line that echoes in the choke tank. The explosions were caused by HHO gas - explosive gas. The explosion in the suction system was caused by the appearance of a pressure wave that prevented suction and the absence of ignition and combustion. The absence of combustion causes a drop in the number of revolutions and the inability to maintain the regime. As the explosions occurred in the intake manifold, they were caused by the portion of fuel injected during intake. By moving this portion of fuel from the suction to the compression stroke, when both valves are closed, this phenomenon completely disappears, and ensures regular engine operation.

The start of the first injection is set at 200°CA before EDC, and the start of injection of the second part of the fuel is set at 30°CA before EDC. The total injection time and ignition timing are the same, only the injected fuel portions are varied, Figure 4.

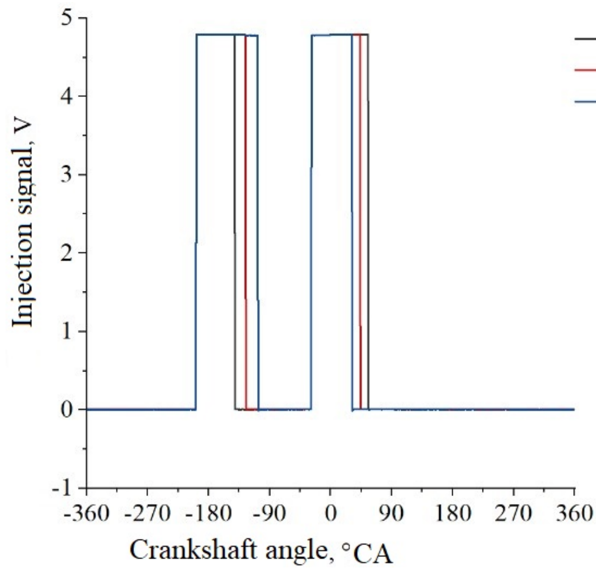


Figure 4. Injection trigger signals for measurements with varying portions of injected fuel

For the first injection method, it is defined that the signal for the first injection lasts 40% and for the second injection 60% of the total injection time. Then, these values were moved to 50% - 50%, and after that to 60% - 40%. During the test, a constant regime was not maintained, but only the influence, redistribution of injection portions was monitored. The headspace pressure for all three measurements is given in Figure 5, and the results in Table 1.

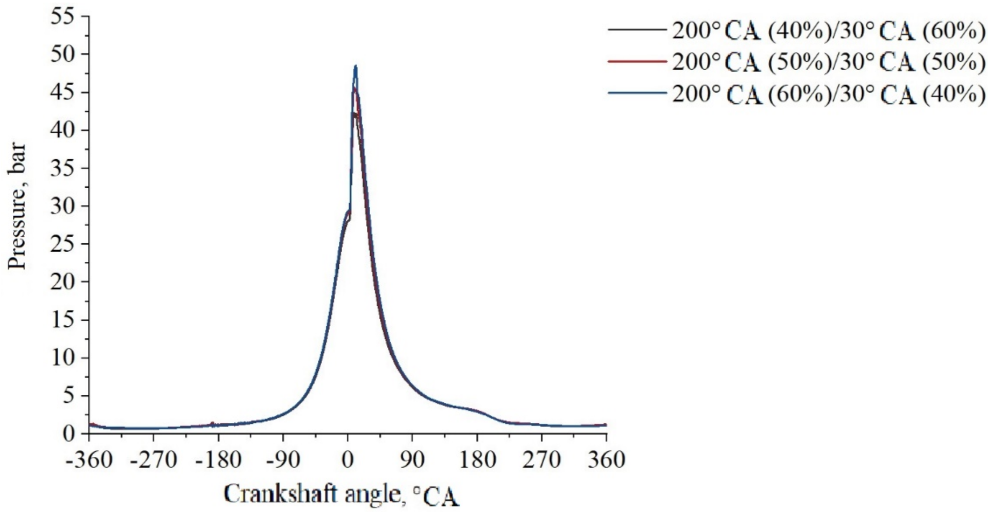


Figure 5. Pressure in the main space for measurements with varying portions of injected fuel

Table 1. Results obtained for measurements with varying portions of injected fuel

Measurements / Results	200°CA (40%) 30°CA (60%)	200°CA (50%) 30°CA (50%)	200°CA (60%) 30°CA (40%)
n , min^{-1}	1963	2015	2102
p_{mi} , bar	4,98	5,33	5,67
η_i ,	0,29	0,31	0,34
$p_{\max}$, bar	43,97	48,15	51,19
$\alpha_{p_{\max}}$, °CA	8,96	8,50	9,32
$dp/d\alpha$, bar·°CA^{-1}	6,91	8,66	9,06
$AI05$, °CA	2,56	2,50	2,56
$AI10$, °CA	3,37	3,23	3,28
$AI50$, °CA	8,60	7,53	7,11
$AI90$, °CA	65,14	60,41	54,62

Labels from the table represent:

- n - number of rotations per minute,
- p_{mi} - mean indicator pressure,
- η_i - indicator degree of usefulness,
- $p_{\max}$ - maximum pressure value
- $\alpha_{p_{\max}}$ - the position of the maximum pressure value,
- $dp/d\alpha$ - the maximum value of the degree of pressure rise.

Looking at figure 5, it is clearly seen that varying the portions has an effect on the engine duty cycle. With the injection of a larger amount of fuel in the first part of the injection, the maximum pressures in the main compartment increase, as well as the specific indicator work and the indicator degree of usefulness. The differential combustion law for all three modes is shown in Figure 6. With the increase in the amount of fuel injected in the first part of the injection, there is an increase in the maximum value of the heat release rate. The combustion itself is extremely fast, which was to be expected for working with hydrogen, despite the fact that in all three cases the engine worked with a globally lean mixture, with a mixture composition coefficient over 2.

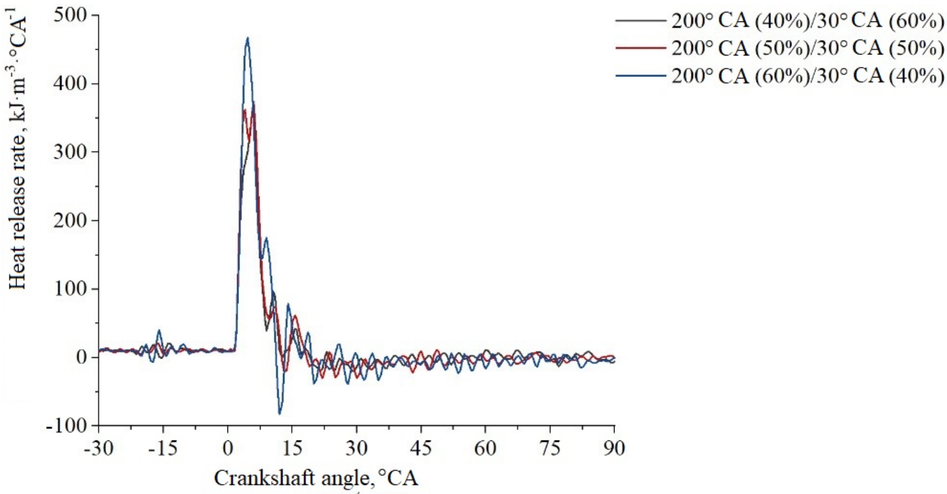


Figure 6. Differential combustion law for regimes with varying portions of injected fuel

2.2 Examination of the hydrogen combustion process

This test was performed on a constant mode defined by the number of revolutions 1570min^{-1} and the load 0.28 kJ·dm^{-3}. This mode did not require a large cycle amount of fuel, which is important both because of the capacity of the injector and because of the limited amount of fuel. At the beginning, it was decided that the injection should be done in two parts. The distribution was adopted such that the injection in each part lasts for 50% of the total injection time. For this test, a constant start of the injection of the first amount at 200°CA before EDC was adopted, which was set as fixed, while the moment of the second injection was varied, shown in Figure 7. Three variants were chosen for the start of the second injection, where two are during compression, and in the third case, the injection starts during the expansion stroke. In all three cases, the portions per injection are divided into 50% of the total injection time.

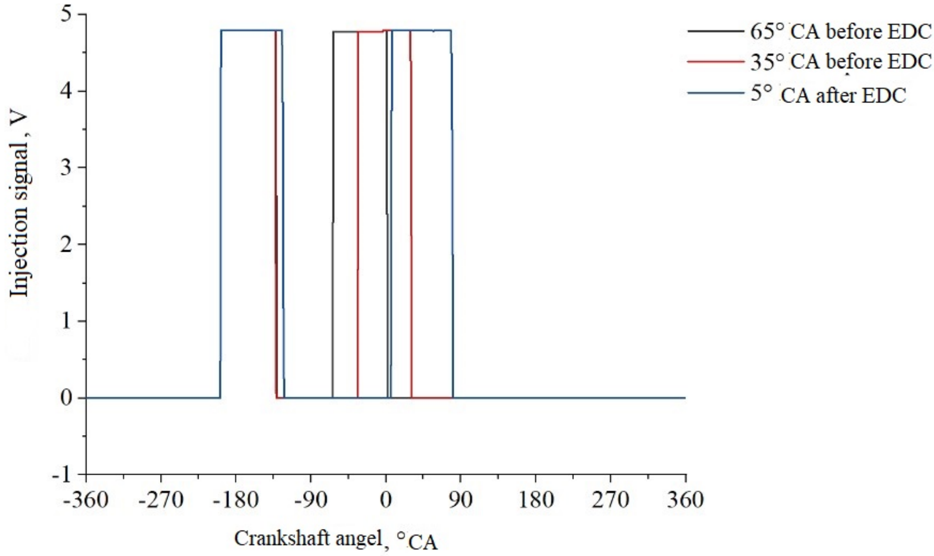


Figure 7. Injection trigger signal for the first three modes

In the research from the previous part, it was shown that the method of injection is an influential parameter, so to maintain a constant mode, the total injection time was changed. The results obtained with this type of injection are shown in Figure 8 and Table 2. It can be seen that with earlier injection, a more violent combustion is achieved, because a larger amount of mixture is successfully formed. This entails higher values of pressures in the main space, as well as higher values of the maximum degree of pressure rise. As for the second portion that occurs during combustion and expansion, its displacement in the direction of expansion has a negative effect on efficiency. The goal was to adopt the best ranking of these three modes based on the results, the first mode can be considered the best, but due to the high degree of pressure increase and the small difference in the indicator level of usefulness between the first and second modes, the second mode was selected for further tests.

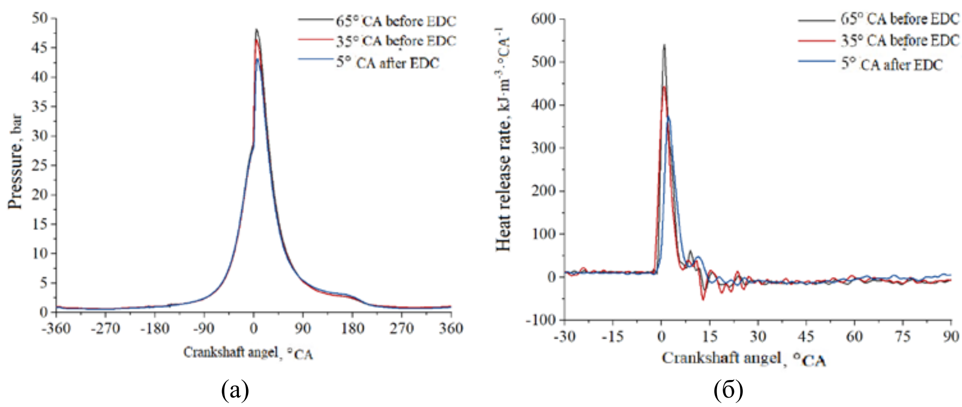


Figure 8. Headspace pressure (a) and differential combustion law (b) for varying the start of injection of the second portion of fuel

Table 2. Results obtained on the regime for varying the start of injection of the second portion of fuel

Measurements / Results	65°CA before EDC	35°CA before EDC	5°CA before EDC
n, min^{-1}	1581	1562	1561
p_{mi}, bar	5,08	4,77	4,69
η_i,	0,32	0,31	0,27
$p_{\max}$, bar	51,11	48,12	44,29
$\alpha_{p_{\max}}$, °CA	5,82	5,62	6,56
$dp/d\alpha$, bar·°CA^{-1}	10,19	7,94	6,48
$AI05$, °CA	-0,87	-1,48	0,87
$AI10$, °CA	-0,23	-0,77	1,69
$AI50$, °CA	2,37	2,23	5,77
$AI90$, °CA	33,02	45,67	62,55

The next step of the research was to vary the portions per injection. For the adopted injection method (start of injection of the first portion at 200° KV before SMT, and start of injection of the second portion at 35° KV before SMT), shown in Figure 9.

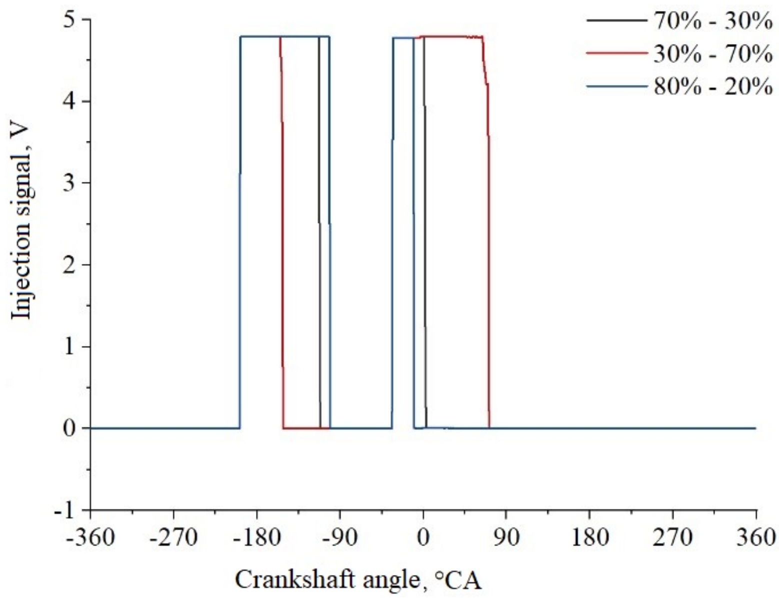
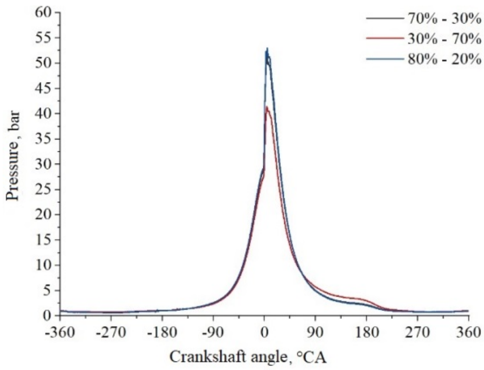


Figure 9. Injection signal for varying the portions of injected fuel

As in the previous case, keeping the regime stable was achieved by redistributing the injection time for the same total injection time. The results obtained with the injection method shown in Figure 9 can be seen in Figure 10 and in Table 3. Injection of a large portion close to the EDC resulted in combustion during the expansion stroke. Since one part of the injection entered the expansion stroke, combustion was caused during the expansion, which is also proven by the angle to which 90% of the cycle fuel was burned. This type of injection led to a decrease in the indicator level of usefulness, and therefore it can be considered that this principle is not favorable from the aspect of efficiency. The other two injection principles, with larger injection portions at the beginning, gave relatively similar results. There was a very short burn in both cases, with the shortest burn recorded at the largest portion of the first injection.



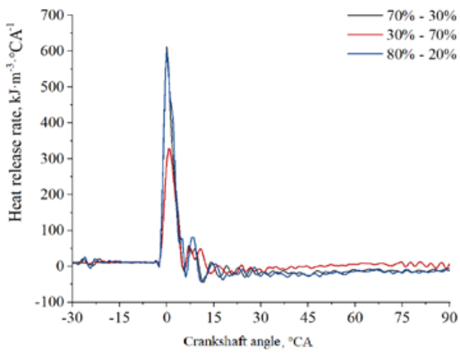


Figure 10. Headspace pressure (a) and differential combustion law (b) for varying fuel injection portions

Table 3. Results obtained on the regime for varying the start of injection of the second portion of fuel

Measurements / Results	70% - 30%	30% - 70%	80% - 20%
n, min^{-1}	1567	1567	1572
p_{mi}, bar	4,77	4,58	4,78
η_i,	0,32	0,25	0,33
p_{max}, bar	53,52	46,62	55,08
$\alpha_{p_{max}}$, °CA	4,52	4,48	4,34
$dp/d\alpha$, bar·°CA^{-1}	11,20	6,80	11,21
$AI05$, °CA	-1,70	-0,52	-1,68
$AI10$, °CA	-1,10	-0,56	-1,10
$AI50$, °CA	1,03	8,80	0,99
$AI90$, °CA	16,93	71,17	8,80

It should be noted that the injection pressure for all shown modes was 100 bar. After the cylinder pressure drop, modes with lower injection pressures were tested, and the injection was successfully moved deeper into the intake stroke. Unfortunately, at lower injection pressures, the cycle amount of fuel also decreases for the same time the injectors are open, and it is not possible to achieve regimes with a higher load. For future research, the possibility of applying the antechamber, especially for working with hydrogen, should not be neglected. However, you need to find a more adequate injector with a larger capacity, which will certainly provide greater engine operation possibilities with this fuel.

3. CONCLUSION

As the need for vehicles is constantly growing, and the requirements for environmental protection are also growing, engineers are under constant temptation to find the best possible solution. Alternative solutions have been developed in the form of alternative drives and alternative fuels. The alternative fuel with the most potential is certainly hydrogen. With hydrogen as a fuel, IC engines can work efficiently with negligible emissions of harmful combustion products, which will surely play a key role in the application of this fuel on vehicles with IC engines.

Experimental studies of engine operation with hydrogen as the only fuel were carried out, injection methods were considered and the combustion process was monitored. It was found that the injection parameters significantly affect the combustion process, and therefore also the operation of the engine. Early hydrogen injection can achieve the best engine performance, although this can lead to unstable operation and excessive mechanical loads on the engine itself, while injection during combustion is not recommended. Injection during combustion does not allow enough time for the mixture to form, which causes stretched combustion and low efficiency. The best solution is injection in two occasions, the first part should be injected during the compression cycle, and the second part around the EDC, injection should be done so that the first portion is significantly larger than the second. This type of injection leads to the enrichment of the mixture at the right moment and slows down combustion..

REFERENCES

[1] Pešić R., Petković S., Veinović S., Motorna vozila i motori oprema, Mašinski fakultet u Kragujevcu, Mašinski fakultet u Banjoj Luci, Kragujevac, Banja Luka, 2008.

[2] Davinić A., Pešić R., Pogonski sistemi u transportu, Fakultet inženjerskih nauka Univerziteta u Kragujevcu, Kragujevac, 2018.

[3] Pavlos D., Taku T., A review of hydrogen as a compression ignition engine fuel; vol. 42, no. 38, International Journal of Hydrogen Energy, 2017

[4] Saravanan N., Nagarajan G., Sanjay G., Dhanasekaran C., Kalaiselvan K.M., Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode. vol. 87, no. 17-18, Fuel, 2008

[5] TsolakisJ A., Hernandez J., Megaritis A., Crampton M., Dual Fuel Diesel Engine Operation Using H2. Effect on Particulate Emissions, vol. 19, no. 2, Energy & Fuels, 2005

[6] Pana C., Negurescu N., Cernat A., Nutu C., Mirica I., Fuiorescu D., Experimental aspects of the hydrogen use at diesel engine, vol. 181, Procedia Engineering, 2017

[7] Das L.M., Hydrogen-Oxygen Reaction Mechanism and its Implication to Hydrogen Engine Combustion, vol. 21, no. 8, International Journal of Hydrogen Energy, 1996

[8] Srinivasana C.B., Subramanian R., Hydrogen as a spark ignition engine fuel technical review., vol. 14, no. 5, International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS, 2014

[9] Soria A.H.H., Jiménez R.F.E., Morales J.G., Gómez-Aguilar J.F., Pliego T.E.H., Peregrino V.H.O., Theoretical Analysis of the Power of a Spark Ignition Internal Combustion Engine With Different Fuel Blends. The International Conference on Innovative Applied Energy (IAPE'19), 14th-15th March, Oxford, United Kingdom, 2019

[10] Zanforlin S., Frigo S., Implementation of a novel hydrogen direct-injection concept in single and multi-cylinder engines: CFD, experimental and engine powertrain design studies, vol. 3, no. 1, International Journal of Powertrains, 2014

[11] Saravanan N., Nagarajan G., An experimental investigation of hydrogen-enriched airinduction in a diesel engine system, vol. 33, no. 6 International Journal of Hydrogen Energy, 2008

[12] Boretti A., Advances in hydrogen compression ignition internal combustion engines, vol. 36, no. 19, International Journal of Hydrogen Energy, 2011

[13] Tauzia X., Maiboom A., Shah S.R., Experimental study of inlet manifold water injection on combustion andemissions of an automotive direct injection Diesel engine, vol. 35, no. 9, Energy, (2010)

[14] Subramanian K.A., A comparison of water–diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions, vol. 52, no. 2, Energy Conversion and Management, 2011

[15] Ghazal O.H., Combustion analysis of hydrogen-diesel dual fuel engine with water injection technique, vol. 13, Case Studies in Thermal Engineering, 2019

[16] Adnan R., Masjuki H.H., Mahlia T.M.I., Performance and emission analysis of hydrogen fueled compression ignition engine with variable water injection timing, vol. 43, no. 1, Energy, 2012

[17] Gonca G., Sahin B., Simulation of performance and nitrogen oxide formation of a hydrogen-enriched diesel engine with the steam injection method, vol. 19, no. 6, Thermal Science, 2015