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Optimizing the Ignition Timing of a Converted CNG Mono-gas Engine

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Abstract. Governmental policies on renewable energy and environmental act are aggressively being enforced to mitigate recent climate change. Natural gas is not renewable but it is the most abundant and has the lowest Lifecycle CO2 emission among fossil fuel. Realizing such promising alternative, many logistics and transportation companies are converting their existing diesel-fueled vehicle to CNG-fueled. Researchers have shown that CNG engines offer advantages compared to diesel and gasoline engines such as high efficiency and low emissions. Prior to this work, a 4.3L 4-cylinder diesel engine was modified and retrofitted with a CNG mono gas system. However, it was observed that the engine, CNG-fueled combustion is not stable especially at idling speed. The purpose of this study is to optimize the ignition timing best suited for idling both in normal operating mode (700-850 rpm) and in cold start mode (1000-2000 rpm). The ignition timings tested were 20°BTDC and 25°BTDC. The measurements were made at engine speeds from 700 to 2500 rpm. Some irregularities were found in the result, but overall, the ignition timing 25°BTDC is better than 20°BTDC in terms of fuel consumption and exhaust gas emissions. For this particular system, the results recommend that the idling engine speed should be at 700-800 rpm and 1500 rpm during the normal mode and cold start mode respectively. The use of engine speed of 1000 to 1300 rpm should be minimized to reduce overall exhaust gas emissions.

Introduction

The price of fossil fuels and recent climate change concerns among governmental bodies has led to aggressive enforcement of green and environmental policies throughout the world. All those policies have one common aim, which is to minimize the degradation of the environment while conserving the use of energy and natural resources. Until today, most shipping and logistics companies still use diesel to fuel their medium-duty, heavy-duty engines and prime mover vehicles. All these vehicles partly contribute to the pollution of our green environment. Addressing this area, a study was done by Battelle, NREL and West Virginia University. Significant exhaust gas emissions improvement was gained by modifying diesel-fueled trucks into CNG-fueled. The converted CNG engines produces 25% lower carbon monoxide, 49% lower nitrogen oxides and up to 95% lower particulate matter compared to the standard diesel engine [1].

Compressed Natural Gas (CNG) is not renewable but it is the most abundant and has the lowest Lifecycle CO2 emission among fossil fuel. CNG engines offer several advantages compared to diesel and gasoline engines such as high efficiency and low emissions while operating in lean mode [2-4]. It has long been used in stationary engines, but the application of CNG as a transport engine's fuel has been considerably advanced over the last decade with the development of lightweight high-pressure storage cylinders [5].

Researches on CNG-fueled engine ignition timing have been done by Hassan et al. in [6] and Kakaee et al. in [7]. Hassan et al. demonstrated the characteristic of engine performance when the ignition angle was varied between 22°BTDC and 34°BTDC. These ignition timings have been selected according to the characteristic of the single cylinder CNGDI engine as reported in previous
experiment conducted by the author. The torque and power trend indicate an arc with a gradient after 29°BTDC. Thus, it showed that maximum brake torque (MBT) occurs at 29°BTDC. Kakae et al., on the other hand, studied on the sensitivity and effect of ignition timing on spark ignition engine. The speed is fixed at 3400 rpm, the ignition timing has been changed in the range of 10°CA ATDC to 41°CA BTDC, and the performance characteristics such as power, torque, thermal efficiency, pressure, and heat release are obtained and compared. Their works showed that ignition timings have a significant effect on engine performances.

Prior to this study, a 4.3L 4-cylinder diesel engine was modified and retrofitted with a CNG gas system [8]. This type of engine is mainly used by medium duty trucks, such as tanker and mini dump truck. The conversion of diesel-fueled engine which uses compression ignition into CNG-fueled which uses spark ignition, requires a spark ignition system installation in each cylinder. Following the recommended setting in the installation manual, the ignition timing was pegged at crank angle 20°BTDC. Such recommendation ignition crank angle timing may have given the best performance based on the manufacturer’s findings. However, for this particular engine, we observed that with such ignition setting, the combustion is not capable and stable especially at idling speed. The purpose of this study is to optimize the ignition timing best suited for idling both in normal operating mode (700-850rpm) and in cold start mode (1000-2000 rpm).

Experiment Setup

The 4.3L 4-cylinder diesel engine specification in its standard and modified state is presented in Table 1. The compression ratio was lowered by increasing the volume of the piston crown. The original piston was machined to obtain a compression ratio of 19:1 to 11:0. This reduction is necessary to prevent engine knocking while maintaining high thermal efficiency. The diesel direct injection system was taken out and replaced by a dedicated CNG mixer installed in the engine intake pipe next to a throttle body. A close loop lambda control subsystem was also installed.

### Table 1 Specification of test engine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard value</th>
<th>Modified value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>4-stroke</td>
<td></td>
</tr>
<tr>
<td>No. of cylinders</td>
<td>4 cylinders</td>
<td></td>
</tr>
<tr>
<td>Stroke x Bore</td>
<td>112 mm x 110 mm</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>4334 cc</td>
<td></td>
</tr>
<tr>
<td>Compression ratio</td>
<td>19:1</td>
<td>11:1</td>
</tr>
<tr>
<td>Power</td>
<td>85 kW @ 3200 RPM</td>
<td>-</td>
</tr>
<tr>
<td>Torque</td>
<td>285 Nm @ 1800 RPM</td>
<td>-</td>
</tr>
<tr>
<td>Fuel system</td>
<td>Diesel direct injection</td>
<td>CNG mixer at intake</td>
</tr>
<tr>
<td>Ignition system</td>
<td>Compression ignition</td>
<td>Spark ignition</td>
</tr>
<tr>
<td>Overall dimension</td>
<td>771 × 687 × 790 mm</td>
<td>-</td>
</tr>
</tbody>
</table>

Since the conversion was made from diesel fuel to mono CNG fuel, the ignition system needs to be changed from compression ignition to spark ignition. Therefore, a spark plug was installed in each cylinder, and a coil-on-plug to provide direct ignition for each firing order. A custom ignition timing system consists of an electromagnetic-type cam sensor, and a 4+1 tooth wheel was attached to the diesel pump shaft. The sensor picks up signals from the toothed wheel which indicate the rpm of the engine and the angular position of the piston (cam shaft or crank shaft). The signals then tell the ECU the base time when to start spark and the spark sequences. A diagram of the tooth wheel is shown in Fig. 1. The relationship between the cam wheel marking, θ_m, and ignition timing, θ_g is presented in Table 2.

The CNG fuel used in this study was obtained at a local Petronas (a Malaysian petroleum company) gas station. It was stored in a certified CNG steel tank with a pressure of 210 bar. The CNG has the following composition; methane, CH₄ = 94.4 vol.%; ethane, C₂H₆ = 2.3 vol.%; propane, C₃H₈ and butane, C₄H₁₀ = 0.3 vol.% [6]. The CNG exiting the tank was regulated in two
stages until it pressure is approximately near to atmospheric pressure. Fuel flow meter and air flow meter were attached at the line just before gas and air enter the mixer. The exhaust gas emission probe was inserted at the end of the exhaust pipe while an exhaust temperature probe was placed in the exhaust manifold 30cm from the engine head. The engine was connected to a hydraulic dynamometer. Signals from the ECU were read and displayed using a PC.

In this study, the ignition timings tested were 20°BTDC and 25°BTDC, corresponding to cam wheel marking of 25°CA and 27.5°CA respectively. As mentioned earlier, the ignition timing of 20°BTDC is recommended by the developer of the ignition system. The measurements were made at engine speeds of 700, 850, 1000, 1150, 1300, 1500, 2000 and 2500 rpm. The engine load was kept at zero. A non-dispersive infrared (NDIR) type exhaust gas analyzer (SPTC Auto-Check) was used for measurement of CO, CO₂, HC and O₂. The Dräger MSI-200E gas analyzer was used to measure the values of NO and NOx concentration emissions.

Table 2 Ignition timing setting

<table>
<thead>
<tr>
<th>Cam marking, θₘ (°CA)</th>
<th>Ignition timing, θ₉ (°BTDC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.5</td>
<td>35</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>27.5</td>
<td>25</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>22.5</td>
<td>15</td>
</tr>
</tbody>
</table>

Where;
Ignition timing, θ₉ = 2 x (θₘ - 15)

Result and Discussions

Figure 2(a) and 2(b) show the converted mono CNG gas engine hydrocarbon and carbon monoxide exhaust gas emission respectively. In each figure there are two curves, circle markers for ignition timing θ₉ = 20°BTDC and square markers for θ₉ = 25°BTDC. Because of the conversion from diesel to mono CNG during this study has not been fully optimized, the overall HC exhaust gas emission is relatively high, where the minimum value is approximately 7000ppm. Both graphs show similar trends where the ignition timing θ₉ = 25°BTDC produces lower HC and CO gas emissions throughout the engine speed between 700 and 2500 rpm. It indicates that the ignition timing θ₉ = 25°BTDC produced better combustion than the recommended ignition timing value.

Highly noticeable in Fig. 2(a) and 2(b) are irregular values of HC and CO emission measured between engine speed 1000 and 1300. According to the conversion system developer, the engine ECU installed does not use any fuel delivery or ignition mapping; it is simply just a PID controller. The fuel supply through the fuel mixer stepper motor is controlled by O₂ signal from a lambda sensor. The conversion system was designed so that engine rotational speed does not affect the fuel control except cutting off the gas when the engine speed is lower than a certain level. At this point, even after considering the above mentioned facts, the cause of such irregularities in the exhaust gas emission have not yet discovered.

Figure 3(a) shows nitrogen oxides (NOx) emissions at specified engine speed between 700 and 2500 rpm. From the figure, the ignition timing θ₉ = 25°BTDC produces higher NOx emission at engine speed from 700 to 1300 rpm, but at higher engine speed (1700 to 2500 rpm) the NOx values
are significantly lower. Figure 3(b) is the air-fuel ratio (AFR) recorded during the tests. The stoichiometric AFR for CNG is 17.0. The optimized ignition timing \( \theta_g = 25^\circ\text{BTDC} \), shows a slightly rich mixture from 700 to 1000 RPM, and maintain near stoichiometric as the engine speed is increased to 2500 rpm. In contrast, the ignition timing \( \theta_g = 20^\circ\text{BTDC} \) shows a lean mixture at low engine speed and rich mixture at high engine speeds.

From Fig. 4(a), ignition timing \( \theta_g = 25^\circ\text{BTDC} \) shows better fuel consumption throughout the tested engine speed ranges, compared with ignition timing \( \theta_g = 20^\circ\text{BTDC} \). Using the same data, coefficient of variation (COV) of the fuel measurement was calculated, and presented in Fig. 4(b). With an ignition timing \( \theta_g = 20^\circ\text{BTDC} \), the COV of fuel consumption at engine speed 700 rpm is 6%. This high value indicates a large variation in the fuel consumption measured, thus indicates highly unstable engine operation. After changing the ignition timing to \( \theta_g = 25^\circ\text{BTDC} \), the COV of fuel consumption is reduced near to zero, which signifies relatively stabler combustion during idling.
Conclusions

A standard diesel engine was converted to a mono gas CNG engine. A gaseous fuel delivery system, and spark ignition system were installed. The ignition timing was optimized using no load condition. Overall, the ignition timing $\theta_g = 25^\circ$BTDC is better than $\theta_g = 20^\circ$BTDC in terms of fuel consumption and exhaust gas emissions. The results recommend that the idling engine speed should be at 700-800 RPM and 1500 RPM during the normal mode and cold start mode respectively. The use of engine speed of 1000 to 1300 rpm should be minimized to reduce overall exhaust gas emissions.

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References


