Engine performance, emissions characteristics of the compression ignition engine using HHO gas (Brown’s gas)

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Abstract. HHO gas (Brown’s gas) has recently been used as a new source of energy. The study presents the experimental results at 50% of the accelerator pedal when installed hydroxy (HHO) gas generator on 490 QZL diesel engines. HHO gas was provided into the engine manifold. Comparing the experimental results found that: the economic, technical and exhaust emissions of the diesel engine was improved. The brake power index increased by 2.8% in average compared to pure diesel and 4.2% was the percentage of the maximum engine power increasing at 2200 rpm. Especially, the amount of brake specific fuel consumption (BSFC) in pure diesel was always higher than one in diesel with HHO gas, which was 13.7% in average. At 1800 rpm, the difference of the minimum value of BSFC in two cases was 12.6%. The HC and CO emissions value reduced by 7.7% and 19.8% in average, respectively, while NOx increased by 13.3% in average compared to pure diesel.

1. Introduction

The internal combustion engine (ICE) is widely used in the world because of their higher thermal and economic efficiencies than other types. However, it is one of the major sources of air pollution with toxic substances such as carbon monoxide (CO), sulfur oxides (SOx), hydrocarbons (HC), especially particulate matter (PM) and nitrogen oxides (NOx). In addition, fossil fuels (oil, coal, gas) are the primary fuel for ICE while their reserves in nature are being depleted. This problem becomes too exacerbate with the increasing of vehicle numbers. In recent years, many studies have been done to find solutions to the above problems. Including use of catalytic convert and particle filters; bio fuel; redesign and improvement the engine structure [1, 2, 3].

Regarding to diesel engines, the tightening environmental requirements and the need to improve their energy efficiency have led to the implement the following solutions:

- Increasing the injection pressure up to 3000 bar [4, 5];
- Ensuring the required shape of the tip edge of the injection characteristic [6, 7], taking into account the wave phenomena arising during fuel injection [8];
- Controlling of fuel distribution by the combustion chamber zones [9];
- Converting diesel into gas engine or gas-diesel [10, 11].

One of the most effective solutions is to use that using hydrogen as a fuel, which is characterized by high energy efficiency and without impurities.

There are different ways to use hydrogen. One of these is the production and storage of hydrogen
[12, 13, 14, 15]. In this way, the hydrogen is compressed into the tanks and installed on the vehicle, therefore, vehicles need to redesign to have space for hydrogen tanks, and to ensure safety when operating. In addition, it is necessary to have a hydrogen distribution station system for vehicles [16]. As a result, it makes the use of hydrogen more complicated and increases costs. Another way is to produce HHO in a generator by the electrolysis of water, which is being studied and widely applied. The HHO gas can be injected with diesel fuel or supplied into the engine's manifold [16, 17, 18, 19]. The generator can be wet or dry type. This is the most basic method for making almost pure hydrogen [20]. The amount of hydrogen formed depends on the number of the electrode plates, the current supply as well as the electrolyte of solution [21, 22].

The resulting HHO gas is colourless and tasteless. The major components of HHO gas are H₂ and O₂, with H₂ accounting for 60.79%, O₂ accounting for 30.39% and a small amount of water vapor, O, OH ions and some other active elements [23]. Molar mass of HHO gas is 12.3 g/mol. At a pressure level of p = 0.1 MPa and at a temperature of T = 0°C, the density of oxygen gas is ρ_o = 1.43 kg/m³, the density of hydrogen gas is ρ_H₂ = 0.09 kg/m³, and the density of the HHO gas is ρ_HHO = 0.54 kg/m³ [26]. The energy in one-liter HHO is about 600J (± 34 J). The HHO gas is unstable and can live for about 11 minutes [24]. After the active elements of the HHO disappear, what it leaves is a mixture gas of common H₂ and O₂, with a volume ratio of 2:1. The lower heating value of hydrogen is almost three times that of diesel, but hydrogen has an auto-ignition temperature of 585°C, so hydrogen cannot be used directly in compression ignition engines without spark plugs or glow plugs [25].

In this study, the HHO gas generator will be manufactured and installed for the experiment. The HHO gas was fed into the engine's intake manifold. The values of engine power, brake specific fuel consumption and exhaust emissions were collected, analysed and compared in two cases that is pure diesel and diesel with HHO gas. The results received will be the basis for improvements of diesel engines.

2. Experimental setup

2.1. Principle of the HHO generation process

The HHO generator works on the principle of water electrolysis that generates hydrogen and oxygen. Diagram of the electrolysis principle is displayed in Figure 1. The electrolysis process uses direct current with inert electrodes. Reactions taking place at the electrodes are given below:

\[
\begin{align*}
\text{At cathode:} & \quad 2\text{H}_2\text{O} + 2e & \rightarrow & \text{H}_2 + 2\text{OH}^- \\
\text{At anode:} & \quad 4\text{OH}^- & \rightarrow & \text{O}_2 + 2\text{H}_2\text{O} + 4e \\
\text{Overall reaction:} & \quad 2\text{H}_2\text{O} & \rightarrow & 2\text{H}_2 + \text{O}_2
\end{align*}
\]
The amount of gas from electrolysis is calculated following the second Faraday’s law:

\[
m = \frac{A \cdot t \cdot I}{z \cdot F},
\]

where:
- \( m \) is the mass of the substance liberated at an electrode in grams
- \( F = 96,485 \, \text{C/mol} \) is the Faraday constant
- \( A \) is the molar mass of the substance in grams per mol
- \( z \) is the valency number of ions of the substance (electrons transferred per ion).
- \( t \) is the total time the constant current was applied.
- \( I \) is electric current in Amperes

The volume of gas in ideal gas conditions is determined by the formula (5):

\[
V = \frac{q \cdot R \cdot T \cdot t}{p \cdot z \cdot F}
\]

where:
- \( V \) is volume of gas (l)
- \( R \) is ideal gas constant (l.atm/(mol.K))
- \( p \) is ambient pressure (atm)
- \( T \) is temperature (K)
- \( q \) is number of water compartments

### 2.2. HHO generator

The optimal surface of electrolyte needed to generate sufficient amount of HHO was 20 times the piston area and the volume of water needed in electrolysis cell was about 1.5 times that of engine capacity [27]. Moreover, the input voltage to the electrodes must be higher than the minimum dissociation voltage of ions in the water. For these reasons, the electrodes are made of stainless steel, which contains at least 7% nickel, 16% chromium and 0.08% (maximum concentration) of carbon.

In Figure 2 shows the HHO gas generator diagram. It is made with dry cells following the scheme – nnn + nnn–, where n is a plate of 304 stainless steels with dimensions 140 x 140 x 1 mm (width x length x thickness). In Figure 3 shows the experimental model of the gas generator.

In order to increase the efficiency of the electrolytic process, an electrolyte solution using concentration of NaOH is used.

![Figure 2. Diagram of a gas generator for the HHO gas production.](image)

![Figure 3. An experimental model of a gas generator for the HHO gas production.](image)

The relationship between electrolytic efficiency for using different concentrations of NaOH at different engine speeds Figure 4, which can be seen that 4 g/L of NaOH concentration gave the highest efficiency of the electrolysis process compared to other NaOH concentration at different engine speeds [28].
Figure 4. Average efficiencies for using different concentrations of NaOH at different engine speeds [28].

2.3. Experimental equipment
The experimental diagram is shown in Figure 5. Table 1 compares the properties of hydrogen and diesel [25, 29]. The detail of the test engine is listed in the Table 2.

Table 1. Properties of diesel and hydrogen [25, 29].

| Properties                          | Diesel      | Hydrogen   |
|-------------------------------------|-------------|------------|
| Density (kg/m³) at 16°C and 1.01 bar| 840         | 0.082      |
| Lower heating value (MJ/kg)         | 42.7        | 120.21     |
| Higher heating value (MJ/kg)        | 45.58       | 142.18     |
| Flame velocity (m/s)               | 0.3         | 2.70       |
| Auto ignition temp. (°C)            | 254-285     | 585        |
| Carbon residue (%)                 | 0.1         | 0.0        |
| Stoichiometric AFR on mass basic    | 14.7        | 34.3       |
| Molar mass (kg/kmol)               | 200         | 2.02       |

Table 2. Experimental engine specification.

| Stroke (mm) | 100  |
| Bore (mm)   | 90   |
| Number of cylinders (-) | 4    |
| Connecting rod length (mm) | 200  |
| Maximum power at 3200 rpm (Hp) | 80   |
| Torque at 2200 rpm (N.m)       | 230  |
| Diesel fuel injection            | Inline Pump |
| Compression ratio (-)            | 17    |
To measure the parameters of the diesel engine during the experiment, Dyno max 2012 software is used. In addition, the 5-component exhaust analysis system - DYNOmite Exhaust Measuring System – is connected. Exhaust gas 5-components include HC, CO, NO\textsubscript{x}, O\textsubscript{2}, and CO\textsubscript{2}.

3. Experimental results and evaluation
The economic, technical and exhaust emission parameters of the engine are measured when the engine runs at 50% of the accelerator pedal with different engine speeds and a jump of 200 rpm. The results are as follows:

3.1. Engine performance

3.1.1. Brake power
The variation of brake power when using diesel and diesel with HHO is demonstrated in Figure 6. Both of these cases, brake power value increases when engine speeds is from 1400 to 2200 rpm, while the engine speeds between 2200 and 2400 rpm, brake power value decreases. The engine performance is improved when HHO gas is added. The brake power index increases by 2.8% in average compared to pure diesel and 4.2% is the percentage of the maximum engine power increasing at 2200 rpm.

It can be explained because of the addition of oxygen concentration from the water electrolysis. At the same time, the additional gas component has OH\textsuperscript{-}, therefore, it increases the fire reaction area of fuel. In addition, due to the high burning rate and calorific value of hydrogen, the delayed combustion decreases, the burning time is shorter, and the heat loss is less. A mixture of diesel-hydrogen can be more ignited and quickly combusted than using the pure diesel. The combustion of the engine improves, the thermal efficiency increases, so the engine power increases with HHO gas.

3.1.2. Brake specific fuel consumption (BSFC).
Figure 7 shows the variation of BSFC with engine speed in both cases. The BSFC greatly reduces with speeds from 1400 to 1800 rpm. When speeds from 1800 rpm to 2000 rpm, BSFC fluctuates slightly and reaches the lowest point of value. BSFC increases rapidly as the speed between 2000 and 2400 rpm. The BSFC in pure diesel is always higher than one in diesel with HHO gas, which is 13.7% in average. At 1800 rpm, the difference of the minimum value of BSFC in two cases is 12.6%. BSFC decreased because the HHO is supplied on the intake manifold so times for diffusion, mixing HHO gas with fresh air increases. Gas mixture is better. At the same time, the oxygen value from the electrolysis process is also added to the mixture. OH ions have a large impact radius, which affects the C-H chains of the fuel, therefore, combustion reaction efficiency in combustion chamber is improved. In addition, with the high speed (a 2000 rpm), the diesel-air mixture is difficult to completely burn at lean conditions because of
the increase in the residual gas fraction and poor mixing. HHO has a wide ignition ability and high fire rate, which improves significantly the combustion at the high speed conditions.

3.2. Exhaust gas emissions

3.2.1. HC emissions
The relationship between HC and engine speed is illustrated in Figure 8. HC value is the unburnt fuel. When engine speed rises, which decreases the time of fuel combustion process, as the result the amount of unburnt fuel increases. However, when the HHO gas is added, the rate and burning area of the flame in the combustion chamber are improved, therefore, HC value goes down. HC decreases by 7.7% in average compared to pure diesel.

![Figure 8. Variation of hydrocarbon (HC) emissions with engine speed.](image1)

![Figure 9. Variation of carbon monoxide (CO) emissions with engine speed.](image2)

3.2.2. CO emissions
CO variation is similar to the change of HC. As the engine speed increases, the turbulence of the gas flow in the combustion chamber goes up, therefore, the amount of CO decreases in both cases. CO decreases with addition of HHO gas, which can be explained because HHO has a wide combustion range and a high burning rate, and the HHO component has oxygen and active OH ions. The OH ions have a powerful impact on H-C chain of diesel fuel. Moreover, the amount of oxygen is added to help the combustion reaction of the fuel completely. As a result, the CO value reduces by 19.8% in average. Experimental results are shown in Figure 9.

![Figure 10. Variation of nitrogen oxides (NO_x) emissions with engine speed.](image3)
3.2.3. NO\textsubscript{x} emissions

NO\textsubscript{x} generation requires three simultaneous conditions, including high temperature, more oxygen concentration for reaction with nitrogen and large combustion area. When the engine speed increases, the burning time in each cycle decreases, therefore, the reaction time between oxygen and nitrogen reduces, which leads to the amount of NO\textsubscript{x} declines. Figure 10 demonstrates the NO\textsubscript{x} value when using pure diesel and diesel with HHO gas. Overall, there is an increase in the NO\textsubscript{x} value when using HHO generator. It can be seen that the amount of NO\textsubscript{x} increases by 13.3% in average, which is caused by adding the oxygen to the fuel combustion reaction. Besides, HHO gas has an impact on the burning area, and high temperature area in the combustion chamber. As a result, NO\textsubscript{x} goes up at all measuring points.

4. Conclusions

In this study, HHO gas was provided into the engine manifold. The effects of HHO gas on the economic, technical and emission parameters of the diesel engine were presented. These values were compared to pure diesel with the corresponding values. Should be noted:

- The dry type of HHO generator is designed, manufactured and installed on engine test bed for experiment which have small diameter and easy to install on vehicles.
- The experimental investigation on diesel engine with the HHO gas generator at 50% of the accelerator pedal, the results showed that improvement of engine power, brake specific fuel consumption and exhaust emissions over the measuring speed range.
  - The brake power index increased by 2.8% in average compared to pure diesel and 4.2% was the percentage of the maximum engine power increasing at 2200 rpm. The BSFC in pure diesel was always higher than one in diesel with HHO gas, which was 13.7% in average. At 1800 rpm, the difference of the minimum value of BSFC in two cases was 12.6%.
  - The HC and CO emissions value reduced by 7.7% and 19.8% in average respectively, while NO\textsubscript{x} increased by 13.3% in average compared to pure diesel.

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