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Investigation of the Effect of Dual Ignition on the Exhaust Emissions of an SI Engine Operating on Different Conditions by Using Quasi-dimensional Thermodynamic Cycle Model

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Preliminary note

In the presented study, the effects of using dual- spark plug and variation of the spark plug location on the exhaust emissions of an SI engine operating in different conditions were investigated theoretically. A quasi-dimensional two-zone thermodynamic cycle model was developed for this purpose. CO_2, CO and NO concentrations in the exhaust emissions were determined for each of operating condition. Obtained results showed that there are considerable effects using dual-ignition and varying spark plug location on exhaust emissions. Using dual-ignition decreases exhaust emissions especially by shortening flame travel length and minimizing combustion duration.

Keywords

Dual spark
Exhaust emissions
Spark ignition engine
Quasi-dimensional two-zone thermodynamic model

Ključne riječi

Dvojna svjećica
Emisije ispuha
Iskrom paljen motor
Kvazi-dimenzionalni dvozonski model

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Istraživanje efekta dvojnog paljenja na emisiju izlaznih plinova kod SI motora koji radi u različitim uvjetima koristeći kvazi-dimenzionalni termodinamički ciklički model

Prethodno priopćenje

U radu se teorijski istražuju efekti korištenja dvije svjećice i varijacije njihova položaja na emisije SI motora pri njihovom radu u različitim uvjetima. Za tu je svrhu razvijen kvazi – dimenijski dvozonski model procesa. Utvrđene su koncentracije emisija CO_2, CO i NO u ispušnom dijelu motora za sve uvjete rada motora. Dobiveni rezultati su pokazali da postoje značajni učinci na emisije pri korištenju dvojnog ubrizgavanja kao i pri variranju položaja svjećice. Korištenjem dvojnog paljenja smanjuju se izlazne emisije, poglavito skraćivanjem duljine puta plamena i smanjenjem trajanja procesa igaranja.

1. Introduction

Hydrocarbon (HC) based fossil fuel consum in motor vehicles are one of the major sources of urban air pollution. Normal combustion products are CO_2, H_2O and N_2 in a complete combustion process of any HC based fuel. These products are not viewed as pollutants, since they do not pose a direct health hazard, and appear as the final product of every complete oxidation of any HC. But, in a real engine combustion process, some additional species, such as carbon monoxide (CO), unburned HCs, nitrogen oxides (NO_x) and particulate matters (PM) also appear in the engine exhaust, which are detrimental to human health and subject to exhaust emission legislation. The quantity of these harmful pollutant emissions are about five times greater for a typical spark ignition (SI) engine than that of the corresponding compression ignition (CI) engine. CO is the dominating pollutant component with about 80 percent of all pollutant emissions, i.e., CO, NO_x, unburned HCs and PM, for an SI engine. Due to its strong adherence to hemoglobin, even low concentrations therefore is sufficient to cause suffocation [2]. This colorless and odorless, poisonous gas is mostly generated in an engine when it is operated with a fuel-rich equivalence ratio. When there is not enough oxygen to convert all carbon to CO_2, some fuel does not get burned and some carbon ends up as CO [10]. Nitrogen oxides correspond to about 12 percent of the pollutants and most of them are in the form of nitrogen monoxide (NO), with a small amount of nitrogen dioxide (NO_2). NO_x is also an undesirable pollutant, which reacts in the atmosphere to form ozone that is known as one of the major causes of photochemical smog. In a combustion process, NO_x is created mostly from the nitrogen of the air in different ways. The dominant process in the formation of NO_x is thermal NO formation that occurs behind the flame front in the burned gas region due to high combustion temperatures. Unburned HCs and PM are the

Symbols/Oznake

Dp	- dual plug - dvije svjećice	ε	- 1/Stoichiometric air-fuel ratio - stehiometrijski omjer zrak-gorivo
ppm	- parts per million - milioniti dio	ϕ	- equivalence ratio - ekvivalentni omjer
Sp	- single plug - jedna svjećica		

rest of pollutants after CO and NO_x from the viewpoint of quantity in SI engines. Unburned HCs are about 8 % of pollutant emissions, while PM concentrations are at the ppm (parts per million) levels.

There are three basic methods used to control exhaust emissions: (1) designing the combustion chamber to achieve an efficient combustion, (2) optimizing operating parameters, i.e., equivalence ratio, spark timing etc., to reduce pollutant emissions, and, (3) using after-treatment devices in the exhaust system (catalytic converters etc.). This study deals with the first one of the mentioned methods and is focused on using two spark plugs as a design parameter to improve combustion.

Dual sparks are one of the important design parameters for SI engines. The primary benefits of using dual sparks are to achieve a stronger and faster combustion. This enables the engine to operate with leaner fuel-air mixture, i.e., with more EGR (exhaust gas recirculation), for emission control. Although there are some experimental studies about performance analysis of dual spark SI engines [3, 6-7, 9, 11, 13], there is a scarcity in the existing literature about theoretical study investigating exhaust emissions of dual spark SI engines. For that reason, this study was concerned with theoretical investigation of the emissions of dual spark SI engines. The emissions of CO_2, CO and NO were especially considered in the study. In order to make comparisons, the computations were performed for both single and dual spark configurations at the same locations of spark plugs. Three engine speeds, i.e., n=1000, 2000, and 3000 rpm, and equivalence ratios, i.e., ϕ=0.9, 1.0 and 1.1, were selected as operating conditions.

2. Mathematical model

2.1. Thermodynamic model

A two-zone quasi-dimensional thermodynamic cycle model was used in the study. Instantaneous in-cylinder pressure, burned and unburned gas temperatures etc. were determined by solving a set of ordinary differential equations simultaneously. The detailed information about the model can be found in reference [1]. Figure 1 shows spark plug locations used in the study. The points illustrated by 1, 2, and 3, in the figure, represent central, mid-radius, and side spark locations, respectively.

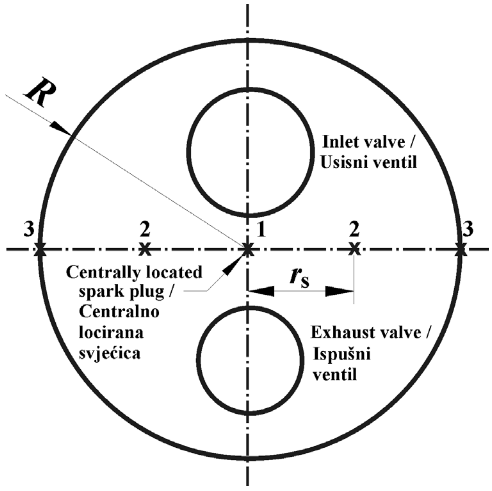

Figure 1. Spark plug locations

Slika 1. Položaji svjećica

2.2. Practical equilibrium combustion

For this modela practical chemical equilibrium of the combustion products with the equivalence ratios of ϕ<3, 10 species is considered [4]. Hence, the combustion equation can be written as:

$$\begin{aligned}\phi\varepsilon C_c H_h O_{o_y} N_n + \left(0.21O_2 + 0.79N_2\right) \rightarrow \\ n_1CO_2 + n_2H_2O + n_3N_2 \\ + n_4O_2 + n_5CO + n_6H_2 + n_7H \\ + n_8O + n_9OH + n_{10}NO.\end{aligned} \tag{1}$$

To determine mol fractions of combustion products 10 equations are needed. Four of equations are obtained from mass balance of C, H, O and N. Additional six equations are obtained from equilibrium constants for dissociation reactions. After linearization of the non-linear equations by using Newton-Raphson method, Gaussian-elimination method is used for solution of linear algebraic equations. [8].

2.3. Model validation

In order to validate the used model, predicted values are compared with the experimental data available in literature [12]. A comparison was performed based on cylinder pressure-crank angle variation. As seen in Figure 2, the predicted values are in excellent agreement with the experimental data of Rakopoulos.

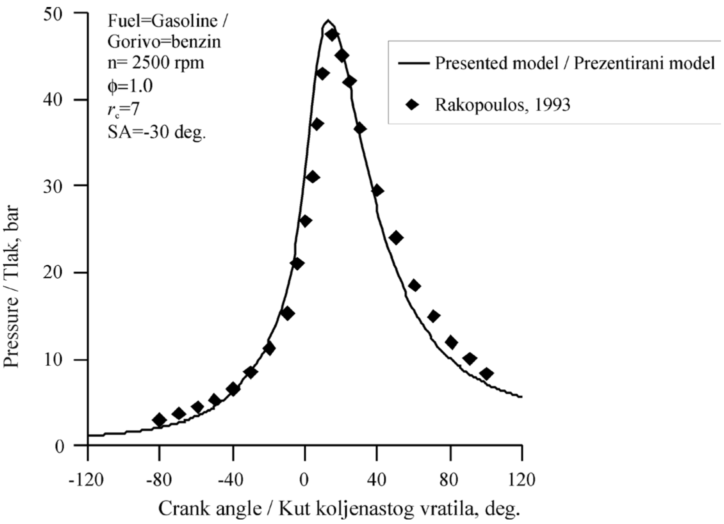

Figure 2. Comparison of predicted and experimental cylinder pressure-crank angle variation

Slika 2. Usporedba izračunatih i eksperimentalnih vrijednosti u cilindru; tlak – kut zakreta korenastog vratila

3. Results and discussions

In this study, two operating parameters (i.e., engine speed and equivalence ratio) and two constructive parameters (i.e., spark plug number and location) were considered to investigate the effects on exhaust emissions. Selected plug locations correspond to two limiting cases as central and side locations, with additional mid-radius location. At mid-radius and side locations, single- and dual-ignition configurations were examined. Engine speeds were selected as 1000, 2000 and 3000 rpm. As known, SI engines operate generally around stoichiometric fuel-air mixtures. For this reason, equivalence ratios were selected as 0.9, 1.0 and 1.1 in the study.

Engine configurations used in the study were given in Table 1 [5].

Table 1. Engine configurations

Tablica 1. Karakteristike motora

Bore / Promjer cilindra, mm	73
Stroke / Stapaj, mm	95.5
Connecting rod length / Dužina ojnice, mm	191
Compression ratio / Stupanj kompresije	9

3.1. The effect of engine speed on the exhaust emissions

In this section, the effect of engine speed on the CO, NO and CO_2 emissions were investigated. Equivalence ratio is selected as ϕ=1.1 for evaluation of CO emissions.

3.1.1. Carbon Monoxide (CO)

Figure 3 shows CO emissions versus engine speed for various spark plug locations and, both single and dual spark configurations. An increase in engine speed causes an increase in CO emissions. This is mostly due to a reduction in combustion duration with increasing engine speed. CO emissions are at the highest level with single-spark at side location. If dual-ignition is used at the same location, CO emissions become lower because of both improved combustion efficiency and shortening flame travel distance. CO emissions are at the lowest level with dual-ignition at mid-radius location.

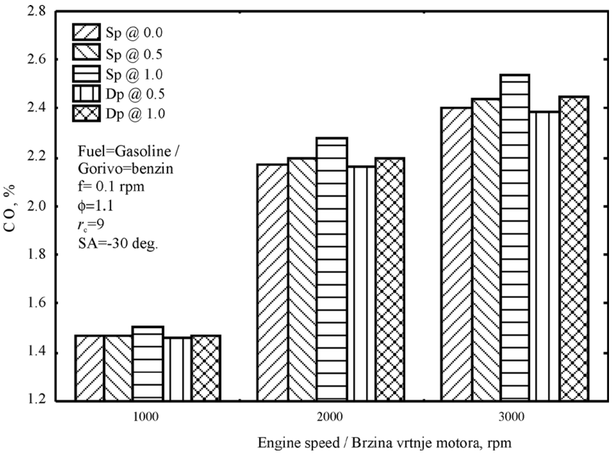

Figure 3. Carbon monoxide emission versus engine speed

Slika 3. Emisija ugljičnog monoksida u ovisnosti o brzini vrtnje motora

3.1.2. Nitrogen Oxide (NO)

Figure 4 shows NO emissions versus engine speed for various spark plug locations and, both single and dual spark configurations. NO emissions increase with increasing engine speed. Like CO emissions, mid-radius dual-ignition gives minimum NO emissions among all configurations. The central ignition is the second better confuguration in terms of NO emissions.

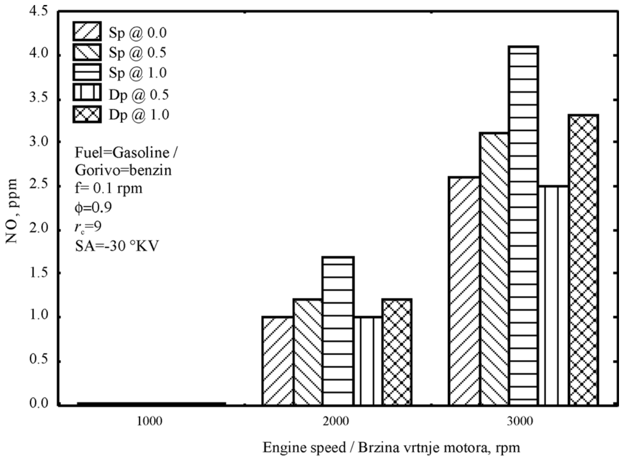

Figure 4. Nitrogen oxide emission versus engine speed

Slika 4. Emisija dušičnog oksida u ovisnosti o brzini vrtnje motora

3.1.3. Carbon Dioxide (CO_2)

Carbon dioxide is a complete combustion product of any HC based fuel. Therefore, it is an indicator of the combustion efficiency. This means that the higher carbon dioxide concentration in combustion products, the better the combustion efficiency. Carbon dioxide versus engine speed for various spark plug locations, and both single and dual spark configurations were shown in Figure 5. CO_2 emissions decrease with increasing engine speed. This is due to decrease in combustion duration with increasing engine speed. The difference in CO_2 emissions for various configurations become more evident at higher engine speeds. As shown in the figure, dual ignition increases combustion speed and contributes to more complete combustion. As is in all cases, single side-ignition is the worst of all configutarions.

3.2. The effect of equivalance ratio on the exhaust emissions

Equivalence ratio is one of the most important parameters affecting the exhaust emissions. The equivalence ratios studied in this study were 0.9, 1.0, and 1.1, which correspond to the lean, stoichiometric and rich fuel-air mixtures. Engine speed is taken as 2000 rpm for the following comparative investigations.

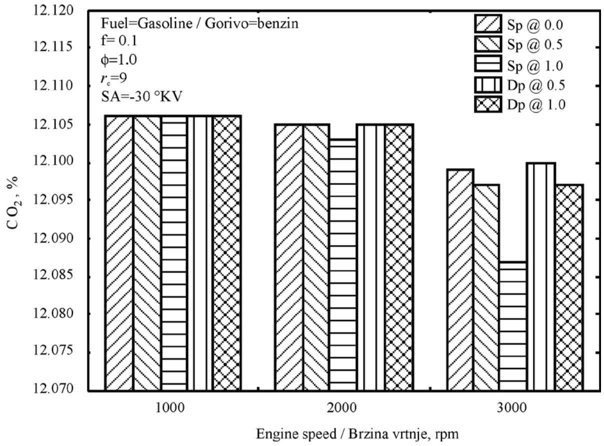

Figure 5. Carbon dioxide emission versus engine speed

Slika 5. Emisija ugljičnog dioksida u ovisnosti o brzini vrtnje motora

3.2.1. Carbon Monoxide (CO)

Carbon monoxide emissions from internal combustion engines are controlled primarily by the fuel-air equivalence ratio. For fuel-rich mixtures, CO concentrations in the exhaust increase with increasing equivalence ratio due to luck of oxygen. Figure 6 shows CO emissions versus equivalence ratio for various spark plug locations and, both single and dual spark configurations. As expected, there is almost no CO emission for stoichiometric (ϕ=1) and lean (ϕ=0.9) fuel-air mixtures. In the case of fuel-rich mixture (ϕ=1.1), hovewer, CO concentrations increase to approximately 2.2 %. Although the differences in the CO concentrations for different configurations are not much, mid-radius dual-ignition gives the minimum CO emissions among all configurations.

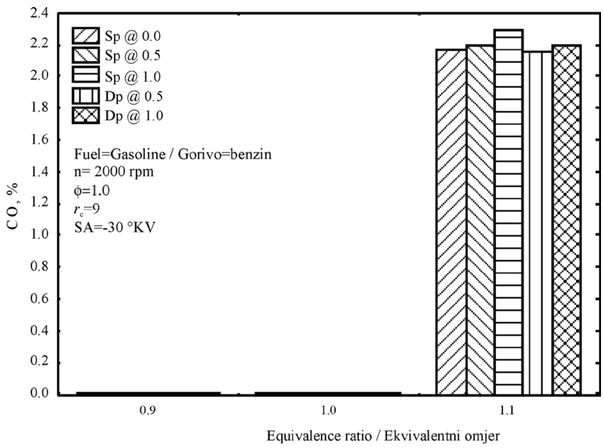

Figure 6. Carbon monoxide emission versus equivalence ratio

Slika 6. Emisija ugljičnog monoksida u ovisnosti o ekvivalentnom omjeru

3.2.2. Nitrogen Oxide (NO)

Figure 8 shows NO emissions versus equivalence ratio for various spark plug locations and, both single- and dual-plug configurations. Nitrogen oxide is a combustion product of the slightly lean fuel-air mixture combustion due to the highest combustion temperatures and abundant nitrogen from the excess air. Therefore, some NO emissions were obtained for ϕ=0.9, while there is almost no NO emission for stoichiometric and rich mixtures. NO levels are similar and less than other configurations for mid-radius dual-spark and central ignitions for equivalence ratio of 0.9. As in the previous cases, side ignition with single-spark gives the highest levels of NO concentrations due to longer combustion time.

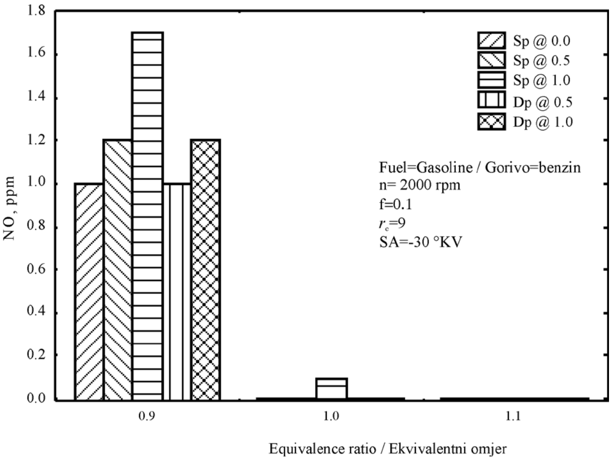

Figure 7. Nitrogen oxide emission versus equivalence ratio

Slika 7. Emisija dušičnog oksida u ovisnosti o ekvivalentnom omjeru

3.2.3. Carbon Dioxide (CO2)

Figure 8 shows CO_2 emissions versus equivalence ratios for various spark plug locations and both single and dual spark configurations. Maximum CO_2 concentrations were obtained for stoichiometric mixture. This is an expected result, since for the rich mixtures there is not sufficient oxygen to completely oxidize all the carbon atoms in the fuel, while for the lean mixtures relative amount of CO_2 decreases due to abundant O_2 and N_2 in the combustion products. Any noticable effect of the plug number and locations on CO_2 emissions were obtained only for the rich mixture as shown in the figure. The best configurations are mid-radius dual-plug and central ignition, as for the previous cases.

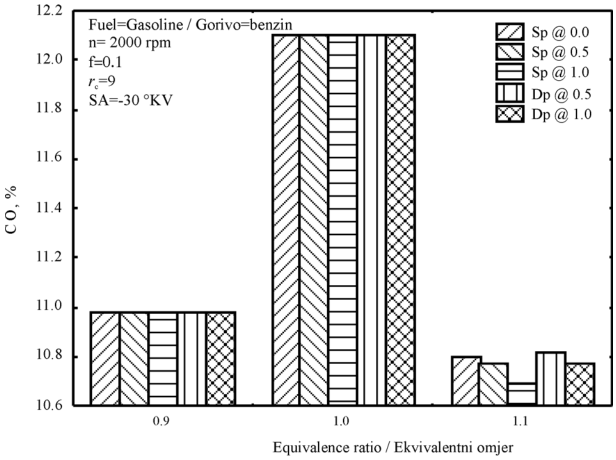

Figure 8. Carbon dioxide emission versus equivalence ratio

Slika 8. Emisija ugljičnog dioksida u ovisnosti o ekvivalentnom omjeru

4. Conclusions

In this study, the effects of using dual-spark plugs and variations of the plug locations on the exhaust emissions of an SI engine operating at different conditions were investigated by using a quasi-dimensional thermodynamic cycle model. The following conclusions can be drawn from the study:

1. Spark plug number and its location have important effect on the SI engine exhaust emissions.
2. The centrally located single-spark and mid-radius located dual-plug configurations gives almost similar and the best combustion with the lowest exhaust emissions in comparison with all other configurations. Therefore, if centrally located single-plug, cannot be used due to any geometrical constraints; mid-radius dual-plug configuration can be used to lower emissions.
3. Side-located dual-spark configuration gives similar results with mid-radius single spark configuration.
4. Increase in CO and NO emissions under various conditions can be diminished by using dual-spark ignition in SI engines.

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