Australian Journal of Basic and Applied Sciences, 4(10): 4870-4879, 2010
ISSN 1991-8178

Influence of Injection and Ignition of CNG Fuelled Direct Injection Engine at Constant Speed

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Abstract: This paper presents an experimental result of engine performance and exhaust gases concentration at various ignition and injection timing for high compression engine fuelled with compressed natural gas (CNG) engine. The engine implements central direct injection (DI) method. All injectors are positioned within a certain degrees of spark plug. It is called as CNGDI engine. The objective of this experiment is to study the influence of injection and ignition towards brake torque, brake power and emission at maximum brake torque (MBT) interval. The experimental tests were carried out using computer-controlled eddy-current dynamometer which measures the CNGDI engine performance. The Horiba analyzer uses infra-red for CO, CO_2, HC and flame ionization for THC for emission measurement. A closed loop wide band lambda sensor has been mounted at the exhaust manifold to indicate the oxygen level during the exercise. The emission concentration level was recorded with respects to engine speed, ignition timing and injection timing. Indicated power and torque of CNGDI engine were also monitored during the course.

Key words: Compressed natural gas, high compression engine, CNGDI engine, ignition timing, exhaust emission of CNGDI engine, direct injection. MBT of CNGDI.

INTRODUCTION

The search for alternative fuels is becoming a major concerned worldwide. This is due to few obvious reasons; an increased of oil price, a declining trend of oil production globally, health-issues due to pollution and an alarming global climate change. One of the most affected industries due this current situation is an automotive sector. Automotive sector is one of the highest contributions to pollution and global warming. Thus, the demand for alternative fuel is always a burning issue. Natural gas is regarded as one of the most promising alternative fuels and probably the cleanest fuels. Natural gas vehicles (NGVs) typically offer greenhouse gas reductions as much as 30%. With climate change now firmly on the agenda at all levels of society, NGVs offer an economic and environment advantage unmatched by any other fuel. It also has been noted in literature that natural gas have high-octane value, a good cold-starting characteristics that cause less wear on engine and can be fueled at home.

Basically, there are two in-cylinder direct injection systems as reported by J.G Smyth (Smyth *et al.,* 2001), (i) side injection and (ii) central direct injection. The side injection consists of two methods tumble controlled and swirl controlled. The central direct injection system consists of open chamber and spray jet system. In this particular experiment central direct injection with homogenous piston and high compression engine has investigated. The CNGDI spark ignition engine for light duty vehicle in replacement of gasoline engine is a new direction of engine development, which could bring hopes to natural gas vehicles. Therefore, the search for technical reference for CNGDI spark ignition engine development worldwide is very limited.

Literature Review:

Most of researched on CNGDI engines are focused on diesel engine cycle but diesel engines emit high emission especially particulate matter. The diesel engine uses compression heating for ignition while the gasoline engine uses spark plug for ignition. The only car manufacturer that proposed and developed CNGDI

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diesel cycle engine is ISUZU. They developed CNGDI with glow spark plug ignition with hot surface system mounted on cylinder head, which will improve engine efficiency. Hence, CNGDI is a direction of natural gas engine technology for gasoline or Otto cycle combustion implementation. Fumitaka Honjo, (2002) from Nissan Diesel Motor Co. Ltd Experience has reported some of their findings on the development of stratified charge combustion CNG DI engine. Two spray angles, 30^0 and 50^0 of injector were selected for their research. The finding are as follow; (i) CNG-DI can run ultra lean burn along with stratified combustion, (ii) Fuel consumption lower than diesel and (iii) high speed combustion stability is was not promising.

Yuichi Goto, (1998) has studied the combustion and emission characteristics in direct injection natural gas engine using multiple stage injection. The main concerned is to study the stabilization of combustion and the possibility of reducing NOx emission using two-stage injection, which is a method for producing a stratified fuel-air mixture suitable for mixture in the vicinity of a spark plug by splitting gas injection into two stages per cycle. The investigation had been done on the modified single cylinder diesel engine. The influence was investigated under the condition that primary injection quantity is larger than the secondary one in order to reduce NOx emission. The result shows that implementing two-stage injection may reduce the NOx emission drastically. However, since the spark timing is after the top dead centre, the thermal efficiency drops sharply and THC and CO concentration rise as the fuel-air mixture becomes lean. The engine modeling in terms of performance of CNG fuelled engine with direct injection are also reported by several researchers, (Goto yuici, 1998; Agawal and Assanis, 2000; Peter Meekl and Anupam Gangopadhal, 2001). The results have shown that the potential of CNG implementing direct injection system.

Injection and Ignition of CNGDI:

The basic combustion characteristic of compressed natural gas engine was reported by Z.Huang *et al*., (2003) as comparison with gasoline combustion characteristics. The characteristics of stratified combustion and emission of natural gas and gasoline implementing DI method at the optimum injection settings over a wide range of equivalent ratios were investigated. The result showed that, CNG stratified DI produces more hydrocarbon (HC) than gasoline stratified DI at a low overall equivalence ratio. The effect of injection timing as reported by Z.Huang *et al.*, (2003), also revealed some basic combustion characteristics of CNGDI. He used rapid compression machine (RCM) to investigate the effect of fuel injection timing relative to ignition on CNGDI. As a result of his experimental exercised, he stated three findings; (i) heat release pattern of early injection showed a slower burn in the initial stage and a faster burn in the late stage, which is similar with premixed gas. In contrast to late injection, the heat release pattern shows faster burn in the initial stage and slower burn in the late stage which is similar to diesel combustion. (ii) early injection leads to a longer duration of initial combustion, whereas late injection leads to a longer duration of the late combustion. (iii) late injection produces lower NOx at equivalent ratio greater than 0.5, while CO level is higher for the injection at high equivalence ratio greater than 0.9.

Haeng Muk Cho *et al.*, (2007) has suggested that to keep the output power and torque of natural gas engine comparable to those of their gasoline or diesel counterparts, high boost of pressure should be used. High activity of catalyst for methane oxidation and lean NOx system or three-way catalyst with precise air-fuel ratio control strategies should be developed to meet future stringent emission standards. The characteristic of single cylinder engine has conducted by Shahril *et a*l., (2005) and Wendy Hardyono Kurniawan, (2007). The CNGDI combustion was analyzed at various speeds with different set of combustion and spark ignition timing. The engine performance, CO and NO concentrated were monitored. It was concluded that the combinations of the right injection timing and ignition timing, increased engine performance and reduced its emission.

The latest research to the ignition of CNG was reported by Kidoguchi.Y *et al*., (2008). The CNG was injected directly into the combustion chamber by gas injector and the jet was ignited by spark plug. The results showed that the ignitability of CNG jet could be improved by controlling jet velocity. Ignition near injector at jet boundary is effective to reduce jet velocity, resulting in improvement of ignitability. Multiple injections were applied to CNG jet combustion and it was found the multistage injection is useful to reduce initial jet velocity and promote initial flame development. The method of controlling jet velocity is leading to high ignitability of CNG jet with high injection pressure. The experimental was conducted on single cylinder engine.

Besides mechanical approaches used to enhance the engine performance, the engine management system and its calibration technique are other important factors need to be considered. By setting the ignition angle and injection timings properly, the improvement in the engine performance and emission level could be achieved (Aris *et al.,* 2005; Mohd Khair Hassan *et al.,* 2005). The best suited injection timing, ignition timing, air-fuel ratio are few main parameter that contribute to the enhancement of engine performance (Anupam Gangoadha and Peter Meekl, 2001).

Objective of Research:

There is still a limited resource of reference can be found for combustion characteristics of an experimental study of direct injection CNG with Otto cycle especially for multi-cylinder engine. Most of researches have done for gasoline based engine are of preliminary and theoretical study of CNGDI engine or modified diesel based engine or using single cylinder engine. This paper presents an experimental work of high compression direct injection system fuelled with CNG for spark ignition four cylinder engine. It consists of three subsections of result as follow (i) the influence of EOI, ignition and dwell time to engine power and torque (ii) NOx, CO and HC at various EOI and ignition (iii) O2 and CO2.

Experimental Setup:

The CNGDI engine has been tested in every engine speed with 1000 rpm interval, starting from 1000 rpm up to 6200 rpm for an overall engine performance test. But, this paper limits the discussion to the influence of fuel injection timing and ignition timing towards brake power, brake torque and exhaust emission only. Therefore, a constant engine speed of 3000 rpm at wide open throttle has been chosen during the analysis. The dynamometer being used is an eddy current typed rated 10,000 rpm and 500 Nm. The engine dynamometer control is calibrated from CP Engineering, United Kingdom. Fuel is injected at the central of the cylinder with 20-bar pressure. The experimental engine is based on 1.6-liter engine and the engine geometry is tabulated in Table 1.

CNGDI Injector and Spark Plug:

The CNGDI injectors based on the Synerject Strata injector with modified spring preload for operation at 2000 kPa. The Strata family of air injectors is designed to minimize package size, while maximizing commonality and flexibility for use across a wide range of applications. It is an electromechanical valve used to deliver metered quantities of fluid in the form of defined and controlled spray plume geometry. Figure 1 demonstrates the arrangement of injectors and spark plugs of CNGDI engine. The CNGDI injector flow rate has been optimized for fueling the 1.6 liter engine at full load to provide best possible vehicle performance. This optimization exercise was characterized at Orbital, Australia Pty. Ltd. The spray geometry of injector nozzle is 70^0 with working pressure 20 bars of CNG. The spray angle is one parameter that could produce best power and torque (Yusoff and Muthana, 2005; 2005). The fuel injection timing determines when the injectors will stop (or start) injecting fuel for each injection pulse. Adjusting the injection timing ensures that all fuel is injected at the optimum point in the engine cycle, so that the engine makes best use of the fuel. Basically, the fuel should end injection at a point where all the fuel will be sucked into the current induction stroke; therefore the end of injection point should be some time before the intake valve closes. The optimum point depends on the engine speed and load. Torque, fuel economy, emissions and idle quality are all affected by the injection timing. The CNGDI engine was controlled by universal electronic control unit known as MOTEC M800. The schematic layouts of experimental work are demonstrated in figures 2 and 3 respectively.

Horiba exhaust gas analyzer interfaced with CADET12 was used to measure emission concentration of the engine. This enable the emission data and engine operating data can be logged instantaneously during the test. The analyzer consists of individual module of each emission parameter. The analyzer uses infra-red for CO, CO_2 and HC and flame ionization for THC for measurement. The NO_x, which is total oxides of nitrogen emissions, NO plus NO_2, is measured by using chemiluminescence's analyzer. The details of Horiba working principle can be referred at Horiba website (horiba.com).

RESULTS AND DISCUSSIONS

The Influence of EOI, Ignition and Dwell Time:

The characteristic of CNGDI performance at various end-of-injections (EOI) is illustrated in Figure 4. Power and torque are decreased as the injection timing is retarded or injection timing is varied towards TDC. As shown in the figure, the best end-of- injection timings lie between 280^0 crank angle (CA) or 80^0 bTDC to 320^0 CA or 40^0 bTDC. Maximum power of 98kWatt occurs at 300^0 bTDC and maximum torque is 32Nm. If the EOI was set at TDC i.e (360^0), the power and torque would produce minimum power and minimum torque.

Figure 5 demonstrates the characteristic of engine performance when the ignition angle was varied between 24^0 bTDC up to 36^0 bTDC. These ignition angles have been selected according to characteristic of 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 29^0 bTDC. Thus, it is a sign of that maximum brake torque (MBT)

occurs at 29^0 bTDC. The MBT can be identified when the magnitude of two opposite trends just offset each others. The timing which is advanced or retarded from 29^0 bTDC gives lower torque. If an engine runs at MBT, the tendency of engine knocking to happen is high. A normal practice by calibration engineer is to retard the ignition timing to 1~3 degrees from the MBT to avoid the engine damage. For example, in this particular exercise, the best ignition timing laid between 25^0 bTDC to 27^0 bTDC. However, there is no quantitative definition in term of how far the spark shall be retarded from the point of maximum torque (Colin *et al.*, 2001).

The phenomenal of torque and power gradient at MBT can be explained by the mass fraction burn rate of the gases in the cylinder during combustion process. If advanced ignition timing is applied, the mass fraction burn rate has rapid response before the piston reaches TDC and after the piston reaches TDC. The mass fraction rate however is slower for retarded ignition timing. The mass fraction burn rate also influenced by variation of dwell time as illustrated in Figure 6 (a) and (b). The dwell time is the interval of spark ignition to occur. The interval at 4- 5 second produced high and stable power and torque and it an arc. The different cylinder pressure is very significant when different dwell angle is applied.

NOx, HC and CO Concentration:

The NOx concentration was measured and the contour of NOx concentrated at various EOI and ignition is illustrated at Figure 7. Higher NO_x occurred at more advanced ignition timing while the EOI were at the range of more retarded timing. The NO_x concentration has relatively linear relationship with injection timing. The rate different is about 53% between 360^0 CA and 250^0CA.

The HC concentration as shown in Figure 8 indicates that the concentration has relatively low at early injection but high concentration occurs when late injection is applied. Ignition timing has not shown much effect on the HC. However if an advanced ignition timing was set, the HC concentrated is becoming lower.

The CO is formed during the combustion process with rich fuel-air mixtures and when there is insufficient oxygen to fully burn all the carbon in the fuel to form CO_2. The variation of CO concentration with various ignition timing is described in Figure 9.The lowest CO concentration occurs at late injection 300^0 CA at 25^0 bTDC of ignition timing. It is clearly shows that spark ignition timing is one most influential factor to the CO sources, thus is strongly related to the mixture of air-fuel ratio. Rich mixture increases the CO concentration, which represents incomplete combustion. However, some engine management strategy use the rich mixture at certain engine speed and load to increase the engine performance in terms of power and torque. The lowest CO concentration is at 300^0 bTDC ignition angle and 360^0 CA injection angle. The more advanced ignition angle implemented, the lesser CO emission formed. The lowest percentage of CO is 0.011% occurs during the 30^0 bTDC.

O_2 and CO_2 Concentration:

CO_2 and O_2 concentration, which indicate a complete combustion process are illustrated at Figure 10 and 11. High O_2 and CO_2 concentration occurred at 300^0 of EOI and between 25^0 to 28^0 bTDC. If sufficient oxygen is available, a hydrocarbon fuel can be completely oxidized. The carbon in the fuel is then converted to carbon dioxide CO_2 and the hydrogen to water H_2O.

Therefore, if sufficient oxygen is available, a hydrocarbon fuel can be completely oxidized. The carbon in the fuel is then converted to carbon dioxide CO_2 and the hydrogen to water H_2O. At stoichiometric, the fuel/air ratio is 1, the NO shows higher than HC and CO respectively. It is well known that at stoichiometric, engine is at an ideal performance i.e. fuel economy and power. Normally, the engine has been set to operate close to stoichiometric, or slightly-rich, to ensure smooth and reliable operation. The shapes of these curves indicate the complexities of emission control.

Summary and Concluding Remarks:

The finding of this experiment can be summarized as follows;

- Advanced ignition timing may result of NOx increment. The NOx concentration has relatively linear relationship with injection timing.
- The HC concentration is relatively low at early injection but high concentration occurs when late injection is applied. The ignition timing has no significant effect of the concentration.
- Low CO concentration occurs at late injection timing and the lowest emission is 0.011% when we applied 30^0 bTDC of ignition at 360^0 CA injection timing. The most influential factor for CO development is ignition timing.
- Complete combustion occurs at (300^0 EOI, 25^0-28^0 bTDC) as illustrated in the CO_2 and O_2 contour.

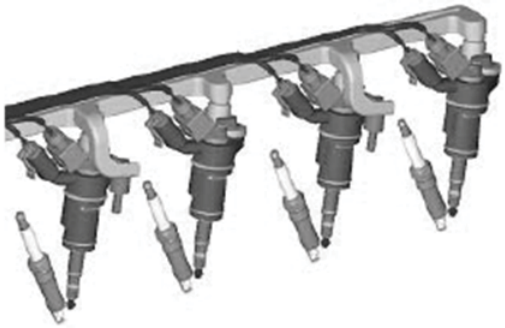

Fig. 1: Fuel rail, injectors and spark plugs arrangement (Shabrn Abdullah *et al.,* 2005)

Fig. 2: Dynamometer and Control Room

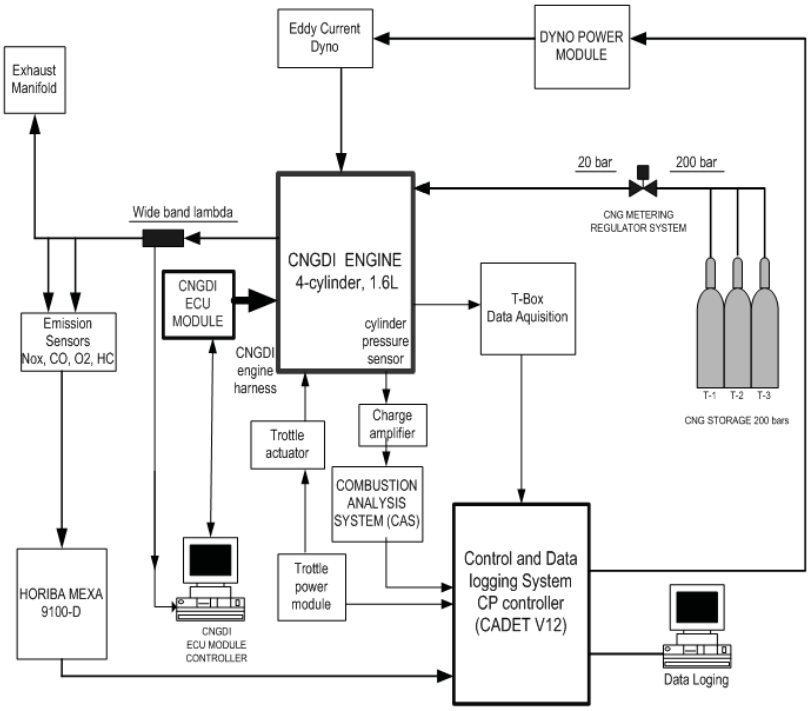

Fig. 3: Experimental set-up

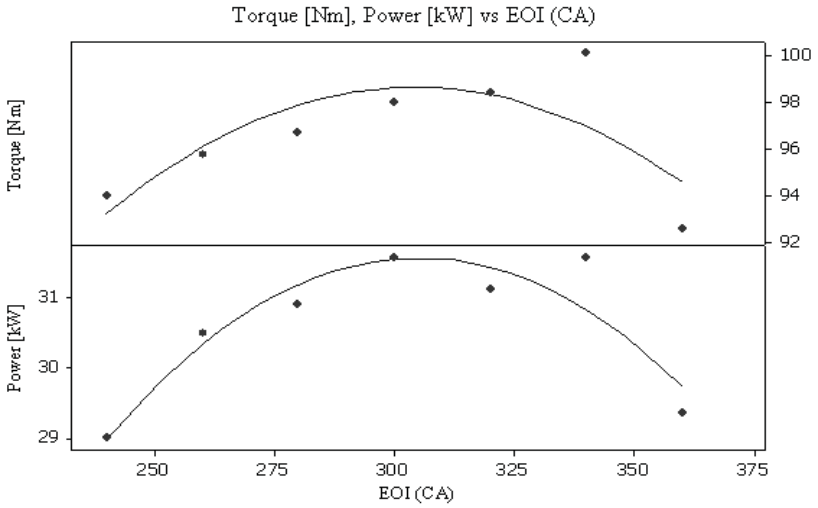

Fig. 4: The characteristics of torque and power at various end of injection.

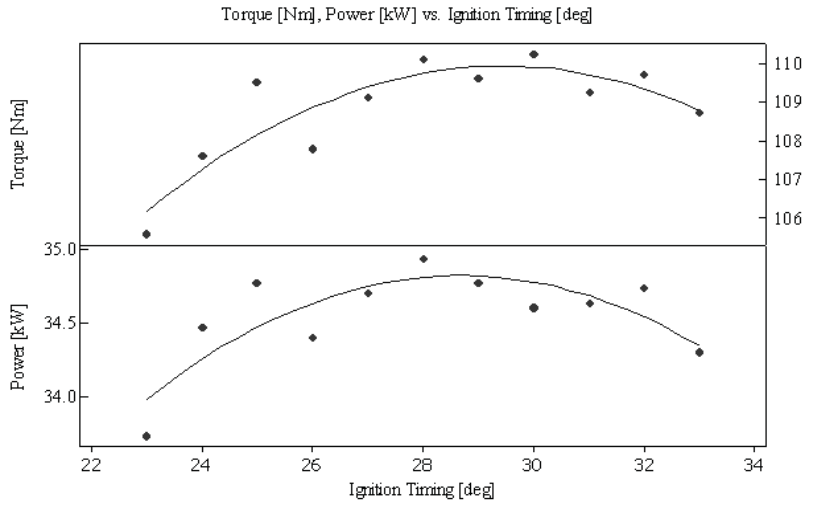

Fig. 5: The characteristics of torque and power at various ignition timing.

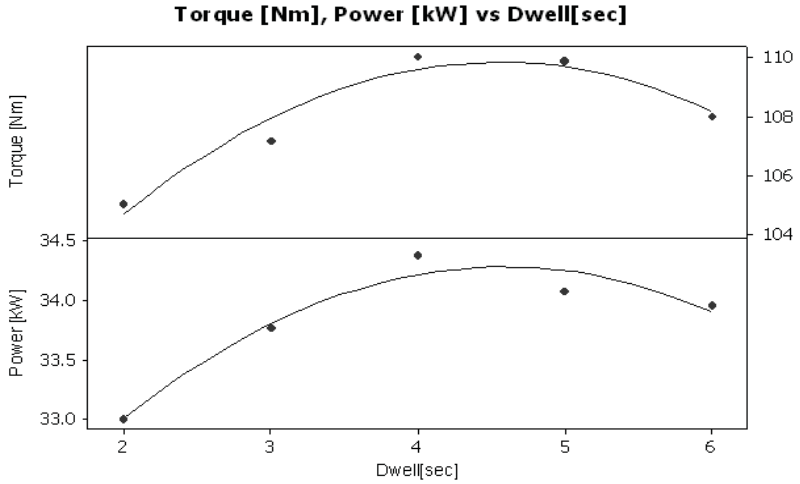

Fig. 6(a): Dwell time of ignition

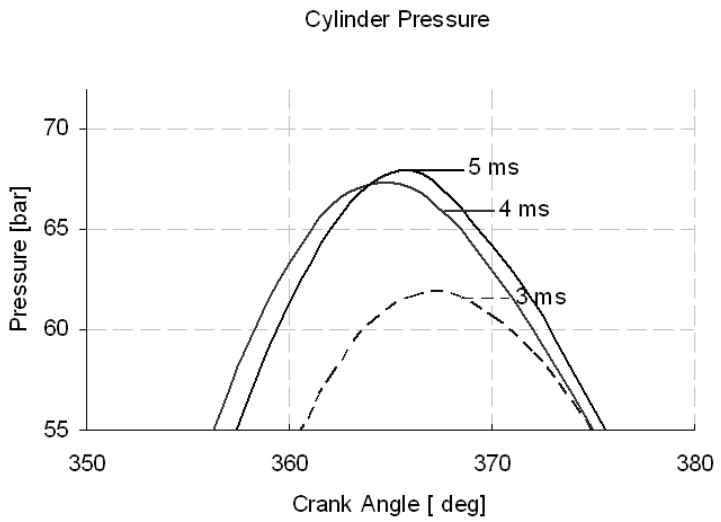

Fig. 6(b): Dwell time

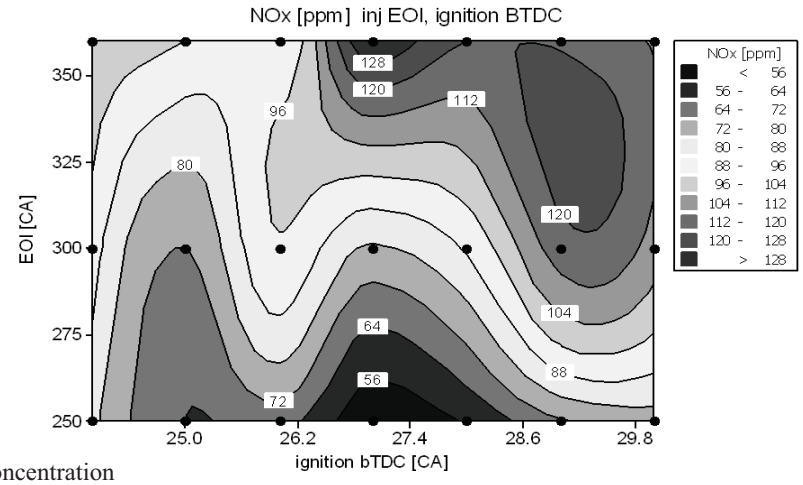

Fig. 7: NOx concentration

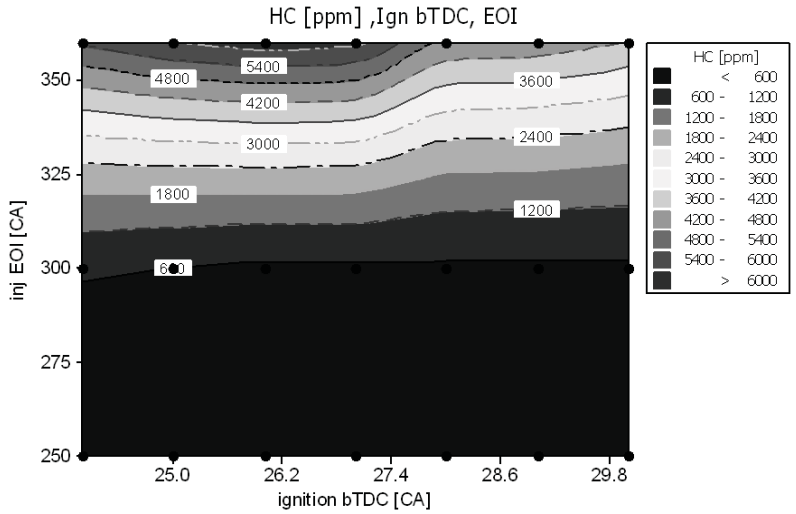

Fig. 8: HC concentration

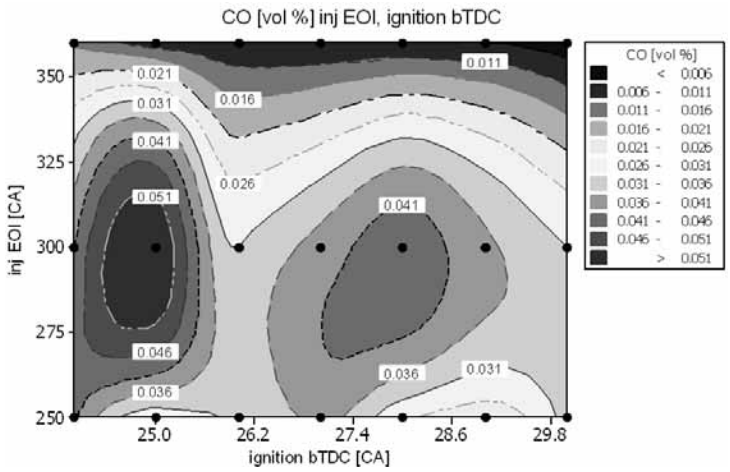

Fig. 9: CO concentration

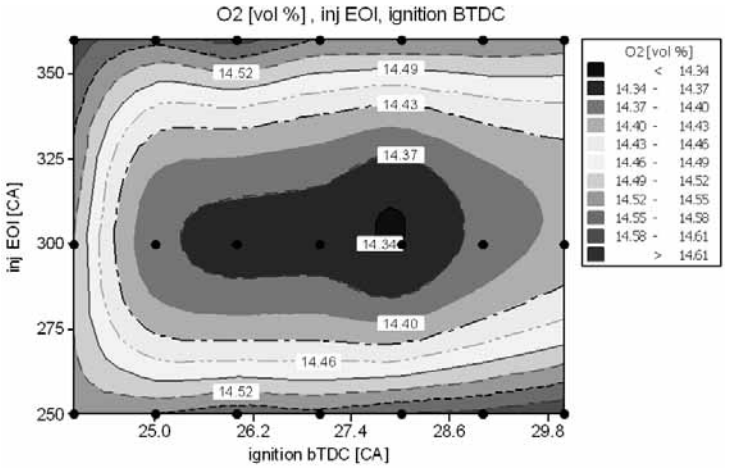

Fig. 10: O2 concentration

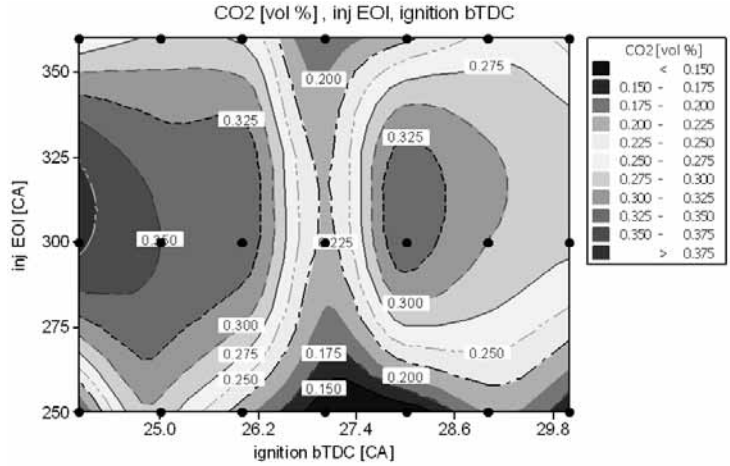

Fig. 11: CO2 Concentration

Table 1: CNGDI Engine specification

Engine parameters	Value
Bore × Stroke (mm)	78 × 84
Connecting rod length (mm)	131
Displacement (cm3)	1596 (4 Cylinders - Inline)
Compression ratio	14:1
Crank radius (mm)	44
Intake valve open (° CA)	12° before TDC
Intake valve close (° CA)	48° after BDC
Exhaust valve open (° CA)	45° before BDC
Exhaust valve close (° CA)	10° after TDC
Fuel Pressure (bar)	20
Valve Train	DOHC 16V & 4 cylinders in-line

ACKNOWLEDGMENT

The author would like to thank Ministry of Science, Technology and Innovation of Malaysia and Universiti Putra Malaysia for the research funding. Special thank also goes to University of Malaya, Kuala Lumpur, (Makmal Tribologi) especially to Mr. Sulaiman and Mr..Mohd Redzwan for the assistance during engine dynamometer testing.

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