Performance of CO$_2$ enrich CNG in direct injection engine

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Abstract. This paper investigates the potential of utilizing the undeveloped natural gas fields in Malaysia with high carbon dioxide (CO$_2$) content ranging from 28% to 87%. For this experiment, various CO$_2$ proportions by volume were added to pure natural gas as a way of simulating raw natural gas compositions in these fields. The experimental tests were carried out using a 4-stroke single cylinder spark ignition (SI) direct injection (DI) compressed natural gas (CNG) engine. The tests were carried out at 180° and 300° before top dead centre (BTDC) injection timing at 3000 rpm, to establish the effects on the engine performance. The results show that CO$_2$ is suppressing the combustion of CNG while on the other hand CNG combustion is causing CO$_2$ dissociation shown by decreasing CO$_2$ emission with the increase in CO$_2$ content. Results for 180° BTDC injection timing shows higher performance compared to 300° BTDC because of two possible reasons, higher volumetric efficiency and higher stratification level. The results also showed the possibility of increasing the CO$_2$ content by injection strategy.

1. Introduction

The search for alternative fuels for internal combustion engines with a vision to improve the engine fuel economy and reduce harmful exhaust emissions becomes necessary [1] as the energy needs in the transportation sector is growing drastically due to the increase in the number of vehicles. However for fossil fuels specifically crude oil has been the major source of fuel for transportation, power generation and other applications. Hence, the crude oil are depleting at alarming rates which leads to increase in fuel prices. Furthermore, the increased in consumption of these fuels are causing environmental pollution thereby causing global warming and health related issues. Therefore, dependency on fossil fuels (gasoline and diesel) calls for alternative energy sources for future energy needs. Moreover, with the increasing stringent emission standards continually legislated, alternative fuels are currently being used [2, 3] to tackle the negative resultant effects of environmental pollution such as unburned hydrocarbon (uHC), carbon monoxide (CO) and nitrogen oxide (NO$_x$) among others generated by all sectors. In lieu of this, extensive research studies have been carried out to determine alternative fuels that are best suited for both spark ignition (SI) and compression ignition engines; and other applications. For spark ignition engines, biogas and syngas [4, 5] have been studied and proved to enhance performance and reduce emissions under appropriate operating condition while for compression ignition engines, seed-oil bio fuels [5, 6] have been examined and found to give similar performance and emissions when compared with conventional diesel fuels, particularly when blended with diesel fuel or emulsified with ethanol or water.
Natural gas is amongst the fast growing component of the world’s primary energy consumption because of its availability, abundance and adaptability to the gasoline and diesel engines. Malaysia is endowed with abundant natural gas reserves of 2400 billion cubic metres (84.76 Trillion cubic feet) and thus ranked the 15th largest in the world [7]. However 37 Tcf of these natural gas reserves are non-developed due to the presence of large quantities of CO₂ (from 28% to 87%), thus rendering it uneconomically valuable. CO₂ capturing from natural gas is seen as an option of utilizing these undeveloped resources. However, there are challenges associated with this technique such as high cost, advanced technology and processes corrosion and high energy demand [8, 9]. This study therefore was focused on increasing the CO₂ minimum requirement in the Malaysian natural gas composition from 0.57% to 40% as a way of simulating the natural gas field’s composition and at the same time study the effect of high CO₂ content-natural gas on engine performance.

Carbon dioxide and hydrogen sulphide are part of the constituents of natural gas reservoirs that are present in large quantities [10]. It is majorly produced from combustion of coal or hydrocarbons, fermentation and decomposition of organic materials and breathing life forms. Carbon dioxide is chemically inert in nature and slightly heavier than air which has high specific heat capacity and would neither combust nor support combustion process.

The presence of high amount of CO₂ in a mixture of natural gas and carbon dioxide can cause lower heating value of the mixture compared to pure natural gas. This leads to reduction in burning velocity which eventually affects the performance of the engine [11]. Experiment conducted on a Ricardo engine using methane and CO₂ at different compression ratios, speeds and equivalent ratios showed that there is an improvement in NOₓ emissions. However, lower cylinder pressure obtained led to the reduction in engine power and thermal efficiency and increase in the level of unburnt hydrocarbon. The results obtained are the same for different engines and operating conditions [4]. Furthermore, the presence of high CO₂ CNG may not affect much on the efficiency of the engine if the right amount of CO₂ is introduced into the mixture. Henham and Makkar [12] found that the efficiency of the mixture of natural gas and carbon dioxide is not much affected up to 37% natural gas substitution. It was reported also that introduction of carbon dioxide more than 40% into the mixture could lead to harsh and irregular running of an engine. Shrestha and Karim also found that the presence of diluents (carbon dioxide) beyond about 50% in the mixture could result to significant drop in the power output of the engine [13].

It is obvious from the results of the experimental studies conducted on engine using mixture of methane and large amount of CO₂ causes performance to dropped, which could be as a result of weak turbulence inside the combustion chamber caused by large specific heat capacity of the mixed fuel which absorbed more heat released and reduced the cylinder gas temperature [14]. In addition, the use of port-injection or carbureted fuel delivery could also be a contributing factor in reduction of power, volumetric efficiency and brake mean effective pressure [15].

2. Experimental Setup
In this research, the experimental work was carried out on a single-cylinder, 4-stroke SI DI-CNG engine. The detailed specifications of the engine are given in Table 1. The CO₂ used in the experiment had a purity of 99.8%. The schematic diagram of the experimental setup is shown in figure 1. All experimental studies were conducted at the Centre for Automotive Research and Energy Management (CAREM) located in the Department of Mechanical Engineering, Universiti Teknologi PETRONAS (UTP), Malaysia.
Table 1. Engine Specifications.

| Engine Description       | Specifications               |
|--------------------------|------------------------------|
| Displacement volume      | 399.25 cm³                  |
| Cylinder Bore            | 76 mm                        |
| Cylinder Stroke          | 88 mm                        |
| Compression Ratio        | 14:1                         |
| Exhaust Valve Closed     | 350° BTDC                    |
| Exhaust Valve Open       | 225° BTDC Inlet              |
| Valve Open               | 12° BTDC Inlet               |
| Valve Closed             | 132° BTDC                    |
| Dynamometer              | Direct Current with maximum reading is 50 Nm |

The operation of the engine used for the experimental work was managed and controlled by a PC-based data acquisition and control system. The in-cylinder pressure was measured using a water cooled Kistler 6061B piezoelectric pressure transducer. The fuel injection system was designed to allow two types of fuels (CNG and CO₂) to be injected at high injection pressure. The CNG and CO₂ were supplied through different gas inlets and directly injected into the combustion chamber at 18 bar using a synerject injector. Prior to the injection, the fuel were mix in a mixing chamber near the injector. The flow rate of carbon dioxide was measured using a CO₂ digital mass flow meter with an accuracy of ±1.0% of the full scale. The amount of the injected CO₂ was varied by adjusting the needle valve which in turn controlled the flow rate.

Figure 1. Experimental setup schematic diagram.
All tests and measurements were carried out on a CNG-DI engine with the injection timing set at 180° and 300° BTDC, the air-fuel ratio was set at stoichiometric ratio ($\lambda = 1$); while the ignition timing was adjusted to obtain the maximum brake torque. The CO$_2$ proportions (0%, 10%, 20%, and 30% by volume) were added to the CNG while the experiments were performed at full open throttle. Engine parameters such as injection timing, ignition timing, and air-fuel ratio were controlled by the ECU Remote Interface (ERI).

3. Results and Discussion

The effect of CO$_2$ content in natural gas to the engine performance at 3000 rpm can be seen in figure 2. It is observed that the torque and power output is decreasing as the CO$_2$ percentage increases. It can be explained by the fact that total energy content of the mixture is reducing as he CO$_2$ content increased. Furthermore, CO$_2$ is a stable compound with -393.5 kJ/mol heat formation in which it requires a significant amount of energy to dissociate its bonding. In the current process, there are high possibilities that CO$_2$ absorbs the energy from the combustion of CNG, which will suppress and slows down the combustion rate of the mixture.

Decreasing CO$_2$, CO, and NO$_x$ emissions and increasing THC emission shown in figure 3 indicates that CO$_2$ addition is suppressing the combustion of CNG. Decreasing CO$_2$ may indicate the event of CO$_2$ dissociation and formation of HC especially for the CO$_2$ percentage above 10%. A significant amount of energy is absorbed by this process and cause torque and power drop.

The presence of CO$_2$ suppression can also be seen in the pressure and heat release rate data in figure 4. The heat rate gradient for CNG is higher compared to the one with CO$_2$ addition. It shows the combustion propagation is slower for high CO$_2$ content fuels. The maximum pressure and heat release also decreases for fuels with CO$_2$ addition due to the low energy content of the mixture.

The effect of CO$_2$ content to the engine performance, emission and combustion for different injection timing also shown in figure 2, figure 3 and figure 4. High performances were recorded for 180° BTDC for all CO$_2$ contents compared to 300° BTDC. The main reason is because of higher volumetric efficiency due to late injection.

Fuel injection starts during the intake process of 300° BTDC injection timing which will disrupt the air intake process to the chamber. Fuel will displace the air thus reducing total air intake to the cylinder which relates to reducing engine volumetric efficiency. This effect amplifies when CO$_2$ was added since the total volume of gas injected increases the effort of maintaining the lambda. Longer injection duration will further reduce the engine volumetric efficiency and causing engine performance to decrease.

The decrease in cylinder peak pressure and heat release rate with increasing CO$_2$ content differs for a variation of injection timing. Performance drop for 180° BTDC is less compared to 300° BTDC especially for 30% CO$_2$ content. Fuel injected at 180° BTDC produces higher level of stratification, rich local air-fuel ratio, therefor suitable for the combustion regardless of CO$_2$ content in the mixture.
Figure 2. Engine performance for various CNG-CO$_2$ mixture composition.

Figure 3. Engine emissions for various CNG-CO$_2$ mixture composition.
Figure 4. Cylinder pressure and heat release rate for various CO₂ composition at 3000 rpm with (a) 180° and (b) 300° BTDC injection timing.
Figure 5. Effect of CO\(_2\) percentage towards ignition delay for 180° and 300° BTDC injection timing at 3000 rpm.

Figure 5 shows two ignition delay profiles for 180° and 300° BTDC injection timing. The profile for 180° BTDC shows consistency throughout the test which indicates that fuel stratification is able to maintain the ignition delay similar to pure CNG and creates wider operating range window for CNG with high CO\(_2\) content. However for 300° BTDC shows an increase in ignition delay as CO\(_2\) percentage increases up to 22.2° BTDC at 30% CO\(_2\) content. The ignition delay profile for 300° will limit engine operations and add complexity in engine control which is not desirable.

4. Conclusions

In this paper, the effect of different CO\(_2\) content in CNG while varying injection timing towards the performance, emission, and combustion were explained. It shows that CO\(_2\) suppresses the combustion of CNG while on the other hand CNG combustion is causing CO\(_2\) dissociation shown by decreasing CO\(_2\) emission when combusted with higher CO\(_2\) content. The performance significantly drops when the CO\(_2\) content percentage is above 10%. Injection timing at 180° BTDC shows higher overall performance compared to 300° BTDC because of two possible reasons which are higher volumetric efficiency and higher stratification level. The results showed possibilities of CO\(_2\) enrich CNG usage as fuel by implementing injection strategy.

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