



e-ISSN: 2146 - 9067

International Journal of Automotive Engineering and Technologies

journal homepage:

<https://dergipark.org.tr/en/pub/ijaet>



Original Research Article

Reducing emissions of an SI engine by alternative spark plugs with hydrogen addition and variable compression ratio



Oğuz Baş^{1*}, Mustafa Atakan Akar², Hasan Serin³

^{1,*}Amasya University, Technology Faculty, Mechanical Engineering, Amasya, Turkey

^{2,3}Cukurova University, The Faculty Of Engineering, Automotive Engineering, Adana, Turkey

ARTICLE INFO

¹ 0000-0003-2301-2306

² 0000-0002-0192-0605

³ 0000-0003-2679-3099

* Corresponding author
oguz.bas@amasya.edu.tr

Received: Mar 20, 2019
Accepted: May 03, 2020

Published by Editorial Board
Members of IJAET

© This article is distributed by
Turk Journal Park System under
the CC 4.0 terms and conditions.

ABSTRACT

As a consequence of the emissions-cheating scandals and more strict emission regulations enforce researchers to reduce emissions out and find alternative fuels for SI engines. For this purpose, various spark plugs are available in the market with different electrode materials. However, they have not been tested together with different engine parameters. Hence, emissions out from a variable compression spark-ignited engine with different spark plugs and hydrogen enrichment were the scope of this study. The tests were conducted with a four-stroke, single-cylinder, naturally aspirated, variable compression ratio (VCR) engine. Two different compression ratios (CR) of 8.5:1 and 10:1 at maximum brake torque (MBT) spark timing applied to assess the effects of different spark plugs and hydrogen usage at different engine loads. Copper, iridium and platinum spark plugs were tested for each experiment condition. Also, hydrogen was added through the intake manifold with flow rates of 0, 2 and 4 l/min to enhance the combustion of the VCR engine. Carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x) and unburned hydrocarbons (UHC) emission values were measured in this study. According to test results, with iridium and platinum spark plug usage, hydrogen addition and higher CR, the engine emitted lower CO and UHC at all engine loads. However, a higher amount of CO₂ was emitted because of increased completeness of the combustion and the amount of NO_x emissions rose due to increment in-cylinder temperatures. These variances were more apparent with platinum spark plug usage compared to the iridium spark plug. As a result, the usage of iridium and platinum spark plugs were shown lower incomplete emissions products out, except NO_x emissions.

Keywords: Exhaust emissions, Spark plug, Iridium, Platinum, Hydrogen Fuel, SI engine

1. Introduction

Fossil fuels such as petroleum, coal and natural gas are the main energy sources of today's world. Day by day, growing energy demand and environmental issues have been getting more critical. Naturally, the automotive industry is

severely challenging to high fuel costs and strict emission regulations due to the above-mentioned issues [1, 2].

As known, people and goods transportation are provided by the utilization of fossil fuels such as gasoline, diesel, compressed natural gas, liquefied petroleum gas, etc. Despite diesel

market share is still very high among them in European Union nations, in mid-term, it is expected that the diesel engine inevitably will lose its share in the market rapidly [3, 4]. Especially, considering recent emission-cheating scandals, the development of the SI engine is being more and more critical for the future of the automotive industry. From this point, it can be interpreted that the gasoline engine must be improved and the usage of alternative fuels has to be evaluated with caution from different aspects [5, 6].

As known, SI engines have high power to weight ratio, stable and silent performance. Besides an SI engine has relatively low prices and requires less maintenance [7, 8]. Furthermore, they are more feasible for fuel alternating such as CNG and LPG compared with a diesel engine which has a similar volume [9, 10]. Yet, thermal efficiency and torque output of SI engines are relatively lower comparing with modern compression ignited engines [11]. These drawbacks have been posed an obstacle to the widespread utilization of SI engines such as heavy-duty types of machinery [12 - 14].

A lean-burn operation is just one of the most effective ways to solve the problems mentioned above [15]. However, lean-burn is limited due to ignition-related problems such as the slow flame initiation and propagation along with potential misfiring [16]. In the future of spark-ignited engine, it is expected that gasoline engines will operate with much higher compression ratios and much leaner fuel-to-air ratios for the sake of combustion enhancement and fuel economy [17, 18]. Furthermore, these will deteriorate the electrode degradation and erosion of the spark plugs more [19 - 21]. To overcome these challenges, usage of durable alternative spark plugs is seemed urgent for spark-ignited engines.

The purpose of a spark plug (SP) is to ensure controlled combustion of the fuel in the engine. By doing so, a high voltage generated by the ignition coil is introduced into the combustion chamber and the compressed fuel/air mixture is then ignited by the electric spark passing between the electrodes. Charge volume and density of the spark plug in the combustion chamber are other serious factors that influence engine performance and emission

characteristics. By increasing combustion volume, charge density or elongating ignition time, combustion completeness can be enhanced [22]. However, there are some objections to improve them. For instance, to increase the charge density ignition system requires higher secondary coil voltage to initiate combustion [23]. Thus, producing the required voltage with these conditions would cause more spark electrode erosion and shorter service lifetime of the spark plug [17, 20, 22].

To improve SPs, suppliers have presented different types of spark plugs with various electrode materials to the market such as yttrium, iridium, platinum, etc. The main purposes of usage of these noble metal materials are rapid attainment of operating temperature, increasing cold starting reliability, enhancing ignition, smooth engine operation and reducing wear rate of the electrode [24]. In this context, these types of spark plugs that are available in the market must be assessed from different aspects such as performance characteristics, emission values, electrode erosions and carbon buildup, etc.

Usage of hydrogen which is one of the most prominent alternative fuels brings a lot of advantages for SI engines due to its some superior properties. Hydrogen is a colorless, inodorous and zero-carbon emitted fuel when fired with oxygen [14, 15, 25, 26]. The chemical reaction of two hydrogen atoms and an oxygen atom generates energy outputs and the product is water only. Characteristic features of hydrogen such as flammability limits, low ignition energy, high burning rate ensure more stable combustion process and engine operation even for ultra-clean air-fuel mixtures. So, hydrogen enables to increase the combustion limits [27]. Hydrogen has a wider flammability range in the air that allows the engine to operate with either rich or lean mixtures. Thus, by leaning the air-fuel mixture better fuel economy can be obtained due to increased combustion completeness of the fuel [28]. In addition to that, lean combustion results in lower NO_x emission depending on lower combustion temperature. More complete combustion ensured by hydrogen enrichment leads to a reduction of the emission products [29, 30]. Zero carbon structure of the hydrogen combustion decreases CO, CO₂ and HC emissions. On the contrary,

hydrogen existence in combustion rises the cylinder temperature with stoichiometric conditions, thus NO_x emission increases. However, NO_x emission rise can be compensated by the lean operation owing to diminished combustion temperature [10, 25].

On the other hand, compression ratio (CR) is one of the key facts that influence engine performance, emissions out and design. Engine efficiency can be improved further with a higher CR that enables increment in the expansion ratio providing effective utilization of the fuel [31 - 34]. Moreover, it yields decreased exhaust gas dilution of a fresh mixture which increases cylinder temperature and pressure. This allows shorter ignition delay and combustion duration as a consequence of increased flame speed. Also, CR increment is a functional way to attain a wider backfire-free running range of the engine. Besides, increasing CR minimizes residual gas amount in the combustion chamber and thereby reduces the possibility of backfire [35].

From those points of views, although there are studies on spark plug locations [22, 36 - 38], spark plug gap, electrode geometry [39], dual spark plug [40], multiple sparks [23], increased spark discharge energy [12, 41], erosion and failure characteristics [18, 19, 21] in literature, however, usage of alternative spark plugs with different electrode materials and their effect on emission characteristics have not been investigated in detail. In this study, the effect of different spark plug types on emissions characteristics of a spark-ignition engine fuelled with hydrogen-enriched gasoline at various engine loads and CRs were studied. Brake specific emission values of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and un-burnt hydrocarbon (UHC) emissions were determined to evaluate test parameters.

2. Experimental Methodology

2.1 Materials

2.1.1. Test Engine

Engine tests were performed on a four-stroke, single-cylinder, naturally aspirated, water-cooled, variable compression engine that can run with both gasoline and diesel fuel by replacing the engine head. "Enginesoft" software was utilized for experimental data

logging. This software logs for 60 seconds when logging starts and at the end of this period gives the average values of experimental data. Technical specifications of the engine and schematic representation test rig were given in Table 1 and Figure 1, respectively.

Table 1. Technical specifications of the engine

Descriptions	Specifications
Brand – Model	Kirloskar Oil Engines-240
Configuration	Single Cylinder
Type	Four Stroke,
Cooling	Water Cooling
Displacement	661 cc
Bore	87.5 mm
Stroke	110 mm
Power	4.5 Kw @ 1800 rpm
CR range	6:1-10:1
Injection Variation	0-25° BTDC
Peak Pressure	77.5 kg/cm ²
Weight	160 kg
Lubricating System	Forced Feed System

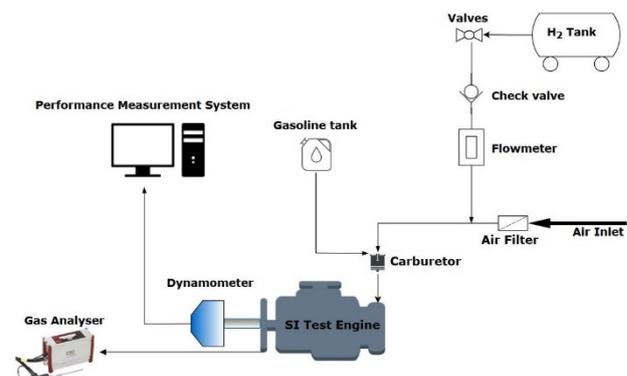


Figure 1. Schematic representation hydrogen-enriched test engine rig

Table 2. Technical specifications of the dynamometer

Descriptions	Specifications
Model	AG10
Make	Saj Test Plant Pvt. Ltd.
End flanges both side	Cardan shaft model 1260 type A
Water inlet	1.6 bar
Hot coil voltage max	60
Continuous current amps	5.0
Load	3.5 kg
Weight	130 kg
Speed max.	10000 rpm

In these experiments, an eddy current dynamometer was used for the determination of power output and a Sa-Beam load cell for setting the torque. The AG series bi-directional eddy current dynamometers can measure engines up to 400kW and it can be adopted with various control systems. Dynamometer load is measured by strain gauge load cell and the engine speed is

Table 5. Technical specifications of spark plugs used in experiments

SPECIFICATIONS	Type	Copper	Iridium	Platinum
	Band	BOSCH	NGK	NGK
	Parts No.	UR3DC	CR9EIX	CR9EHVX-9
	Thread Size	10 mm	10 mm	10 mm
	Thread Pitch	1.0 mm	1.0 mm	1.0 mm
	Seat Type	Gasket	Gasket	Gasket
	Resistor	Yes	Yes	Yes
	Resistor Value	5K Ohm	5K Ohm	5K Ohm
	Reach	19 mm	19 mm	19 mm
	Hex Size	16 mm	16 mm	16 mm
	Terminal Type	Threaded Stud	Threaded Stud	Threaded Stud
	Overall Height	ISO	ISO	Bantam
	Original SPG	0.7 mm	0.8 mm	0.7 mm
	Heat Range	8	8	8
	Longevity	30k	40-50k	50k
CENTER ELECTRODE	Material	Copper	Iridium	Platinum
	Type	Fine wire	Fine wire	Fine wire
	Size	2.5 mm	0.6mm	0.6 mm
GROUND ELECTRODE	Material	Copper	Nickel	Platinum
	Type	Standard	Standard	Standard

determined by shaft mounted 360 PPR rotary encoder. The technical specifications of the dynamometer and load cell are given in Table 2 and Table 3.

Table 3. Technical specifications of the load cell

Descriptions	Specifications
Model	60001
Type	S Beam Universal
Capacity	0-50 kg
Non-linearity	<+/-0.025%
Non-repeatability	<+/-0.010%
Operating temperature range	-20 °C to +70°C
Combined Error	<+/-0.025%

2.1.2. Emission measurement device

MRU Air Delta 1600 V mobile exhaust gas analyzer was utilized to measure exhaust emissions. With the help of analyzer software, necessary emission data was collected. Accuracy of the gas analyzer is ± 10 ppm for CO, 1% for CO₂ and ± 1 ppm for NO_x. In Table 4, measurement ranges, accuracy and resolution values of the emission device were shown.

Table 4. Measurement ranges, accuracy and resolution of the emission device

Descriptions	Specifications
CO	0-10%
CO ₂	0-20%
HC	0-20000 ppm
NO	0-4000 ppm
NO ₂	0-1000 ppm
Accuracy	According to OIML-class 1
Ambient Temperature	+5° - +45 °C
Exhaust Gas Temperature	Max 650 °C

2.1.3. Spark Plugs

In this study, three different spark plugs that are available commercially were used to evaluate their effects on the emission characteristics of the test engine. Technical specifications of copper (conventional), iridium and platinum spark plugs used in these experiments were given in Table 5.

2.2. Experimental Procedure

Throughout the engine experiments, H₂ with 99.99% purity was added through the intake manifold of the engine to reduce emissions out from the test engine. Emission measurement experiments were executed with two different CRs (8.5:1 and 10:1) at MBT. During the experiments, engine loads of 8 Nm, 13 Nm and 17 Nm were implemented to evaluate the effects of different spark plugs and hydrogen usage on emissions under different engine loads. Copper, iridium and platinum spark plugs were adopted with same spark plug gap size for each experiment condition. Besides, hydrogen was induced through the intake manifold with flow rates of 0 l/min (H0), 2 l/min (H2) and 4 l/min (H4) to enhance the combustion of VCR engine. Before experimental measurements, the engine was run for 5 minutes to attain stable operation conditions. Once the engine had warmed up, all experiments were performed approximately at 90 C°. As a result, brake-specific emissions of; carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x) and total unburned

hydrocarbon (UHC) were obtained to evaluate effects of applied methods on emission characteristics of the test engine.

3. Results and Discussion

In this study, each case was tested 5 times to validate the results. The results are given below are arithmetic means of these experiments. The uncertainty of CO, CO₂, NO_x, UHC emissions and brake power measurements were approximately $\pm 2.5\%$, $\pm 2\%$, $\pm 3\%$, $\pm 4\%$ and $\pm 5\%$, respectively.

3.1. CO Emissions

Figures 2-7 illustrate the brake specific CO emission results of the experiments. The formation of CO emission is directly related to the combustion completeness of the fuels and the insufficient amount of oxygen [32].

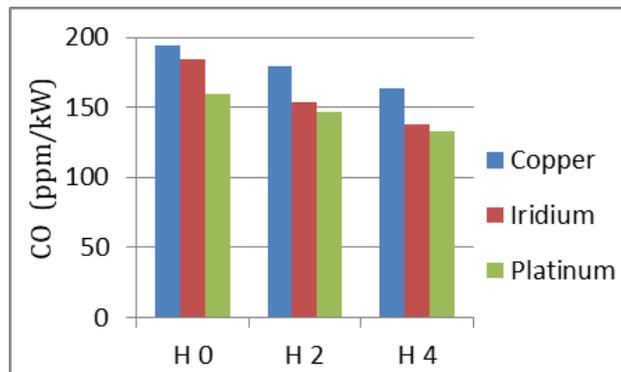


Figure 2 Brake specific CO emission values for engine load of 8 Nm and CR of 8.5:1

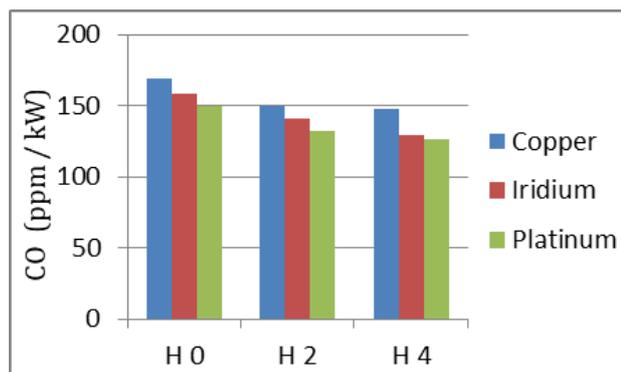


Figure 3 Brake specific CO emission values for engine load of 13 Nm and CR of 8.5:1

It can be seen from the figures that using iridium and platinum SPs reduced CO emissions remarkably at all engine loads. Probably, the higher charge density of these SPs triggered combustion completeness and helped to reduce incomplete combustion products [22, 42]. However, platinum SP reduced CO toxic emissions more than the iridium spark plug in

general. CO emissions were reduced between 1.01% - 15.77% for iridium spark plugs and 7.66% - 18.32% for platinum SP.

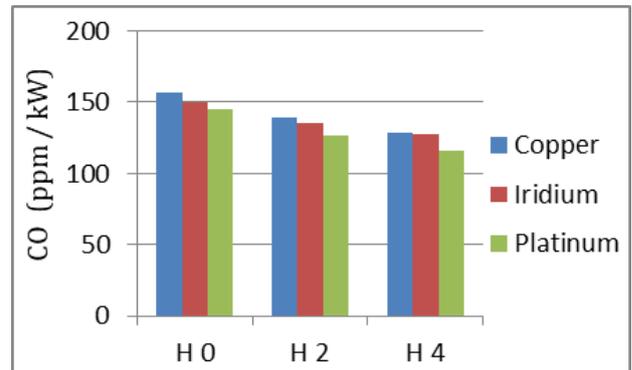


Figure 4 Brake specific CO emission values for engine load of 17 Nm and CR of 8.5:1

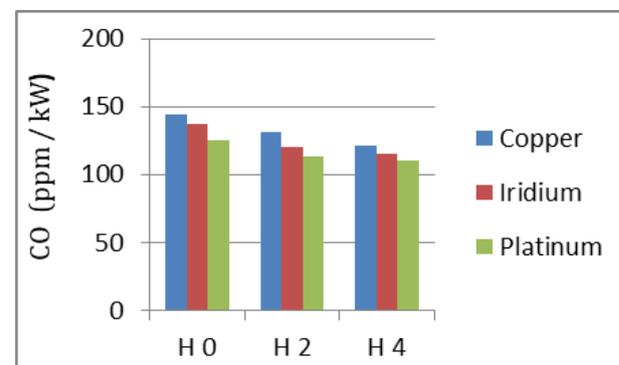


Figure 5 Brake specific CO emission values for engine load of 8 Nm and CR of 10:1

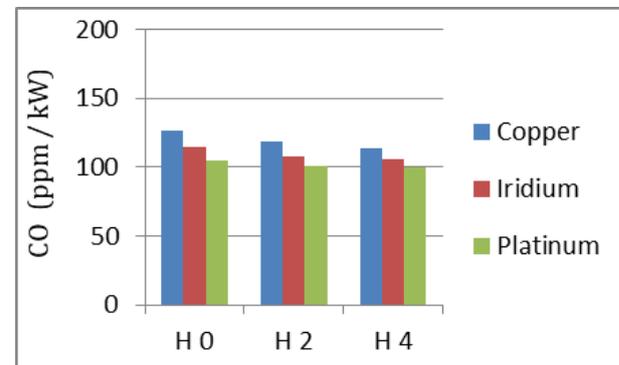


Figure 6 Brake specific CO emission values for engine load of 13 Nm and CR of 10:1

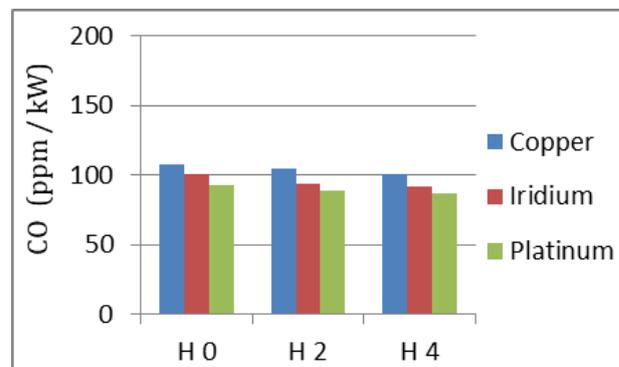


Figure 7 Brake specific CO emission values for engine load of 17 Nm and CR of 10:1

Moreover, hydrogen enrichment decreased CO emissions due to its combustion reaction accelerator function and carbonless structure. Induction hydrogen with the flow rate of 2 l/min (H2) and 4 l/min (H4) reduced CO emissions by 8.93% and 13.68% respectively on average compared to un-hydrogenated operations.

Besides, both higher a compression ratio and higher engine loads resulted in dropping incomplete emission products of CO at all combinations of hydrogen additions and spark plugs. The lowest CO emission out was recorded for the platinum spark plug, H4 fuel, 10:1 compression ratio and 17 Nm engine load combination.

3.2. CO₂ Emissions

As it can be seen from the Figures 8-13, for iridium and platinum SPs, higher CO₂ emissions were measured since these SPs improved the combustion and thus CO and UHC compositions are converted into CO₂ emissions. If they need to be compared, platinum SP increased CO₂ emissions more than iridium SP. CO₂ emissions were increased between 2.91% - 14.11% for iridium SPs and 5% - 25.49% for platinum SP. Nevertheless, hydrogen addition increased CO₂ formation, too. CO₂ emissions may have been expected to be lower because of the combustion of zero-carbon fuel, however, more complete combustion and increased UHC conversion into CO₂ were measured due to hydrogen's burning speed increasing function. As a result, the hydrogen addition of H2 and H4 increased CO₂ emissions by 16.83% and 45.13% respectively on average compared to H0 fuel. On the other hand, increasing compression ratio and engine torque increased CO₂ emissions due to more complete combustion.

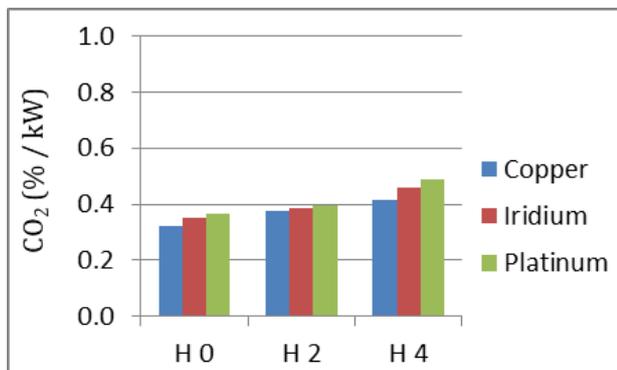


Figure 8 Brake specific CO₂ emission values for engine load of 8 Nm and CR of 8.5:1

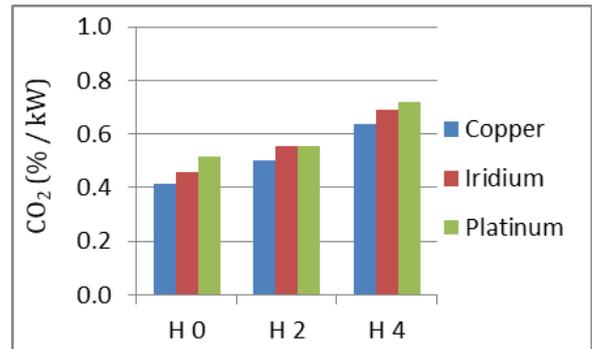


Figure 9 Brake specific CO₂ emission values for engine load of 13 Nm and CR of 8.5:1

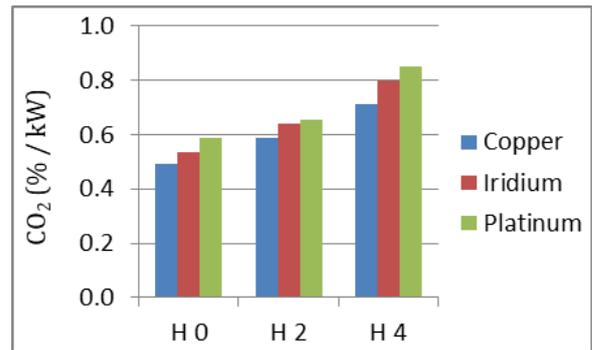


Figure 10 Brake specific CO₂ emission values for engine load of 17 Nm and CR of 8.5:1

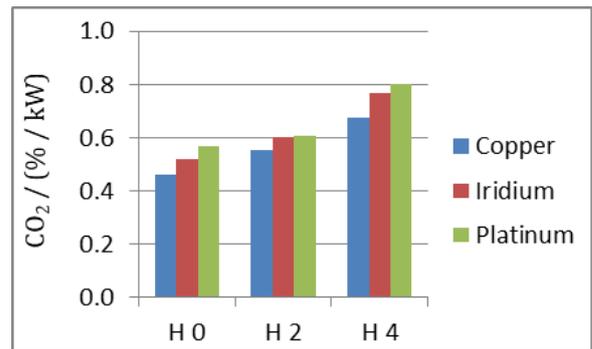


Figure 11 Brake specific CO₂ emission values for engine load of 8 Nm and CR of 10:1

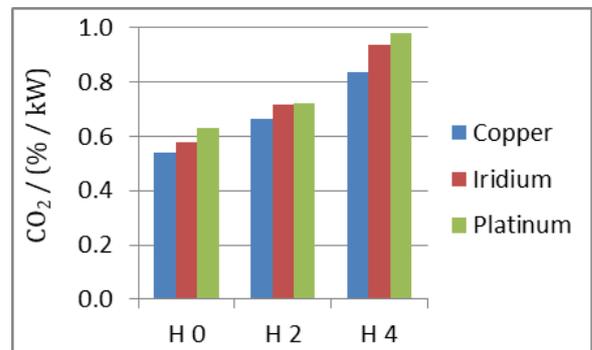


Figure 12 Brake specific CO₂ emission values for engine load of 13 Nm and CR of 10:1

3.3. NO_x Emissions

NO_x results of all tests are shown in Figure 14-19. NO_x emissions were increased when the platinum and iridium SPs were used due to the higher temperature accompanied by the increase

in flame speed and in-cylinder pressure. For platinum SP, the rise in NO_x became more obvious.

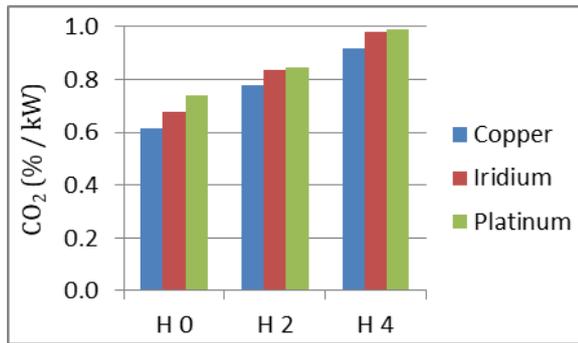


Figure 13 Brake specific CO₂ emission values for engine load of 17 Nm and CR of 10:1

Hydrogen enrichment triggered NO_x formation, too. Higher end-combustion temperature and flame velocity resulted from hydrogen combustion caused a dramatic rise in NO_x formation [43]. On average, 82.16% and 204.53% rise in NO_x emissions were measured for H2 and H4 test conditions, respectively. Moreover, at higher engine loads and higher compression ratios caused NO_x emissions out increment. For the 10:1 compression ratio, higher NO_x emissions by between 21-55.2 % were measured comparing with the 8:1 case.

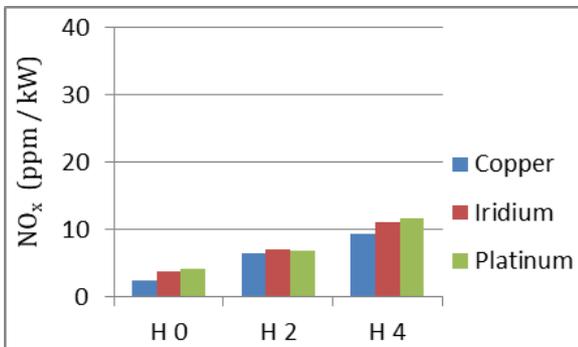


Figure 14 Brake specific NO_x emission values for engine load of 8 Nm and CR of 8.5:1

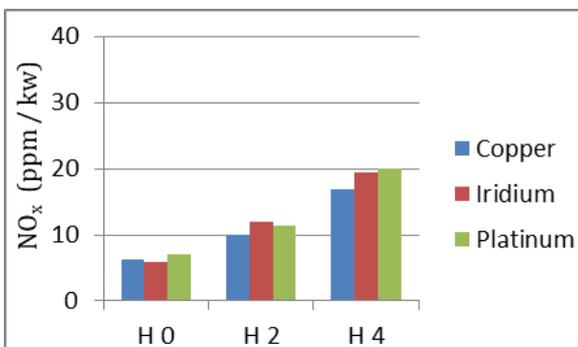


Figure 15 Brake specific NO_x emission values for engine load of 13 Nm and CR of 8.5:1

3.4. UHC Emissions

It can be seen from Figure 20-25, iridium and

platinum SP decreased UHC emission because of improved combustion, remarkably. Platinum SP reduced UHC emissions more than iridium SP. UHC emissions were decreased between 2.51% - 19.59% for iridium SPs and 7.62% - 24.12% for platinum SP.

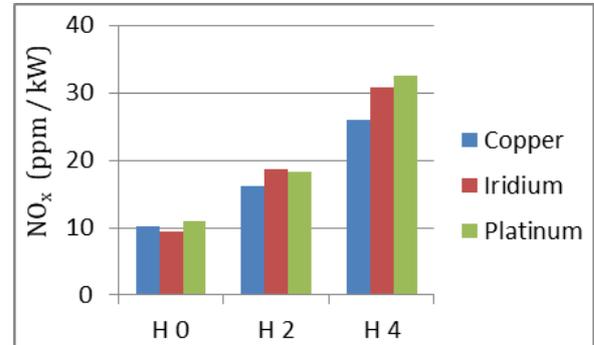


Figure 16 Brake specific NO_x emission values for engine load of 17 Nm and CR of 8.5:1

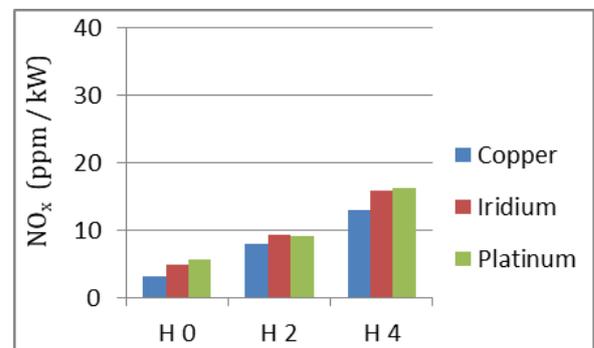


Figure 17 Brake specific NO_x emission values for engine load of 8 Nm and CR of 10:1

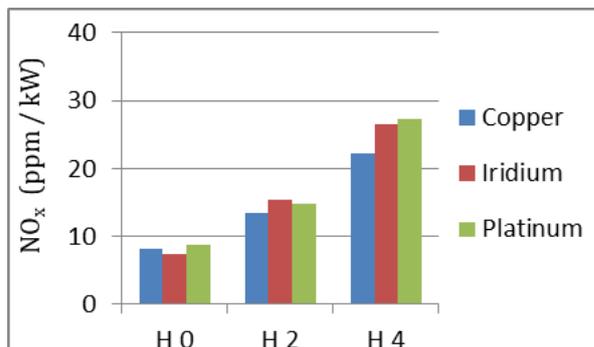


Figure 18 Brake specific NO_x emission values for engine load of 13 Nm and CR of 10:1

Moreover, UHC emissions were effectively reduced with the increment of the hydrogen flow rate. According to the test results, the brake specific UHC emissions were dropped by 16.62% and 25.92% with H2 and H4 test fuel, respectively. This result can be attributed to the improvement of the combustion quality through the shorter combustion duration and hydrogen addition that lead to more complete combustion. Additionally, increasing the engine load and compression ratio of the test engine, lower UHC

was emitted which is an incomplete emission product. The lowest UHC emission out was measured for the platinum spark plug, H4 fuel, 10:1 compression ratio and 17 Nm engine load case.

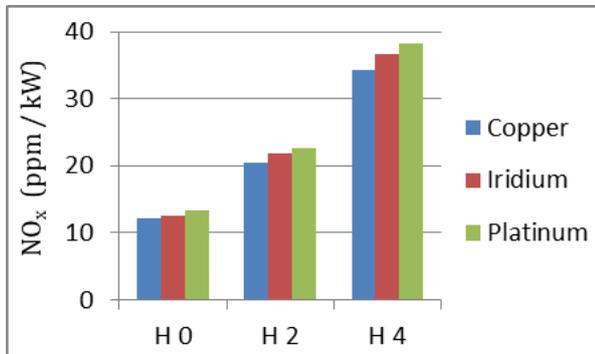


Figure 19 Brake specific NO_x emission values for engine load of 17 Nm and CR of 10:1

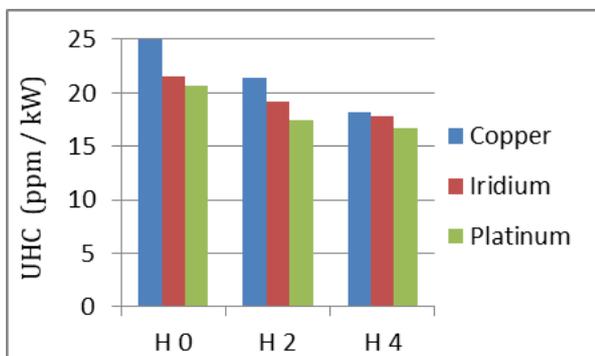


Figure 20 Brake specific UHC emission values for engine load of 8 Nm and CR of 8.5:1

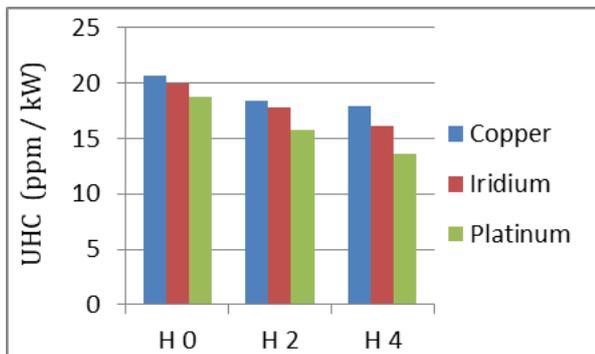


Figure 21 Brake specific UHC emission values for engine load of 13 Nm and CR of 8.5:1

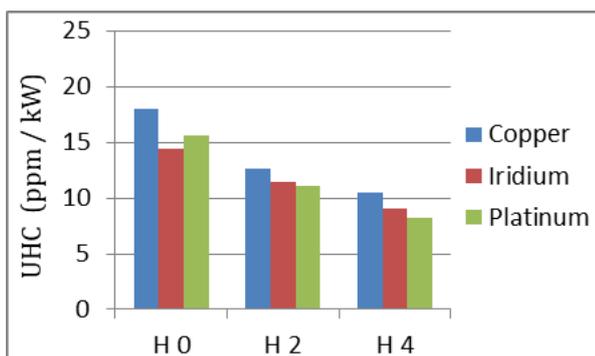


Figure 22 Brake specific UHC emission values for engine load of 17 Nm and CR of 8.5:1

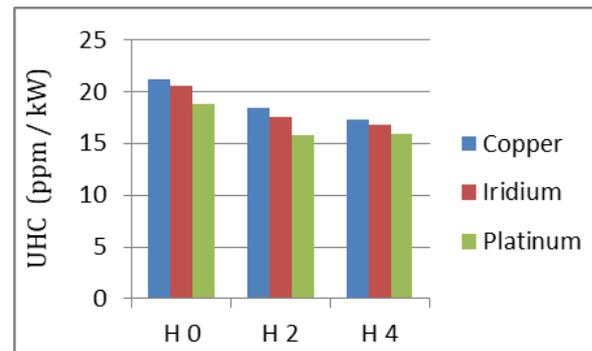


Figure 23 Brake specific UHC emission values for engine load of 8 Nm and CR of 10:1

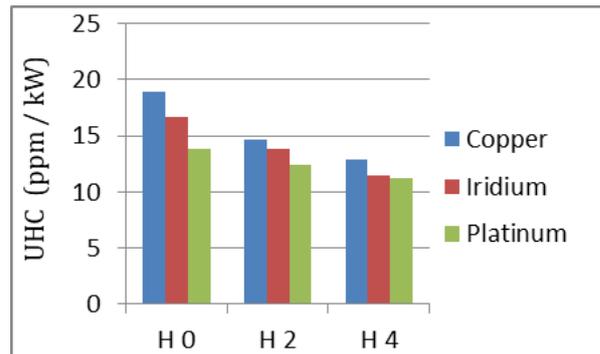


Figure 24 Brake specific UHC emission values for engine load of 13 Nm and CR of 10:1

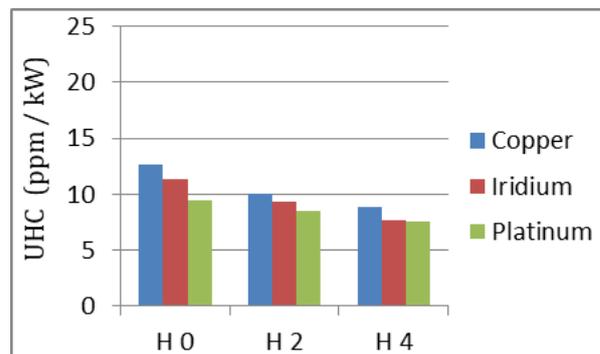


Figure 25 Brake specific UHC emission values for engine load of 17 Nm and CR of 10:1

4. Conclusions

In this study, emission characteristics of an SI engine equipped with different SPs at various CRs, fuelled with pure gasoline and different hydrogen-gasoline bi-fuels were determined. During the experiments the engine CR was set as 8.5:1 and 10:1 and copper, platinum and iridium SPs were performed one by one. Besides, each test condition was executed at different dynamometer loads which are 8 Nm, 13 Nm and 17 Nm. According to experimental results, the following conclusions can be summarized;

- Changing conventional (copper) spark plug with iridium and platinum spark plugs resulted in lower CO and HC and higher CO₂ and NO_x

emissions at all compression ratios, engine loads and hydrogen flow rates.

- Variations in emission parameters mentioned above were more obvious for platinum spark plug than iridium type.
- Similar to spark plug changing, hydrogen addition increased CO₂ and NO_x and reduced CO and UHC values compared to unhydrogenated fuels.
- It is observed that higher CR and engine load provided lower HC and CO emissions and higher CO₂ and NO_x emissions were emitted.

List of Abbreviations and Nomenclature

BTDC	: Before top dead center
CNG	: Compressed natural gas
CO	: Carbon monoxide emissions (ppm/kW)
CO ₂	: Carbon dioxide emissions (ppm / kW)
CR	: Compression ratio
H	: Hydrogen
H 0	: No hydrogen addition
H 2	: 2 l/min hydrogen addition
H 4	: 4 l/min hydrogen addition
l	: Liter
MBT	: Maximum brake torque
min	: Minute
n	: Engine speed (RPM)
NO _x	: Nitrogen oxides emissions (ppm / kW)
PPM	: Particulate per million
SI	: Spark ignition
SP	: Spark plug
SPG	: Spark plug gap
UHC	: Total - unburned hydrocarbon emissions (ppm/kW)
VCR	: Variable compression ratio

5. References

1. S. Yousufuddin, "Experimental study on combustion duration and performance characteristics of a hydrogen-ethanol dual fueled engine", *International Journal of Automotive Engineering and Technologies*, 5 (3), 85–101, 2016.
2. O. Baş et al., "Effect of Spark Plug Alteration on Performance Using Hydrogen Enriched Gasoline in Si Engine Under Various Loads and Compression Ratios", *European Mechanical Science*, 2 (3), 92–95, 2018.
3. C. Brand, "Beyond 'Dieselgate': Implications of unaccounted and future air pollutant emissions and energy use for cars in the United Kingdom", *Energy Policy*, 97, 1–12,

2016.

4. ACEA, "Share of Diesel in New Passenger Cars - 2017", *European Automobile Manufacturers Association*, 2017.
5. M.K. Balki et al., "Experimental Study and Prediction of Performance and Emission in an SI Engine Using Alternative Fuel with Artificial Neural Network", *International Journal of Automotive Engineering and Technologies*, 7 (1), 58–64, 2018.
6. H. Özcan and A. Çakmak, "Comparative Exergy Analysis of Fuel Additives Containing Oxygen and HC based in a Spark-Ignition (SI) engine", *International Journal of Automotive Engineering and Technologies*, 7 (3), 124–133, 2018.
7. A.A. Yontar, "Numerical Comparative Mapping Study to Evaluate Performance of a Dual Sequential Spark Ignition Engine Fuelled with Ethanol and E85", *International Journal of Automotive Engineering and Technologies*, 7 (3), 98–106, 2018.
8. E. Arabacı, "Thermodynamic analysis of endoreversible six-stroke Otto cycle with respect to equivalence ratio, residual gas fraction and mean piston speed", *International Journal of Automotive Engineering and Technologies*, 8 (1), 1–10, 2019.
9. O.H. Ghazal, "Performance and combustion characteristic of CI engine fueled with hydrogen enriched diesel", *International Journal of Hydrogen Energy*, 38 (35), 15469–15476, 2013.
10. B. Zhang et al., "Combustion and emissions characteristics of a spark-ignition engine fueled with hydrogen-methanol blends under lean and various loads conditions", *Energy*, 74, 829–835, 2014.
11. M. Kaplan, "Influence of swirl, tumble and squish flows on combustion characteristics and emissions in internal combustion engine-review", *International Journal of Automotive Engineering and Technologies*, 8 (2), 83–102, 2019.
12. D. Jung, K. Sasaki, and N. Iida, "Effects of increased spark discharge energy and enhanced in-cylinder turbulence level on lean limits and cycle-to-cycle variations of combustion for SI engine operation", *Applied Energy*, 205, 1467–1477, 2017.
13. Y. Karagöz et al., "Effect of hydrogen addition on exhaust emissions and performance

of a spark ignition engine", *Environmental Engineering and Management Journal*, 14 (3), 665–672, 2015.

14. C. Ji et al., "Effect of hydrogen addition on combustion and emissions performance of a gasoline rotary engine at part load and stoichiometric conditions", *Energy Conversion and Management*, 121, 272–280, 2016.

15. F. Amrouche et al., "An experimental investigation of hydrogen-enriched gasoline in a Wankel rotary engine", *International Journal of Hydrogen Energy*, 39 (16), 8525–8534, 2014.

16. O.O. Taskiran, "Fuel-air mixing process of low pressure direct injection in a side ported rotary engine", *International Journal of Automotive Engineering and Technologies*, 8 (4), 186–194, 2019.

17. B.A. Ceper, "Experimental investigation of the effect of spark plug gap on a hydrogen fueled SI engine", *International Journal of Hydrogen Energy*, 37 (22), 17310–17320, 2012.

18. H.T. Lin et al., "Characterization of erosion and failure processes of spark plugs after field service in natural gas engines", *Wear*, 259 (7–12), 1063–1067, 2005.

19. S. Javan, S.V. Hosseini, and A.S. Sh, "An experimental investigation of spark plug temperature in bi-fuel engine and its effect on electrode erosion", *International Journal of Automotive Engineering*, 2 (1), 21–29, 2012.

20. A. Ortiz et al., "Spark plug failure due to a combination of strong magnetic fields and undesirable fuel additives", *Case Studies in Engineering Failure Analysis*, 1 (2), 67–71, 2013.

21. F.A. Soldera et al., "Description of the discharge process in spark plugs and its correlation with the electrode erosion patterns", *IEEE Transactions on Vehicular Technology*, 53 (4), 1257–1265, 2004.

22. N. Pavel et al., "Laser ignition - Spark plug development and application in reciprocating engines", *Progress in Quantum Electronics*, 58, 1–32, 2018.

23. C. Poggiani et al., "Experimental Characterization of a Multiple Spark Ignition System", *Energy Procedia*, 82, 89–95, 2015.

24. T.I. No, "All About Spark Plugs", *Beru*, (02), 2005.

25. F. Amrouche et al., "Extending the lean operation limit of a gasoline Wankel rotary engine using hydrogen enrichment",

International Journal of Hydrogen Energy, 41 (32), 14261–14271, 2016.

26. B. Kurşun and K. Ökten, "Thermodynamic analysis of a Rankine cycle coupled with a concentrated photovoltaic thermal system for hydrogen production by a proton exchange membrane electrolyzer plant", *International Journal of Hydrogen Energy*, 44 (41), 22863–22875, 2019.

27. P. Dimitriou and T. Tsujimura, "A review of hydrogen as a compression ignition engine fuel", *International Journal of Hydrogen Energy*, 42 (38), 24470–24486, 2017.

28. Y. Sun, X. Yu, and L. Jiang, "Effects of direct hydrogen injection on particle number emissions from a lean burn gasoline engine", *International Journal of Hydrogen Energy*, 41 (41), 18631–18640, 2016.

29. T. Su et al., "Investigation on performance of a hydrogen-gasoline rotary engine at part load and lean conditions", *Applied Energy*, 205, 683–691, 2017.

30. B. Zhang, C. Ji, and S. Wang, "Performance of a hydrogen-enriched ethanol engine at unthrottled and lean conditions", *Energy Conversion and Management*, 114, 68–74, 2016.

31. X. Zhen et al., "Study of knock in a high compression ratio spark-ignition methanol engine by multi-dimensional simulation", *Energy*, 50, 150–159, 2013.

32. H. Serin and Ş. Yildizhan, "Influence of the compression ratio on the performance and emission characteristics of a vcr diesel engine fuelled with alcohol blended fuels", *European Mechanical Science*, 1 (2), 39–46, 2017.

33. R. Thomas et al., "Experimental evaluation of the effect of compression ratio on performance and emission of SI engine fuelled with gasoline and n-butanol blend at different loads", *Perspectives in Science*, 8, 743–746, 2016.

34. Ş. Yildizhan et al., "Fuel properties, performance and emission characterization of waste cooking oil (WCO) in a variable compression ratio (VCR) diesel engine", *European Mechanical Science*, 1 (2), 56–62, 2017.

35. B.L. Salvi and K.A. Subramanian, "Experimental investigation on effects of compression ratio and exhaust gas recirculation on backfire, performance and emission

- characteristics in a hydrogen fuelled spark ignition engine", *International Journal of Hydrogen Energy*, 41 (13), 5842–5855, 2016.
36. İ. Altın, A. Bilgin, and B.A. Çeper, "Parametric study on some combustion characteristics in a natural gas fueled dual plug SI engine", *Energy*, 139, 1237–1242, 2017.
37. S. Yamaguchi et al., "Dual-Point Laser Ignition and its Location Effects on Combustion in Lean-Burn Gas Engine", *SAE International Journal of Engines*, 2015.
38. C. Ji et al., "Effect of dual-spark plug arrangements on ignition and combustion processes of a gasoline rotary engine with hydrogen direct-injection enrichment", *Energy Conversion and Management*, 181, 372–381, 2019.
39. S.P.M. Bane, J.L. Ziegler, and J.E. Shepherd, "Investigation of the effect of electrode geometry on spark ignition", *Combustion and Flame*, 162 (2), 462–469, 2015.
40. İ. Altın and A. Bilgin, "A parametric study on the performance parameters of a twin-spark SI engine", *Energy Conversion and Management*, 50 (8), 1902–1907, 2009.
41. D. Jung and N. Iida, "An investigation of multiple spark discharge using multi-coil ignition system for improving thermal efficiency of lean SI engine operation", *Applied Energy*, 212, 322–332, 2018.
42. J.D. Dale, M.D. Checkel, and P.R. Smy, "Application of high energy ignition systems to engines", *Progress in Energy and Combustion Science*, 23 (5–6), 379–398, 1997.
43. İ. Sezer, "A Review Study on the Using of Diethyl Ether in Diesel Engines: Effects on NO_x Emissions", *International Journal of Automotive Engineering and Technologies*, 7 (4), 164–183, 2018.