

# The Effect of Injection Timing on the Performance of Natural Gas with a High Carbon Dioxide (CO<sub>2</sub>) Content in a Direct Injection (DI) Gas Engine

Ayandotun B. Wasiu<sup>1,a</sup>, A. Rashid A. Aziz<sup>1</sup> and Morgan R. Heikal<sup>1</sup>

<sup>1</sup>Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

**Abstract.** This paper investigates the potential of utilizing raw natural gas from its reserves in Malaysia which are not harnessed because they are uneconomical due to the presence of large CO<sub>2</sub> in it ranging from 25 to 89%. For this experimental work, the natural gas fields were simulated by adding CO<sub>2</sub> at 10%, 20%, 30%, and 40% to pure natural gas, and tested in a single-cylinder spark-ignition direct injection (DI) compressed natural gas (CNG) engine. Various injection timings were used, the injection duration was maintained, the ignition timing was adjusted to obtain the maximum brake torque (MBT), and at wide open throttle (WOT). The tests were carried out at a constant engine speed to study the effect of injection timings on performance and emission of the engine. Experimental results show that generally, the presence of high carbon dioxide content in the natural gas reduces the heating value of the mixture when compared with pure natural gas but however could be enhanced with injection timing in the range of 120 and 180 particularly for 20% CO<sub>2</sub> proportion in the mixture. There was a reduction in the NO<sub>x</sub> and CO emissions but an increase in the unburnt hydrocarbons (THC).

## 1 Introduction

The energy needs in the transportation sector is growing drastically as the number of vehicles increases. Fossil fuels, specifically crude oil, are the major sources of energy and serve as fuel for transportation, power generation and other applications. However, the diminishing of fossil fuel reserves, its rising price and environmental pollutions are the reasons for the search for alternative fuels for internal combustion engines with a view to improve the engine fuel economy and reduce harmful exhaust emissions [1]. More so it is imperative to search for alternative energy sources for future energy needs so as to reduce energy dependency on fossil fuels (gasoline and diesel).

The emission of undesirable gases into the atmosphere by an internal combustion engines burning fossil fuels are known to threaten the very survival of life in the world [2]. Alternative fuels are currently being used [3] to meet the stringent emissions standards legislated to regulate environmental pollution. Extensive research studies [4-6] have been carried out to determine alternative fuels that are best suited for both spark ignition (SI) and compression ignition (CI) engines. Among all, natural gas is probably the most widely used alternative fuel due to its availability and abundance throughout the

---

<sup>a</sup> Corresponding author : wasiuayan@gmail.com

world and adaptability to the gasoline and diesel engines. Thus, making it the fast growing component of the world primary energy consumption.

Malaysia is endowed with abundant natural gas reserves of 2400 billion cubic metres (84.76 Trillion cubic feet) and thus ranked the 13th largest in the world. However, 37Tcf of these natural gas reserves are non-developed due to the presence of large quantities of CO<sub>2</sub> (from 25% to 89%). So as the demand of energy is growing rapidly, these resources become very valuable. Separation of CO<sub>2</sub> from natural gas is seen as an option of utilizing these natural resources though with challenges such as high cost, advanced technology and processes, corrosion and high energy demand.

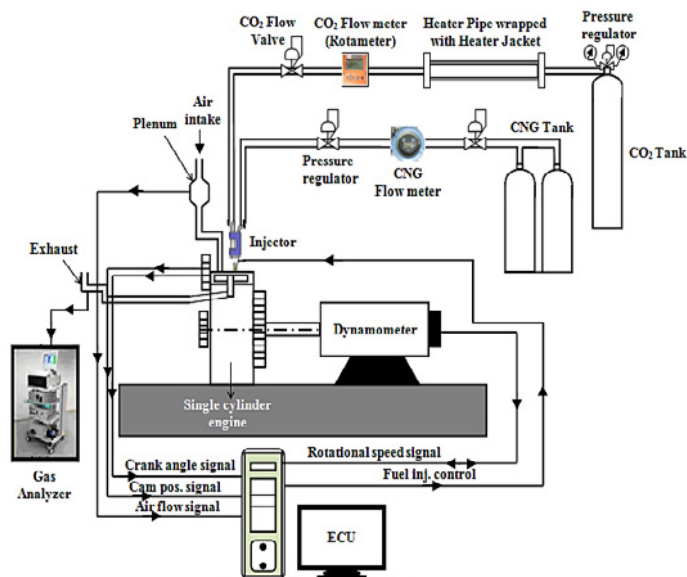
Experimental studies have been conducted on engines using simulated biogas (natural gas and carbon dioxide) [4,7,8] at different compression ratios, engine speeds and equivalent ratios with different composition of carbon dioxide up to 40% addition in the mixture [4]. There was a significant improvement in the performance and reduction in emissions of hydrocarbons (HC) particularly with lean mixtures when the methane concentration in the mixture was enhanced [8]. It was discovered that the flame temperature of diesel (1723°C) was high enough to initiate dissociation of CO<sub>2</sub> in the mixture into CO and O<sub>2</sub> when a fumigated dual fuel engine was used to simulate biogas operated engine [7]. With less than 30% of CO<sub>2</sub> in the mixture, the engine performance proved better with lower brake specific fuel consumption (bsfc) and diesel flow rates. This was due to the presence of dissociated CO which accelerated the burning rate of the mixture, and the increase in O<sub>2</sub> concentration which enhanced the combustion of unburned carbon particles and reduced the ignition delay. However, with more than 30% of CO<sub>2</sub> in the mixture, CO<sub>2</sub> remained undissociated and therefore acted as inert gas which reduced the burning velocity of the mixture and thus resulting in an incomplete combustion. However, the operating condition of biogas or natural gas-carbon dioxide can be optimized [9] and a fast burning engine design could improve performance [4].

The low engine performance that results when high CO<sub>2</sub> is present in a NG-CO<sub>2</sub> mixture can be overcome as suggested by numerous research results that increasing the compression ratio (CR) is a means of improving the performance of the engine when CO<sub>2</sub> is present [5,10] even though there will be an increase in the emissions of NO<sub>x</sub>, CO<sub>2</sub> and HC. However, NO<sub>x</sub> emission is suppressed by the presence of the high CO<sub>2</sub> content in the fuel. Also by advancing the spark timing especially when the diluent is CO<sub>2</sub> is reported in the work of [9]. Injection parameters such as injection timing, injection pressure and injection angle were found to have significant effects on the engine performance and emissions. Injection timing was reported to have significant effect on engine volumetric efficiency and thus engine performance [11]. The research results of [12] showed that the correct injection timing can increase the engine volumetric efficiency and thus brake power. Also the work of [13] showed that late injection timing resulted in a 20% higher engine performance particularly at low engine speed. The object of this study was to show the effects of injection timings on the various proportions of CO<sub>2</sub> in NG on the engine performance and exhaust emissions. The results described in this present work were obtained from a spark-ignition DI CNG engine at a constant low engine speed.

## 2 Experimental setup and procedures

In this research, the experimental work was carried out on a single-cylinder, four-stroke spark-ignition direct injection CNG engine having displacement volume of 399.25mm, compression ratio of 14:1, and an Eddy current dynamometer coupled to it. The CO<sub>2</sub> used in the experiment had a purity of 99%. The schematics diagram of the experimental setup is shown in Figure 1. 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 piezoelectric pressure transducer. The fuel injection system was designed to accommodate two fuels (CNG and CO<sub>2</sub>) and to be used with high injection pressure. The CNG and CO<sub>2</sub> were supplied through different gas inlets at 18bar injection pressure. Prior to the injection of the fuel mixture into the engine cylinder, a mixing chamber mixed the two fuels from the gas inlets. The flow rate of carbon dioxide was controlled using a CO<sub>2</sub> digital mass flow meter with an accuracy of  $\pm 1.0\%$  of the full scale and a

needle valve. The amount of the injected CO<sub>2</sub> was varied by adjusting the needle valve which in turn controlled the flow rate.



**Figure 1.** A Schematic Diagram of the Experimental Setup.

All tests and measurements were carried out at a low engine speed of 1500rpm with the injection timing set at 120, 180 and 300°CA BTDC, the injection duration was maintained; while the ignition timing was adjusted to obtain the maximum brake torque. At full throttle (WOT) condition, engine parameters such as injection timing, ignition timing and air-fuel ratio were controlled by an engine control unit (ECU), which was connected to ECU Remote Interface (ERI) installed in a PC.

## 3 Results and discussion

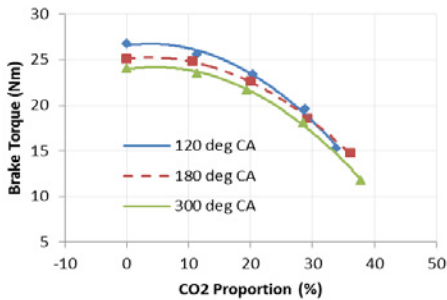
### 3.1 Performance

Figure 3 shows the engine brake torque versus the CO<sub>2</sub> proportion in the mixture at different injection timings and constant injection duration. Generally, it can be seen that the torque curve for all the cases show a decreasing trend as the CO<sub>2</sub> proportion increased. The explanation to this is the fact that the heating value of the mixture decreased as the CO<sub>2</sub> content in the mixture was increased. This thus reduced the burning velocity which in turn affected the engine output. From Figure 3, it was found that the maximum proportion of CO<sub>2</sub> the engine could accommodate in the mixture before it became unstable at injection timings of 120, 180 and 300°CA, were 34.4%, 36.7% and 38.5% respectively. The torque values at 120°CA was observed to be higher than their corresponding values at 180 and 300°CA up to at 30% CO<sub>2</sub> proportion when it decreased by about 8% below that of the 180°CA case. The reason for this could be the fact that rich mixture formation occurred at 120°CA injection timing.

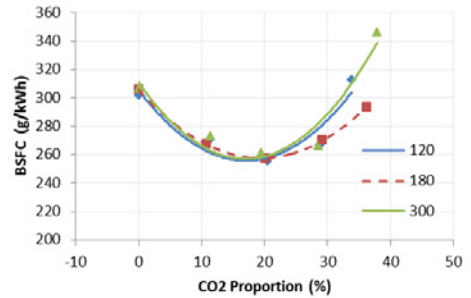
Figure 4 illustrates the brake specific fuel consumption (BSFC) plotted against the CO<sub>2</sub> proportion in the mixture at a constant engine speed and injection duration. In general, the BSFC decreased with the increase in CO<sub>2</sub> proportion until about 20% and then started to increase as the CO<sub>2</sub> proportion were further increased. For all the cases, the BSFC dropped to the lowest value about the same magnitude when the CO<sub>2</sub> proportion was about 20%. It was observed from Figure 4 that addition of some amount of CO<sub>2</sub> to the CNG produced better BSFC as compared to the pure CNG. The explanation to this finding is due to the better combustion of the mixture.

The brake thermal efficiency (BTE) for the mixtures at 1500rpm engine speed and constant injection duration is shown in Figure 5. It is expected that the inverse of the BSFC plot produces the

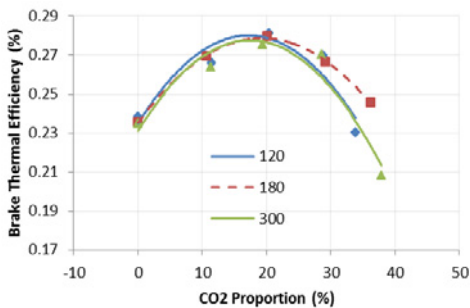
characteristics of the BTE plot. It was observed that the brake thermal efficiency values increased with CO<sub>2</sub> proportion in the mixture up to about 20% proportion of CO<sub>2</sub> and thereafter started to decline. The explanation for this is that with a higher CO<sub>2</sub> proportion above 20%, the specific heat of the mixture increased and thus led to the decrease in the brake thermal efficiency. It can be seen from the Figure 5 that the 120°CA injection timing showed a slightly higher BTE than other injection timings.



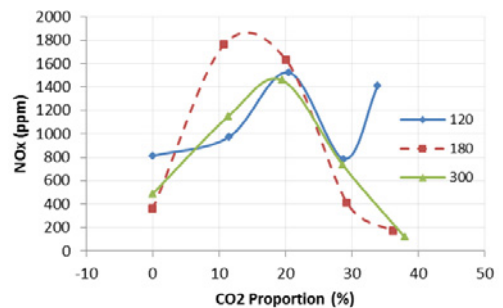
**Figure 3.** Brake torque versus CO<sub>2</sub> proportion in the mixture at different injection timings



**Figure 4.** BSFC versus CO<sub>2</sub> proportion in the mixture at different injection timings



**Figure 5.** BTE versus CO<sub>2</sub> proportion in the mixture at different injection timings



**Figure 6.** NO<sub>x</sub> emission versus CO<sub>2</sub> proportion in the mixture at different injection timings

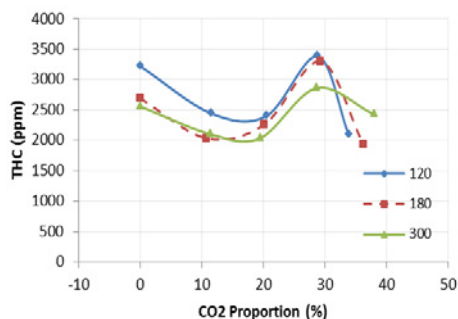
### 3.2 Exhaust emissions

Figure 6 shows the NO<sub>x</sub> emission for various CO<sub>2</sub> proportion in the mixture. Normally, the NO<sub>x</sub> emission should be decreasing as CO<sub>2</sub> in the mixture was increasing due to the high heat capacity of CO<sub>2</sub> which absorbed the released heat leading to the lower combustion temperature. For all the injection timings, the NO<sub>x</sub> emission showed an increasing trend up till about 20% CO<sub>2</sub> proportion, thereafter started decreasing. This could be that the CO<sub>2</sub> at about 20% dissociated and thus showed no significant effect on the combustion temperature but however affected the combustion temperature when CO<sub>2</sub> was more than 20%. It was also observed that the highest and lowest NO<sub>x</sub> emission value occurred at 180°CA injection timing when CO<sub>2</sub> proportions were about 20% and 38% respectively.

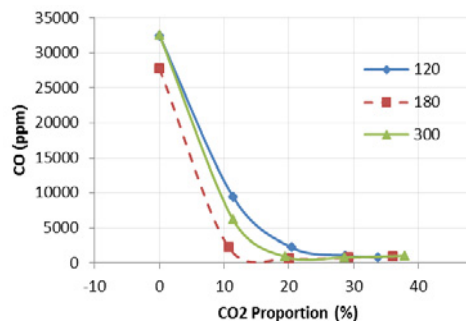
Figure 7 shows the plot of the total unburned hydrocarbons (THC) values against CO<sub>2</sub> proportion in the mixture. It was observed from Figure 7 that the THC in contrast to NO<sub>x</sub> emission decreased for all the injection timings as the CO<sub>2</sub> proportion in the mixture was increased and thereafter increased and then decreased with the variation of CO<sub>2</sub> in the mixture. It was also noted that THC at 120°CA injection timing produced highest emission value than at other injection timings.

Figure 8 illustrates the CO emission. As it can be observed from the figure, there was significant drop in the CO emission as CO<sub>2</sub> proportion in the mixture was increased and thereafter showed little or no change in the emission values for all the cases. The CO emission at 120°CA injection timing showed higher emission up to about 30% before it remained constant while it was about 15% and 20% for 180 and 300°CA injection timings respectively. The reason for the decrease could be due to the

completeness of combustion process as could be seen from Figure 6 up till about 20% while CO<sub>2</sub> effect was seen to produce little or no change in the emission as CO<sub>2</sub>% proportion was increased.



**Figure 7.** THC emission versus CO<sub>2</sub> proportion in the mixture at different injection timings



**Figure 8.** CO emission versus CO<sub>2</sub> proportion in the mixture at different injection timings

## 4 Conclusion

The effect of injection timing on the performance characteristics of a DI CNG engine fueled with NG-CO<sub>2</sub> mixture at constant injection duration and a constant speed was investigated and the results showed that at 120°CA injection timing, the brake torque value was higher than other injection timings. Due to the rich mixture formation up to about 20%, the BSFC was at the lowest value at 120°CA injection timing, however, at higher CO<sub>2</sub> addition, 180°CA proved better. The brake thermal efficiency increases with an increase in the CO<sub>2</sub> addition and higher at 120°CA injection timing. For the exhaust emissions there were significant reduction in the emissions of CO and NO<sub>x</sub> while THC was on the increase at about 20% CO<sub>2</sub> proportion in the mixture. The improvement of engine performance and emission of a DI CNG engine could be enhanced with injection timing in the range of 120 and 180 particularly for 20% CO<sub>2</sub> proportion in the mixture.

## 5 Acknowledgment

This study was supported by the Ministry of Education under the project titled CO<sub>2</sub> Rich Natural Gas Value Chain Program – From Wells to Wealth: A Green Approach and the Center for Automotive Research and Electric Mobility (CAREM), Universiti Teknologi PETRONAS.

## References

1. E. Hu, Z. Huang, B. Liu, J. Zheng, X. Gu, Intl J. of Hydrogen E. **34**, 1035-1044 (2009)
2. L.M. Das, R. Gulati, P.K. Gupta, Intl J. of Hydrogen E. **25**, 783-793 (2000)
3. Semin, R.A. Bakar, Amer. J. of Eng. and Appl. Sc. **1**, 302-311 (2008)
4. J. Huang, R.J. Crookes, Fuel. **77**, 1793-1801 (1998)
5. R.J. Crookes, Biomass and Bioenergy. **30**, 461-468 (2006)
6. T.K. Gogoi, D.C. Baruah, Appl. E. **88**, 2713-2725 (2011)
7. B. Saiful, WREC Renewable E., E. Eff. and the Env. **9**, 1007-1010 (1996)
8. E. Porpatham, A. Ramesh, B. Nagalingam, Fuel. **95**, 247-256 (2012)
9. S.O.B. Shrestha, G.A. Karim, Appl. Ther. Eng. **21**, 331-342 (2001)
10. E. Porpatham, A. Ramesh, B. Nagalingam, Fuel. **87**, 1651-1659 (2008)
11. Z. Huang, S. Shiga, T. Ueda, H. Nakamura, T. Ishima, T. Obokata, M. Tsue, M. Kono, *Proceedings of the Institution of Mech. Engineers, Part D: J. of Aut. Eng.*, **217**, 393-401 (2003)
12. H.S. Hayashida T. Yamato, M. K. Sugahara, SAE. **01**, (1999)
13. Firmansyah, M.Eng., UTP, 2007