THE INFLUENCE OF THE HYDROGEN INJECTION TIMING ON THE INTERNAL COMBUSTION ENGINE WORKING CYCLE

by

Ivan Lj. GRUJIĆ [a], ***Jovan Ž. DORIĆ*** [b], ***Oday I. ABDULLAH*** [c,d], ***Nadica R. STOJANOVIĆ*** [a*], ***and Aleksandar Lj. DAVINIĆ*** [a]

[a] Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia
[b] Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia
[c] Department of Energy Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
[d] Hamburg University of Technology, Hamburg, Germany

Original scientific paper
https://doi.org/10.2298/TSCI190816346G

From an ecological aspect, the hydrogen has all properties to be a very good fuel for internal combustion engines. However the high combustion speed, as well as the possibility of backfire, is inconvenient properties of port injection. In this paper, the influence of the injection timing on the internal combustion engine working cycle parameters (pressure and temperature) was investigated deeply. The investigation, of the injection timing influence on the internal combustion engine working cycle parameters, was performed numerically by application of ANSYS software. It was observed the geometry of the real engine with added pre chamber, in order of layer mixture formation and pressure damping, because of high combustion speed. The results are presented for four cases with different injection timing and the same spark timing. By earlier injection, the time for mixing rise as well as the possibility of homogenization and uniform mixture creation, in pre chamber and cylinder. This claim it is confirmed on the basis of obtaining pressure and pressure rise gradient, which are growing with earlier injection, because of hydrogen combustion characteristics in stoichiometric mixture. The higher pressures as well as the surface under the diagram are positive from the aspect of the engine efficiency. However, with the earlier injection, the values of the pressure rise gradient are higher than for the classic Diesel engine. This means that this phenomena can cause brutal engine work from the aspect of mechanical stresses. However the value of the maximum pressure is smaller than this in a Diesel engine, this is due to added pre chamber, which has decreased the compression ratio.

Key words: *hydrogen, pressure, injection timing, internal combustion engine, ANSYS, pre chamber, pressure rise gradient*

Introduction

By returning to the beginning of vehicles production, it can be seen that the first vehicles were produced as electric. However, over the time, the electric drive train was replaced with the internal combustion (IC) engines, which are far better engines from the aspect of the performances. But it is a fact that electric vehicles are currently considered as the future in the automotive industry. However, for now the IC engine is still the drive train for almost all mobile systems. The reason for this is simplicity of construction that has been improved during the

[*] Corresponding author, e-mail: nadica.stojanovic@kg.ac.rs

decades in the past. Also, the crucial point is the production price, which is far lower than what is needed to produce the electric drive train. Besides the mentioned problems, there are other obstacles for electric vehicles, for example, from the beginning of their manufacturing, the major problem was the driving radius. The main problem is the capacity of batteries, more accurate in the energy that can be stored in batteries. On first look, the hybrid vehicle can overcome this problem, because it has an IC engine as help for batteries charging. However, it should be taken into the consideration the performances of hybrid vehicles, as well as that hybrid vehicle have two drive trains for maintaining, which increase the costs. The costs of the maintaining of the electric part of the drive train and IC engine are requiring to drive at least 50000 km per year, in order to pay off such vehicle [1].

The other aspect that should be observed, the influence of drive trains on the environment. At first glance, the electric vehicle seems like something clean, which not pollutes the environment. However, it should think about, what is the source to produce the electric energy that is necessary to charge the batteries. It is a well-known fact that power plants have a negative influence on the environment, so the application of electric vehicles is just the dislocation of the pollution. Besides that, rarely which country will have enough production of electric energy for charging, when all vehicles will be replaced with electric [2].

The country with the most electric vehicles is the Norway [3]. However, it should not forget that the Norway is leading in the world with production of the electric energy from the hydro and wind power [4]. By that it can be said that electric vehicles in Norway really represented the practical solution and clean replacement for vehicles that use IC engines.

By analyzing mentioned facts, the IC engine still represents the best variant. However, the major problem is not the engine, but the oil that is used for fuel production, and which is exploited in huge amounts. It is a well-known fact that the oil formation is necessary and it is takes very long period. Because of this reason, there exist information, the oil will disappear in next 50 years. But also expectations were the same before 50 years. However, one is for sure, the oil will disappear. When, nobody knows for sure, because every day technology progress allows further exploitation, but this result with jumps in oil price [5].

The oil price as well as the possibility of the oil disappearing, represents the problem for IC engines sustainability. Because of this it should think about some alternatives.

The alternative that does not include the electric vehicles is the usage of some new fuel, which can be convenient fuel for IC engine. One of the alternative fuels that can be taken into the consideration is the hydrogen. The hydrogen represents gaseous fuel, and as such is very convenient from the aspect of mixing, as well as for winter conditions, because there is not exist necessity for the vaporization. As well the good advantage of the hydrogen usage can be the ecology.

The essential point for automotive engineers that work in the IC engines field is the ecology issue. The most importance is given to the CO, CO_2, NO_x, and unburned HC. In three of these four components there is carbon. Carbon is a component that can be found in almost all fuels, gasoline, diesel, LPG, methane, but not in hydrogen. Hydrogen as substance, in its chemical composition does not have carbon, which means that all components that have carbon can be reduced to the minimum value. The only carbon components can be found from oil that is used for lubrication.

This paper will be dedicated to modify the IC engine to work with the hydrogen. It will be considered the influence of the injection timing on the working cycle, and this investigation will be performed numerically. The engine that is considered is basically the experimental a Diesel engine that is already modified as multi-process, which means that is can work as diesel, and as a gasoline engine.

The Diesel engines are considered as one of the greatest polluters, their sustainability is endangered [6]. Pavlos and Taku [6] considered, which effect will be accomplished by using the hydrogen as additive at the conventional Diesel engine. They concluded that the hydrogen as substance without carbon will effect on reduction on all components that consists carbon. However, the hydrogen has high energy, and the maximum temperatures that will occur during the combustion process are higher. As a result of this phenomenon, the concentration of NO_x will be raised, which are one of the biggest problems for cars with Diesel engines. As the solution for this problem, it was mentioned that the possibility of use exhaust gas re-circulation (EGR) in order to reduce the combustion speed and maximum temperature as well. The same conclusions can be found in the research of Saravanan *et al.* [7]. More accurately, they have also found that if the hydrogen is used as additive, all carbon will be reduced, and of course the concentration of the NO_x will rise. They have performed their research on the naturally aspirated Diesel engine, where the hydrogen is injected into the intake port. The similar research is performed by Tsolakis *et al.* [8]. The interesting fact from this research paper and previous one is that by adding a minor amount of the hydrogen, it can be accomplished the reduction of NO*x* and particulate matters (PM). However, with increasing the amount of hydrogen, the concentrations of those two-components rise too. The significant reduction of PM and 5.5% NO_x was noticed by Pana *et al.* [9]. They performed their work using the truck Diesel engine. It was accomplished the reduction of the 5.5% NO_x by using the 3.9% of hydrogen. The 3.9% of hydrogen represented the percentage of the entire energy value that has been imported into the engine cycle, trough diesel and hydrogen. Also, Miyamoto *et al.* [10] accomplished the reduction of the NO_x by applying the EGR. This was earlier mentioned as the possibility by Pavlos and Taku [6]. There are other researchers studied the problem from a different point of view, Christodoulou and Megaritis [11]. Besides hydrogen, they have also used nitrogen as additive. The amount of those two gases was from 2-8 vol.%. The use of hydrogen was given the results as previous researches, while by usage of the nitrogen, the concentration of the PM increased, while NO_x is reduced.

One of the oldest research's in the subject of the hydrogen usage is performed by Das [12], where he stated that the hydrogen is a better fuel for gasoline engines, because of the auto ignition temperature, that is around 848 K. The technical analysis of the hydrogen usage for the gasoline engine is has been performed by Srinivasana and Subramanian [13]. The similar as for the Diesel engine, they concluded that by adding the hydrogen as the additive it can be accomplished the reduction of toxic components. Also, the gasoline engine can be easy modified for the work with the hydrogen. One of the biggest problems with port injection is the possibility of backfire, because of possible formation of HHO that can be autoignited very easily. Zhenzhong *et al.* [14] investigated the possibility of hydrogen usage based on the numerical analysis. Analysis has been performed for gasoline engine with port injection. The types of injections are tested, with one and with two injectors in the intake port, which are separated one from another in the direction of the intake port axis. They concluded that better characteristics, from aspect of mixture homogenization and indicating power, can be achieved by using the two injectors. Soria *et al.* [15] made comparison between the hydrogen and ethanol in mixture with gasoline. They concluded that in order to obtain better results in the performances, it is necessary to set-up the spark timing and air fuel ratio in dependence from fuel mixture. The spark timing is crucial because those fuels have great differences in combustion speeds.

Based on the available literature, it can be concluded, that the main purpose of the hydrogen usage for Diesel engines, is to reduce the toxic components in the exhaust gasses. There are not too many researchers that have investigated the application of the hydrogen in Diesel engines, from the aspect of the engine working cycle. However, the application and the analysis of the characteristics have been performed for gasoline engines, because they considered the better solution when used the hydrogen.

In this paper, numerical analysis was achieved of the engine working cycle. As the fuel that will be used only is hydrogen. The aim of this analysis is to investigate the influence of injection timing on the engine working cycle. Also the analysis that is presented in the paper represents the investigation before the experiment on the real engine. It was made the development on real experimental multi-process engine. Based on the development, it was manufactured pre chamber, which by overall dimensions corresponds to the engine injector. This pre chamber should minimize problems that can occur due to hydrogen combustion speed. More accurately, the pre chamber should have damping effect. Furthermore, it was performed deep analysis for a stoichiometric mixture of the hydrogen and air. Also by injection the pre chamber, the possibility of backfire is excluded.

The 3-D model

Numerical analyses represent the modern replacement for mathematical models and calculations that were often used earlier, during the development of new or improvement of existing products. One of their advantages is a visualization of the simulated process, as well as the reduced time for obtaining results. Therefore, the numerical analyses are widely accepted in the scientific researches, as well as in all engineering fields of industry. The first step before starting with the numerical analyses, it should develop the 3-D model that corresponds to the specific product. For this paper, it is chosen the experimental IC engine, which is by origin Diesel engine, but, which is modified as multi-process. The multi-process engine is developed, that can work as diesel and as well as a gasoline engine. Also exist the possibility of using the alcohol fuels, as well LPG. It will be used the 3-D model to achieve the numerical analysis, which corresponds to the multi-process engine in gasoline mode, with an added pre chamber for operating with hydrogen as shown in fig. 1.

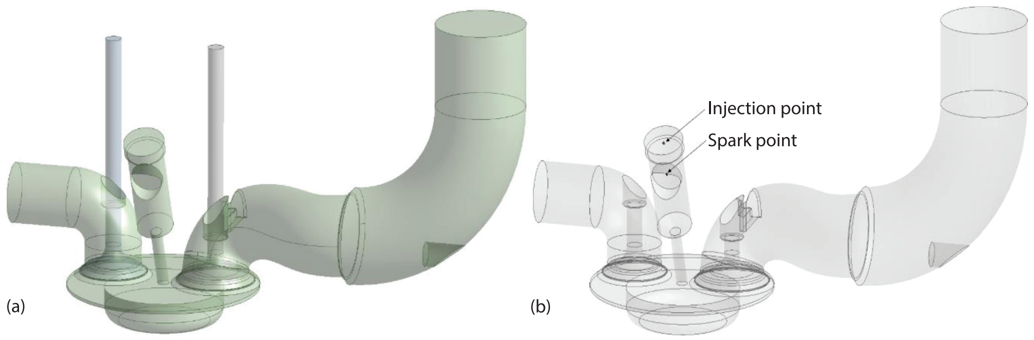


Figure 1. (a) The 3-D model and (b) the 3-D model prepared for FLUENT

The added pre chamber by overall dimensions corresponds to the diesel injector, so the mounting is the same as for diesel injector of the existing engine. Earlier it was mentioned that geometry is corresponds to the multi-process engine. In order to work as a gasoline engine, in the intake port exists place for gasoline injector, which can be seen in the fig. 1. This is included in developed 3-D model to get the same geometry as experimental engine. It is very important to include such modifications, because of air-flow in the intake port, which direct influence on the cylinder charge. Also, it can be seen in this figure the inside look of the pre chamber. The pre chamber consists the place for the spark plug as well as for the gasoline direct injection (GDI) injector. The seat of the injector is not included in the geometry, because it is not a part of the working space. With added pre chamber, the compression volume of the engine will be bigger, which means that have changes in geometrical characteristics of the engine. The geometrical characteristics of the IC engine with the added pre chamber are given in tab. 1.

After developing the 3-D model for FLUENT, it is necessary to select the suitable mesh for the model. The selected type of the element is tetrahedron, fig. 2.

Table 1. Geometrical characteristics of the modified IC engine

Name	Value
Bore, [mm]	85
Stroke, [mm]	80
Connection rod length, [mm]	145
Compression ratio	10.3
Stroke volume, [mm^3]	454000
Compression volume, [mm]	49000

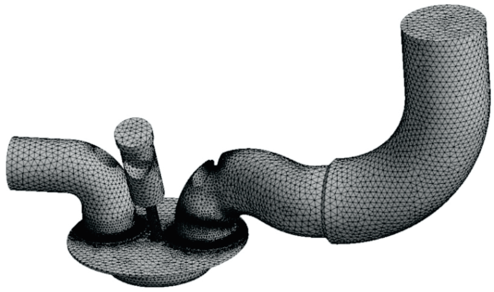


Figure 2. The mesh of IC engine

The reason select this type of element is the best selection of the complex shapes of the intake port and valve seats. The number of elements is 467635, and the number of nodes is 95881.

Boundary conditions

In this section, the boundary conditions will define based on the experimental data that are obtained from the experimental multi-process engine in gasoline mode [16], where the experiment was performed according to the Europe stationary cycle, which consist 13 modes. For boundary conditions, it was chosen the mode 10. This is the most rigorous mode that is performed during the experiment, more accurate the mode at the highest engine speed and the highest engine load. The boundary conditions that are used for the numerical analysis are given in tab. 2.

Table 2. Boundary conditions

Name	Value
Engine speed, [rpm]	2692
Air/fuel ratio, [–]	1
Intake port temperature, [K]	312
Ambient temperature, [K]	304
Ambient pressure, [bar]	0.994

Of course it is necessary to take into the consideration, that the lower calorific value of the hydrogen is different from the lower calorific value of the gasoline. For stoichiometric mixture of 1 kg of the gasoline, it will need 14.7 kg of air. When hydrogen is used, this is will be a little bit different. The amount of the hydrogen in the stoichiometric mixture with air is 29.53%vol. [17]. The mass amount of hydrogen can be calculated [18, 19]:

$$pV = m\mathrm{R}T \tag{1}$$

By applying the eq. (1) on the hydrogen and the air, the mass ratio between the hydrogen and the air was found 33.6. More accurate for the stoichiometric mixture of 1 kg of hydrogen, it is necessary needs 33.6 kg of air. By comparison, between the hydrogen and the gasoline, it can be seen that the amount of the air for the hydrogen is much higher than for the gasoline.

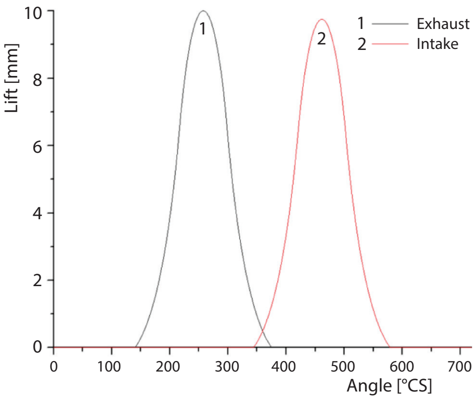


Figure 3. Valve lift profile

The reason for this is the great difference in lower calorific value, which has value for the gasoline around 44850 kJ/kg, and for the hydrogen around 120080 kJ/kg.

For last input data, it is necessary to get the valve lift profile. The valve lift profile is very important, because it contains the direct influence on air-flowing into the cylinder, and by that on cylinder charge. So, it can be said, that the exact and correct valve lift profile is necessary for most accurate results. The valve lift profile is given in fig. 3.

The geometrical characteristics of valve mechanism are given in tab. 3.

Table 3. Geometrical characteristics of valve mechanism

	Intake valve	Exhaust valve
Valve diameter, [mm]	30	27.5
Valve lift, [mm]	9.75	10
Valve opening, [°CS]	16 bTDC	40 aTDC
Valve closing, [°CS]	40 °CS bTDC	16 aTDC

Analyses have been performed for four different cases, with the same spark timing for all selected cases. In this analysis, the only influence of injection parameters on the working cycle will be observed. The injection and spark parameters are given in tab. 4.

Table 4. Injection and spark parameters

	1st case	2nd case	3rd case	4th case
Injection pressure, [bar]	100	100	100	100
Injection timing, [°CS]	15 bTDC	30 bTDC	70 bTDC	140 bTDC
Injection duration, [°CS]	20	20	20	20
Injector position	In pre chamber	In pre chamber	In pre chamber	In pre chamber
Spark timing, [°CS]	5 bTDC	5 bTDC	5 bTDC	5 bTDC
Number of spark plugs	1	1	1	1
Spark plug position	In pre chamber	In pre chamber	In pre chamber	In pre chamber

It can be seen from tab. 4, that only parameter that changes is the hydrogen injection timing in pre chamber. The hydrogen is known by high combustion speed. But this is not the only characteristic. The hydrogen, as well has very wide flammability boarders. More accurately, the hydrogen can be combusted in mixture with air, in boarders from 4-75% [17]. The interesting fact is that the highest combustion speed appears in stoichiometric mixture, while this is not the case for rich and lean mixture [20]. It can be noticed that by varying the injection timing, it can get different time for mixture homogenization. Based on this outcome, it can be obtained different air/fuel mixture ratios in pre chamber and cylinder. Because of high combustion speed, the spark timing was always set up at 5 °CS bTDC. This was done in order to get always peek pressure aTDC, which is crucial for properly engine work.

Results and discussions

In this section will present the results of the IC engine working cycle with the hydrogen based on the input data that discussed in the previous section. The first step in the analysis is selected the intake valve opening, and at the end the exhaust valve opening was selected. In other words, all analyses were performed for only three strokes and for combustion process: intake stroke, compression stroke, combustion process and for the power stroke. The exhaust stroke was not taken into the consideration.

In the first case, the injection started at 15 °CS bTDC, this means that until the spark timing, the only half of the injection process is finished. Which means that is not injected entire amount of fuel, but it will be in period of 10 °CS simultaneously injection and combustion. It is important to mention in this analysis; the mixture in pre chamber is very rich and in the cylinder is very lean.

In the second case, injection started at 30 °CS bTDC. This means that the entire amount of fuel is injected and 5 °CS for mixing. The time for the mixing is a little bit longer, but not enough for mixture equalization. This is because the mixture in pre chamber is little bit leaner, but is still very rich and in cylinder still very lean, but a little bit richer than in the first case.

In the third case, as the beginning of the injection, the 70 °CS bTDC was selected. It was got after injection of the entire amount of fuel 45 °CS more for mixing before the spark and ignition. It can be said that in this case, it was much longer time for mixing, and this case should be showing a significant differences in the results. This is because of the time of mixing that is now longer, the mixture in the cylinder will be richer, and in pre chamber will be leaner. Of course, its logic to conclude that the mixture will still be richer in pre chamber than in the cylinder.

The injection timing for the fourth case is defined at 140 °CS bTDC. This moment was selected with purpose, where this is the moment of intake valve closing. Also the pressure in the cylinder is still low. In this case, after injection and before ignition, it has stayed 115 °CS for mixing, homogenization and creation of uniform mixture. In this situation, the mixture in pre chamber and cylinder will be stoichiometric or very close to it. This will be proved trough high combustion speed, or in selected case trough high cylinder pressure increasing.

The advantage of the numerical analysis is the visualization of the simulated process. This smoothing cannot be accomplished by using the mathematical models. Specifically for this research paper, it was selected to show the simulation for the working cycle with the hydrogen. The contours of the results are shown in tab. 5, where the results presented every 45 °CS with the beginning at TDC, and the results for TDC during the combustion process are given for every 5 °CS.

It can be seen from the results that the temperature contours for the first case, where the values of the maximum temperature is found 2776 K. In general, the range of temperature for all four cases is found 2752-2924 K as shown in fig. 4.

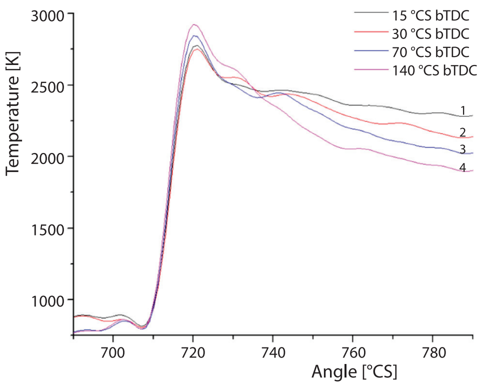
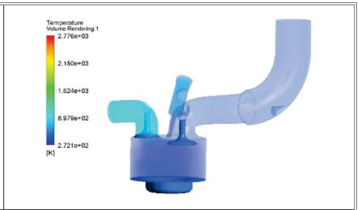
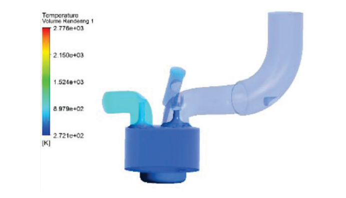
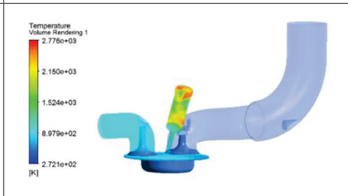
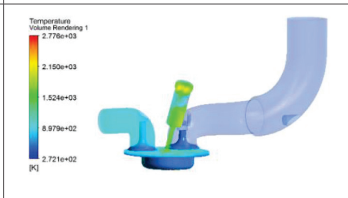
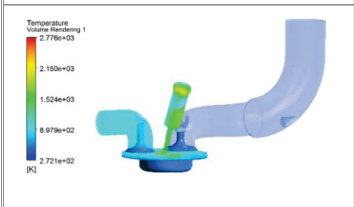
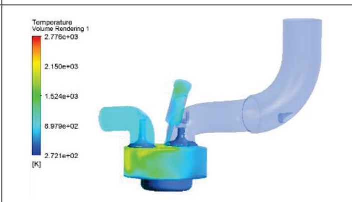
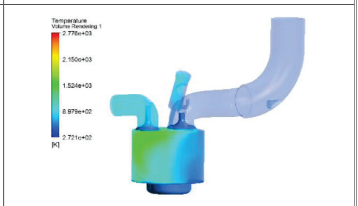


Figure 4. The variation of temperatures during the combustion

The results for the maximum temperature of the fourth case were logical; a little bit lower was obtained for third case and the lowest for the second case. It's interested that the temperature in the first case was not lower than in the second

Table 5. Simulation of the IC engine working cycle with the hydrogen

		
360 °CS	405 °CS	450 °CS
		
495 °CS	540 °CS	585 °CS
		
630 °CS	675 °CS	705 °CS
		
710 °CS	715 °CS	720 °CS
		
725 °CS	730 °CS	735 °CS
		
740 °CS	785 °CS	830 °CS

case. The most probable reason for this result is because the time interval for mixing between first and second case is not too high. However, with increasing the time period for homogenization, the maximum temperature rise. Also, it was found in all cases that the temperature before the ignition is not above 848 K [12], which means that there don't exist possibility of auto ignition.

However, the pressure in the cylinder is may be the best for the results analysis. It can be noticed in fig. 5 the cylinder pressure curves for all four cases.

The results of the cylinder pressure proved the earlier claim. By earlier injection, when increasing the time for mixture homogenization, the pressure will grow quickly. This confirms that the combustion speed is high in the area of stoichiometric mixture. Because of this result, the pressure growth increased. Most important parameter for the cylinder pressure analysis is the maximum value of pressure and its position as lists in tab. 6.

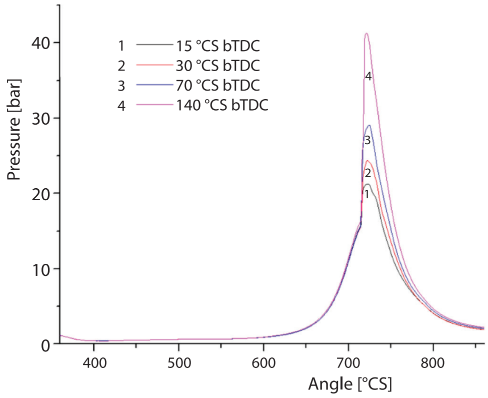


Figure 5. The variation of cylinder pressure

Table 6. Value and the position of the maximum pressure

	1st case	2nd case	3rd case	4th case
Maximum pressure value, [bar]	21.3	24.4	29.1	41.3
Position of the maximal pressure, [°CS]	2 aTDC	2 aTDC	5 aTDC	1 aTDC

The position of the maximum pressure is always aTDC, which is very good. The more accurate, the position of the maximum pressure should not appear at TDC, because this can cause destruction of the engine. Owing to this, the spark timing is purposely defined very close to the TDC due to the high combustion speed. Based on the pressure result, it can be concluded that the better performances can be obtained by earlier injection. However, the position of the maximum pressure is still very close to the TDC, where the pressure increased rapidly. In order to analyze this situation, the results of the pressure rise gradient are shown in fig. 6.

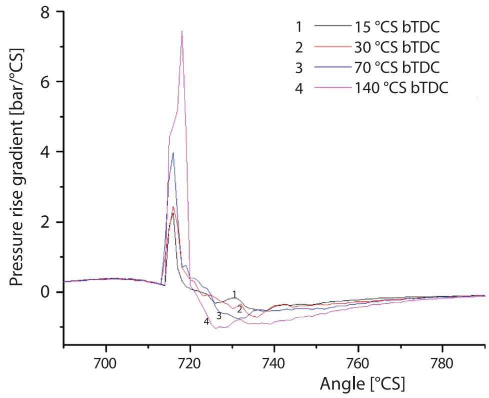


Figure 6. Pressure rise gradient

The maximum values of the pressure rise gradient for selected cases are:
- 1st Case 2.3 bar/°CS
- 2nd Case 2.4 bar/°CS
- 3rd Case 3.9 bar/°CS
- 4th Case 7.4 bar/°CS

In the experimental results from the multi-process engine, the maximum value of the pressure rise gradient for the gasoline mode in observed mode is 1.3 bar/°CS, and for diesel mode is 5.6 bar/°CS. The comparison was made between the results for hydrogen with the experimental. It can be concluded that the pressure rise gradient in the case of the hydrogen is always higher with respect to the experimental results for the gasoline mode. But in respect to the diesel mode, it is higher only for fourth case where pressure rise gradient has value 7.4 bar/°CS. This value is 32% higher than the diesel mode. This can produce brutal engine work from the aspect of mechanical loads. However, the maximum pressure is much lower than those obtained for the diesel, but when added pre chamber, the compression ratio decreased.

Conclusions and remarks

In the paper, it was presented a new development for IC engine, and the analysis was performed for the working cycle with the hydrogen as a fuel. This new development is not something new geometrically, but represents a new approach for using the gaseous fuels, with injection pressure, which is a lot higher than injection pressure of usually used systems for gas injection. For this new approach, the pre chamber was added. The pre chamber is constructed to have the external dimensions as the fuel injector. Also, the pre chamber has the place for GDI injector and for a spark plug. This included technology for injection and ignition systems that are much cheaper than injection system for modern diesel engines. Because of chemical composition of hydrogen as fuel, carbon components in exhaust emission will be reduced. The only carbon that can appear is from oil that is used for engine lubrication. The temperatures during the combustion were high, which means that are accomplished conditions for NO_x formation that agreed with the results of other researches. However, it is much easier to work on the reduction of only one-component. With earlier injection, the pressure grown as well as the pressure rise gradient. According to the early injection, the brutal work of the engine can be caused. Also, it is obviously found that the surface beneath the pressure curve grown, although the exhaust stroke is not included in the simulation. This means that the engine efficiency will rise with earlier injection. This assumption should be considered for future research, in order to choose the best injection and spark parameters for engine work optimization.

Acknowledgment

This paper was realized within the framework of the project *The research of vehicle safety as part of a cybernetic system: Driver-Vehicle-Environment*, ref. No. TR35041, funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia. Also, the authors would like to thank the System Technology and Mechanical Design Methodology Group/Hamburg University of Technology to support this research paper.

Nomenclature

°CS – crank shaft degree
m – mass, [kg]
P – pressure, [Pa]
R – gas constant, [$Jkg^{-1}K^{-1}$]
T – temperature, [K]
V – volume, [m^3]

Acronyms

GDI – gasoline direct injection
IC – internal combustion

References

[1] Grujic, I., *et al.*, Economic Analysis of Application of Different Drive Trains in Vehicles, *Mobility and Vehicle Mechanics*, *43* (2017), 2, pp. 29-38
[2] Pešić, R., *et al,* Vehicle Powertrain and Fuel Strategy, *Tractors and Power Machines*, *23* (2018), 3-4, pp. 39-48
[3] ***, Auto Wow, https://avtowow.com/countries-by-electric-car-use
[4] ***, IEA Wind, https://community.ieawind.org/about/member-activities/norway

[5] ***, Macrotrends, https://www.macrotrends.net/1369/crude-oil-price-history-chart
[6] Pavlos, D., Taku, T., A Review of Hydrogen as a Compression Ignition Engine Fuel, *International Journal of Hydrogen Energy*, *42* (2017), 38, pp. 24470-24486
[7] Saravanan, N., *et al.*, Combustion Analysis on a DI Diesel Engine with Hydrogen in Dual Fuel Mode, *Fuel*, *87* (2008), 17-18, pp. 3591-3599
[8] Tsolakis, A., *et al.*, Dual Fuel Diesel Engine Operation Using H_2, Effect on Particulate Emissions, *Energy and Fuels*, *19* (2005), 2, pp. 418-425
[9] Pana, C., *et al.*, Experimental Aspects of the Hydrogen Use at Diesel Engine, *Procedia Engineering*, *181* (2017), pp. 649-657
[10] Miyamoto, T., *et al.*, Effect of Hydrogen Addition Intake Gas on Combustion and Exhaust Emission Characteristics of a Diesel Engine, *International Journal of Hydrogen Energy*, *36* (2011), 20, pp. 13138-13149
[11] Christodoulou, F., Megaritis, A., Experimental Investigation of the Effects of Separate Hydrogen and Nitrogen Addition on the Emissions and Combustion of a Diesel Engine, *International Journal of Hydrogen Energy*, *38* (2013), 24, pp. 10126-10140
[12] Das, L. M., Hydrogen-Oxygen Reaction Mechanism and its Implication Hydrogen Engine Combustion, *International Journal of Hydrogen Energy*, *21* (1996), 8, pp. 703-715
[13] Srinivasana, C. B., Subramanian, R., Hydrogen as a Spark Ignition Engine Fuel Technical Review, *International Journal of Mechanical and Mechatronics Engineering IJMME-IJENS*, *14* (2014), 5, pp. 111-117
[14] Zhenzhong, Y., *et al.*, Effects of Injection Mode on the Mixture Formation and Combustion Performance of the Hydrogen Internal Combustion Engine, *Energy*, *147* (2018), Mar., pp. 715-728
[15] Soria, A. H. H., *et al.*, Theoretical Analysis of the Power of a Spark Ignition Internal Combustion Engine With Different Fuel Blends, *Proceedings*, The International Conference on Innovative Applied Energy (IAPE'19), Oxford, UK, 2019
[16] Davinić, A., Identification of Characteristics of Multi-Process Operation of the Piston IC Engine (in Serbian), Ph. D. thesis, Faculty of Engineering, University of Kragujevac, Kragujevac, Serbia, 2013
[17] ***, HySafe, http://www.hysafe.org/download/997/brhs_ch1_fundamentals-version%201_0_1.pdf
[18] Radonjić, D., Pešić, R., *Heat Calculation of IC Engines*, (in Serbian), Faculty of Mechanical Engineering Kragujevac, Serbia, 1996
[19] Lukić, N., *The Handbook for Thermodinamic*, (in Serbian), Faculty of Mechanical Engineering, Kragujevac, Serbia, 2003
[20] Cheng, G., *et al*., Large Eddy Simulation of Hydrogen Combustion in Supersonic Flows Using an Eulerian Stochastic Fields Method, *International Journal of Hydrogen Energy*, *42* (2017), 2, pp. 1264-1275

Paper submitted: August 16, 2019
Paper revised: June 4, 2020
Paper accepted: November 30, 2020