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

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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 (NOₓ) 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 NOₓ 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 NOₓ 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 NOx 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\textsubscript{x} emission increases. However, NO\textsubscript{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\textsubscript{2}), nitrogen oxides (NO\textsubscript{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

| Description          | Specification          |
|----------------------|------------------------|
| 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  | 0-25º BTDC             |
| Peak Pressure        | 77.5 kg/cm\textsuperscript{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

| Description           | Specification |
|-----------------------|---------------|
| 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    | 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 | CR9EHSVX-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     |          |

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 NOₓ. 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%          |
| CO₂                   | 0-20%          |
| HC                    | 0-20000 ppm    |
| NO                    | 0-4000 ppm     |
| NO₂                   | 0-1000 ppm     |
| Accuracy              | According to OIML-class 1 |
| Ambient Temperature   | +5° to +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 (NOₓ) 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, NOₓ, UHC emissions and brake power measurements were approximately ±2.5%, ±2%, ±3%, ±4% and ±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].

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.
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.

3.3. NOx Emissions

NOx results of all tests are shown in Figure 14-19. NOx 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\textsubscript{x} became more obvious.

Hydrogen enrichment triggered NO\textsubscript{x} formation, too. Higher end-combustion temperature and flame velocity resulted from hydrogen combustion caused a dramatic rise in NO\textsubscript{x} formation [43]. On average, 82.16% and 204.53% rise in NO\textsubscript{x} emissions were measured for H2 and H4 test conditions, respectively. Moreover, at higher engine loads and higher compression ratios caused NO\textsubscript{x} emissions out increment. For the 10:1 compression ratio, higher NO\textsubscript{x} emissions by between 21-55.2 % were measured comparing with the 8:1 case.

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 emissions were measured.
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.

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 NOₓ.
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 CO\(_2\) 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 CO\(_2\) and NO\(_x\) emissions were emitted.

**List of Abbreviations and Nomenclature**

| Abbreviation | Description |
|--------------|-------------|
| 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 |

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