INHERENT FUEL CONSUMPTION AND EXHAUST EMISSION OF THE CNG-PETROL BI-FUEL ENGINE BASED AT NON-LOADED OPERATION

RAHMAT MOHSIN[1*], ZULKEFLI YAACOB[2], ZULKIFLI ABDUL MAJID[3] & SHAMEED ASHRAF[4]

Abstract. Compressed natural gas (CNG) is the most successful and widely used alternative fuel for vehicles in the market today. Petrol fuelled vehicles are fitted with natural gas vehicle (NGV) conversion kit to enable bi-fuel operation between CNG and petrol. This experimental approach is focused on the fuel consumption, exhaust emission and fuel cost between natural gas and petrol operations. The specially constructed test rig comprises of the bi-fuel fuel system employed in the 1500 cc 12 valves carburettor engine NGV taxis. The inherent fuel consumption and corresponding exhaust emission are acquired at different engine revolution per minute (rpm) during petrol and CNG operation separately. The engine rpm operating without load is varied from idle to more than 5000 rpm to acquire the fuel consumption and exhaust emission profile. These two acquired data are then used to calculate the engine's air fuel ratio. All three parameters acquired are used to conduct comparisons between petrol and natural gas operation. It is seen that the bi-fuel system operates with air fuel ratio ranging from 19 to 16.3 for petrol operation and ranges from 40 to 18.7 for natural gas operations. The emission during CNG operation clearly shows significant decrease in hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO_x) over the use of petrol. In terms of cost, the use of CNG provides savings exceeding 50% through all engine rpm compared to petrol non-loaded operations.

Keywords: NGV, bi-fuel engine, fuel consumption, exhaust emission, CNG, natural gas

Abstrak. Gas asli termampat (CNG) merupakan bahan api alternatif yang paling berjaya dan digunakan dengan meluas bagi kenderaan terkini yang berada di pasaran. Kenderaan pacuan petrol bagi tujuan ini biasanya dilengkapkan dengan kit penukar gas asli bagi membolehkan operasian dwi-bahan api di antara CNG dan petrol. Pendekatan secara uji kaji ini difokuskan ke atas penggunaan bahan api, emisi ekzos dan kos bahan api di antara operasian gas asli dan petrol. Rig ujian terdiri dari sebuah sistem enjin teksi dwi-bahan api menggunakan 1500 cc dengan 12 injap sistem karburetor adalah dibina khusus. Penggunaan bahan api dan emisi ekzos yang setara diperolehi pada kelajuan putaran seminit (rpm) enjin yang berbeza ketika operasian menggunakan bahan api CNG dan petrol secara berasingan. Pengoperasian rpm enjin tanpa bebanan diubahsuai dari kedudukan pegun kepada kedudukan melebihi 5000 rpm untuk memperolehi profil penggunaan bahan api dan emisi ekzos. Kedua-dua data yang diperolehi ini kemudiannya digunakan bagi mengira kadar udara bahan api enjin. Kesemua ketiga-tiga

[1-4] Gas Technology Centre (GASTEG), Faculty of Chemical and Natural Resources Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Darul Takzim, Malaysia

* Corresponding author: Tel: 07-5535653, Fax: 07-5545667, Email: rahmat@fkkksa.utm.my

parameter yang diperolehi digunakan untuk membuat perbandingan terhadap operasian gas asli dan petrol. Pemerhatian yang dibuat menunjukkan kadar udara bahan api bermula dari 19 ke 16.3 bagi operasian petrol dan dari 40 ke 18.7 untuk operasian menggunakan gas asli. Emisi ketika operasian menggunakan CNG jelas menunjukkan penurunan ketara ke atas keluaran hidrokarbon (HC), karbon monoksida (CO), karbon dioksida (CO_2) dan nitrogen oksida (NOx) dibandingkan dengan operasian menggunakan petrol. Dari segi kos, penggunaan CNG memberikan keuntungan melebihi 50% terhadap kesemua kelajuan rpm enjin jika dibandingkan dengan operasi menggunakan petrol.

Kata kunci: NGV, enjin dwi-bahan api, pengunaan bahan api, emisi ekzos, CNG, gas asli

1.0   INTRODUCTION

Natural gas can be used as motor vehicles fuel in compressed form known as compressed natural gas (CNG). Natural gas is currently the most successful alternative fuel in the world. CNG vehicles emit much less carbon monoxide than gasoline or methanol vehicles, because CNG mixes better with air than do liquid fuels and requires less enrichment for engine start-up, but the extent of the reduction in pollutants will depend upon the emission control system. Because natural gas is mostly methane, NGVs will emit fewer non-methane hydrocarbons (NMHCs) than gasoline and methanol vehicles. NGVs will emit essentially no unregulated pollutants (e.g. benzene), smoke or sulphur oxides, and slightly less formaldehyde than gasoline vehicles, and their use would be expected to reduce ozone levels relative to the levels resulting from gasoline vehicles use [1].

There are approximately 3 317 036 NGV in the world, and Malaysia has 8300 NGV as up to January 2004. The NGV in Malaysia mostly consist of bi-fuel taxis having a 1500 cc carburetor engine. A typical petrol powered vehicle is fitted with a conversion kit to enable the bi-fuel operation that provides the user with fuel options of petrol and natural gas with the ease of a switch. The bi-fuel NGV conversion kit used on the 1500 cc carburettor taxis consist of a fuel selector switch, a spark advancer, air fuel mixer, pressure regulator, CNG solenoid valve, petrol solenoid valve and a storage cylinder. A typical configuration of CNG system is shown in Figure 1. When the fuel sector switch is turned to natural gas, the petrol solenoid valve will block the flow of the petrol to the carburettor while the current is supplied to the NGV solenoid valve that permits natural gas to flow into the pressure regulator. The pressure regulator regulates the CNG from the storage cylinder according to the engine requirement and sends it to the mixer (placed between the air filter and the carburettor). The natural gas supplied to the engine is proportional to the vacuum pressure generated by the air flow through the mixer. This vacuum signal generated by the mixer geometry acts on the 3rd stage diaphragm of the pressure regulator to ensure suitable supply of natural gas according to the engine speed. The spark advancer is activated during natural gas operation to alter the spark angle.

Due to various differences between petrol and natural gas operation, this study on 1500 cc carburettor engine is focused on the inherent fuel consumption and exhaust emission at various engine speeds. Both parameters are used to calculate the air fuel ratio of the carburetion system during petrol and natural gas operations. This will develop a relation between the inherent fuel consumption, air fuel ratio and the corresponding exhaust emission according to engine speed. This is used to compare fuel consumption, operational cost and exhaust emission between fuels.

2.0 METHODOLOGY

The sole dependency on conventional fuel for vehicles and its polluting emission have caused the growth of alternative fuel vehicles. By virtue of its abundance reserves, the natural gas is the most widely used alternative fuel. The commercially available fuel system serves as a basis for the new fuel system design. A schematic diagram of the bi-fuel engine rig set up is shown in Figure 1 whilst the flow diagram in Figure 2 provides the frame work for the entire study.

A bi-fuel engine test skid is designed and fabricated to form strong theoretical and practical understanding on its functionality and operation. A carburettor engine is fitted with an NGV conversion kit to form the bi-fuel engine test skid. The skid is also fitted with wheels to ease the maneuvering of the skid.

The engine rpm gauged using an infrared tachometer installed at the flywheel is varied and held constant by manipulating the throttle at the control panel. The fuel consumption and emission are obtained while the engine rpm is held constant. The petrol consumption is measured using a Gilmont variable area flow meter whereas the exhaust emission is analysed using an autocheck emission analyser. Three runs were conducted for each engine rpm to ensure the repeatability of the result obtained. The engine rpm is then increased from idle to values greater then 5000 in order to obtain the fuel consumption and emission profile of the bi-fuel engine operating on petrol.

Similar test are conducted to obtain the natural gas consumption and the emission generated at different engine rpm. The method used to measure the natural gas consumption is based on the fact that the storage cylinder pressure will deplete proportionally to the moles of gas consumed at constant engine rpm. Higher engine rpm consumes more fuel causing greater rate of pressure depletion within storage cylinder. The storage cylinder pressure at constant engine rpm was monitored using a Beamex MC5 Calibrator for accurate pressure reading. The time taken for the acquired pressure depletion during constant rpm operation will be used to attain the mol flowrate of natural gas to the engine.


Figure 1   Schematic diagram of the bi-fuel engine rig set up
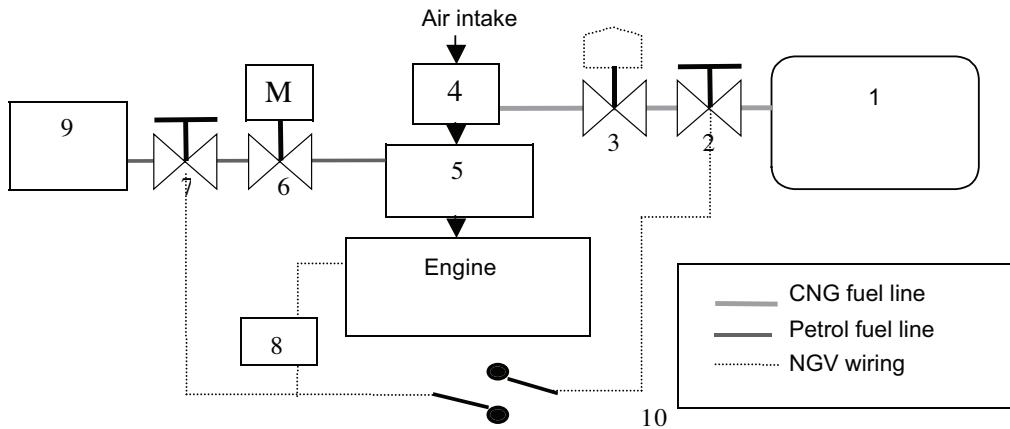
No	Component	No	Component
1	CNG storage cylinder	2	CNG solenoid valve
3	CNG pressure regulator	4	Natural gas mixer
5	Carburettor	6	Petrol flow meter
7	Petrol solenoid valve	8	Spark timing advancer
9	Petrol tank	10	Fuel selector switch

2.1   Experimental Rig Setup

A Proton Magma 1.5 litre 12 valve carburettor engine as described in Table 1 was fitted with an NGV conversion kit to form the bi-fuel engine test rig. All three mounting points are made adjustable in both horizontal and vertical direction to aid the alignment of the engine and suit other similar engines. The rig has closure panels to safe guard the operator from moving component hazard and fitted with wheels to ease the manoeuvring of the rig.
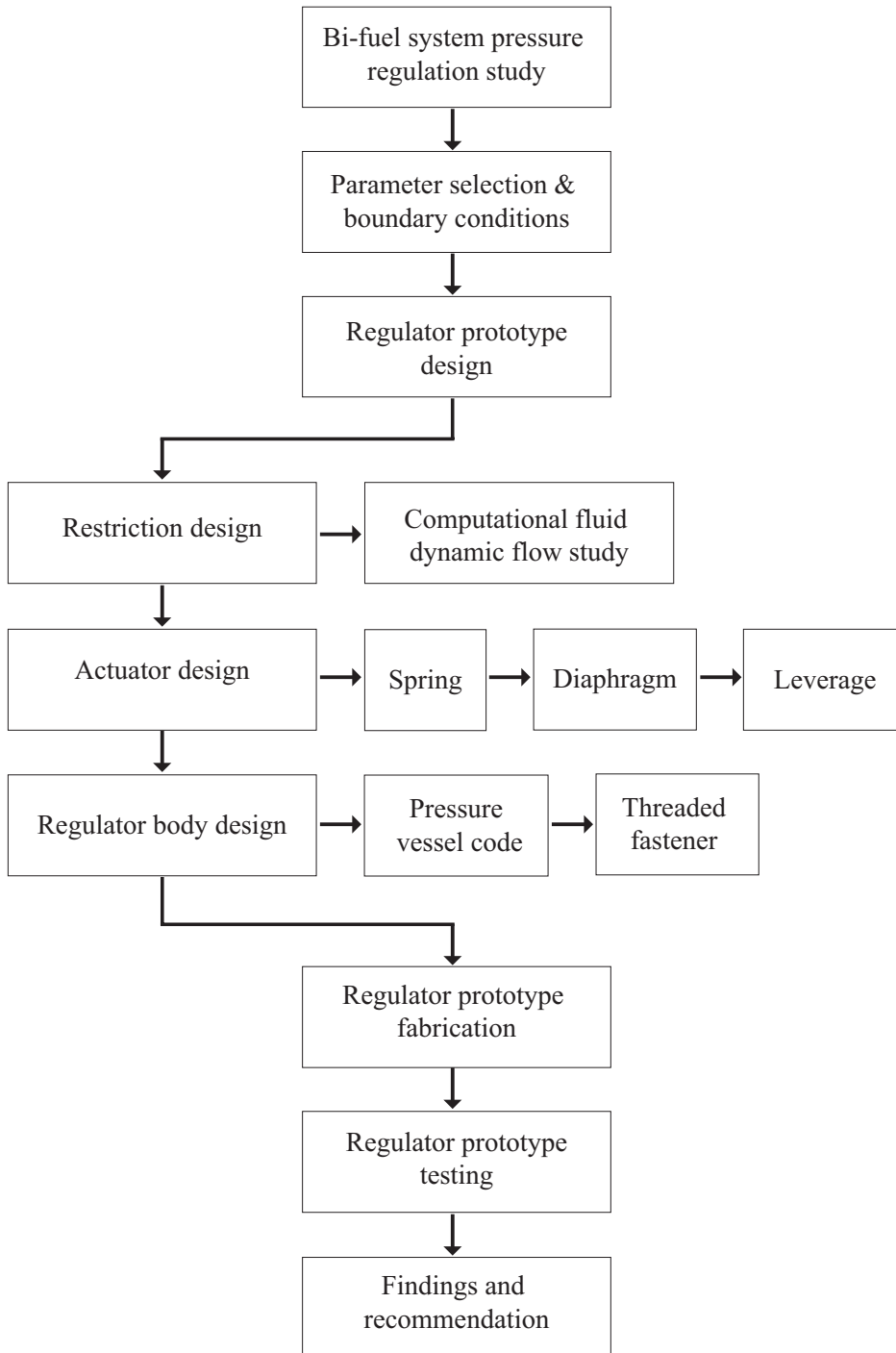
Figure 2 Research methodology

The rig metal structure is coated with epoxy (powder coating) to avoid corrosion caused by extreme working conditions. The installations of the NGV fuel system were based on the MS 1096 [2], MS 1024 [3] and NFPA 52 [4] to ensure safe operation. Drawing of the main structures used to support the engine and the NGV storage cylinder are shown in Figures 3 and 4 that display the control panel structure used to hold controlling devices such as the throttle control, ignition key, emergency shut-off, pressure sensor, pressure display unit and also the petrol tank. Figure 5 depicts the bi-fuel system suspended from the rig structure. Figure 6 presents the entire rig equipped with closure panels and extended exhaust pipe for safe operation.

Table 1   Test engine specifications

| Characteristics	Proton Magma -12 valves
Displacement, cc	1468
Compression ratio	9.2
Bore, mm	75.5
Stroke, mm	82
Max output (DIN) PS/rpm net (kW/rpm)	87/6000/(64/6000)
Max torque (DIN) kg.m/rpm net (Nm/rpm)	12.5/3500/(122/3500)
Carburettor	Down-draft 2-barrel
Specification of NGV Carburetion System Tested:	
Regulator	Landi Renzo TN1-B-SIC
Mixer	Remote extractor
Spark advancer	STAP 51
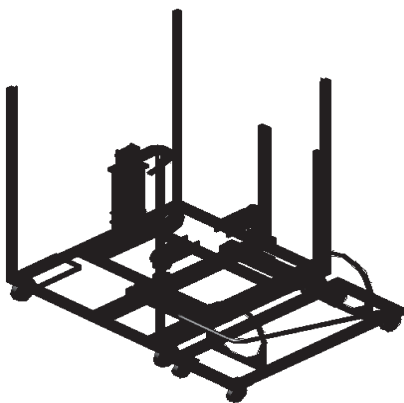
Figure 3   Main engine frame
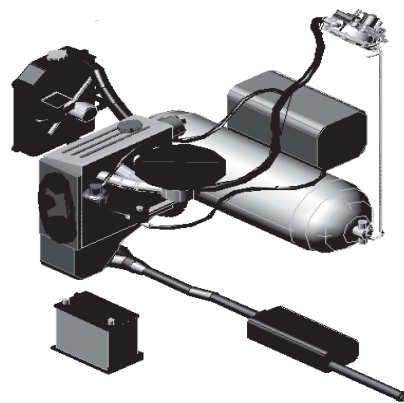
Figure 4   Bi-fuel fuel systems
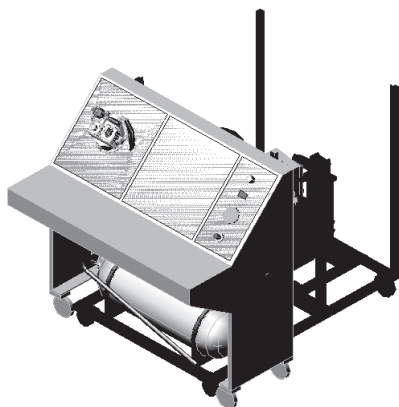
Figure 5   Test rig with control panel
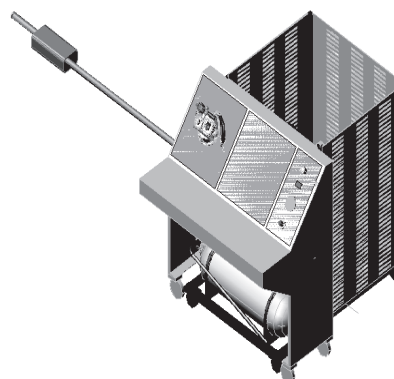
**Figure 6**   Engine test rig for operation

2.2   Calculations Relating to Cylinder Pressure and Mol Content

Due to the energy equivalent factor, the energy within the natural gas priced at RM 0.68 per litre is the same as the energy content within 1 litre of petrol priced at RM 2.70. It is known from reference that 1 litre of petrol has approximately 30.676 MJ of energy [5]. The energy content of Malaysian natural gas is 1053 Btu per cubic ft which translates to 0.9574 MJ per mol of natural gas. From experiments conducted, one 55 litre water capacity tank would accommodate approximately RM 8.43 worth of natural gas. The energy content of this fully charged tank is calculated as 380 MJ by the energy content calculations (shown in Appendix A). The value is then divided with the energy content per mol of natural gas to obtain 397 moles of natural gas per charge of a 55 litre cylinder. The petrol cost for similar amount of energy would sum up to RM 33.45, giving savings up to RM 25.00 for every charge of the NGV tank.

Referring to MS 1096, the cylinder temperature would rise up to 800°C (353 K) during charging [2]. This internal temperature increase during charging depends on the cylinder's material of construction that has different heat dissipation abilities. The storage capacity of a cylinder is inversely related to the internal temperature during fast fill. CNG cylinders constructed primarily from steel (NGV Type 2) employed on the system understudy provides the most cost effective storage capabilities [6]. Currently the most commercially available CNG dispensers rely on a mathematical model or algorithm utilizing the measured temperature of the gas flowing in the dispenser to determine full charge pressure [6]. This temperature compensating

mechanism included in the CNG dispenser causes the full charge pressure of the storage cylinder to be below the NGV fuel system designed operating pressure of 20.68 MPa during charging. This safety mechanism helps avoid extreme internal pressure build up caused by heat within the vehicle during extreme weather.

The amount of moles within the NGV cylinder as predicted by the energy equivalent calculation shown in Appendix A and described above is validated using correlations based on storage cylinder internal pressure. The generalized correlation for gases by Pitzer [7], Benedict /Webb/Rubin [8] is compared in Figure 7 to obtain the best prediction of mol content within the 55 litre storage cylinder. The finding by Benedict/Webb/Rubin validates the cylinder content of 400 moles at 350 K [2] which would bring about 18.62 MPa of pressure. This value corresponds to the 18.62 MPa value obtained during the experimental charging done with an empty cylinder. The Pitzer correlation deviates greatly at 350 K in the vicinity of 18 616 kPa region, proving its deviation from the actual value.
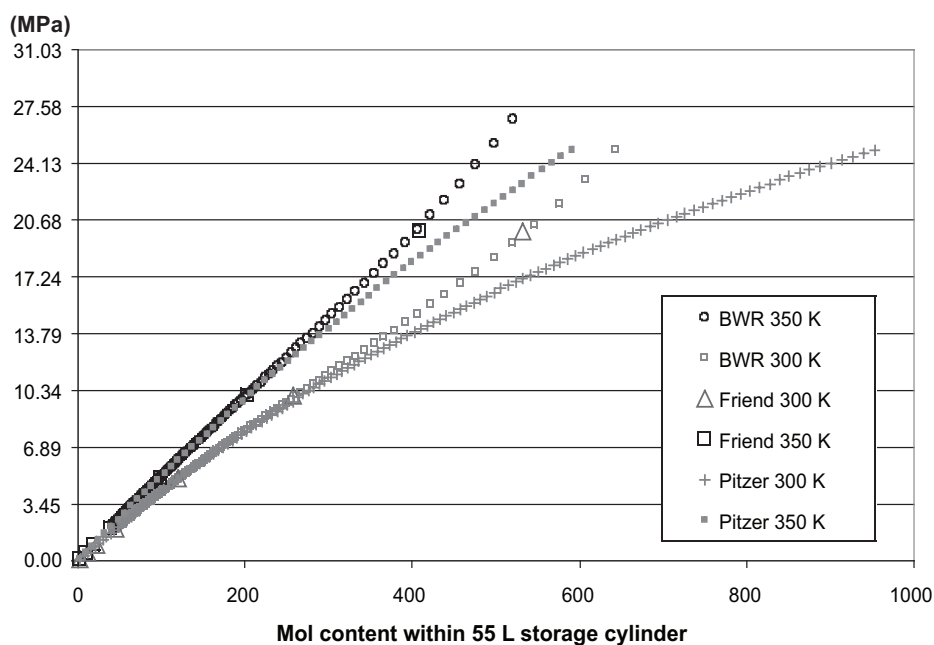
Figure 7   Comparisons between Benedict/Webb/Rubin, Pitzer and Friend relations of mol content within the storage cylinder at 300 K and 350 K

Table 2   Typical natural gas compositions [9]

Component	Mole (%)
Methane	83.44
Ethane	10.55
Propane	1.31
Isobutane	0.13
Normal-butane	0.07
Isopentane	0.01
Hexane	0.01
Carbon dioxide	4.17
Nitrogen	0.31
Density (kg/cm^3)	0.81
Gross calorific value (MJ/kg)	49.00
Molecular weight	19.19
Specific gravity	0.64

2.3   Calculations Relating to Air-Fuel Ratio, Fuel Consumption and Emission

The fuel consumption together with the emission results were used to conduct carbon, hydrogen and oxygen balanced to determine the air fuel ratio [9]. The gross calorific value and specific gravity of the used gasoline fuel (C_8H_{18}) are 45 kg/m^3 and 0.692 respectively [9]. The physicochemical properties of CNG used in this experiment are shown in Table 2. From this table, a chemical formula for CNG was derived as $C_\alpha H_\beta O_\gamma N_\delta$, where $\alpha = 1.136$, $\beta = 4.098$, $\gamma = 0.0834$ and $\delta = 0.0062$.

$$\frac{\left(\dfrac{\text{Air}}{\text{Fuel}} \right)_{\text{actual}}}{\left(\dfrac{\text{Air}}{\text{Fuel}} \right)_{\text{stoichiometric}}} = \text{air fuel equivalence ratio} = \lambda \tag{1}$$

λ is the ratio between actual air fuel ratio against the stoichiometric air fuel ratio given by Equation (1) [10]. Equation (2) provides complete derivation of the stoichiometric air fuel ratio calculations for the gasoline C_8H_{18} [7]. The stoichiometric air fuel ratio for natural gas $C_{1.136} H_{4.098} O_{0.0834} N_{0.0062}$ is carried out based on Equation

(3) [10]. The actual air fuel ratio is calculated based by conducting mass balance on C, O and H [9]. The ratio between actual and stoichiometric air fuel ratio is used to calculate the inherent lambda value of the bi-fuel operation of both fuels separately.

$$\left(\frac{A}{F}\right)_S^{\text{Petrol}} = \frac{4.321\times15.999\times\left[2+(0.5)\times\left(\frac{H}{C}\right)\right]}{\left[(12.011\times1)+(1.0079)\times\left(\frac{H}{C}\right)\right]}$$

$$\left(\frac{A}{F}\right)_S^{\text{Petrol}} = \frac{4.3211\times15.999\times\left[2+(0.5)\times(2.25)\right]}{\left[(12.011\times1)+(1.0079)\times(2.25)\right]}$$

$$\left(\frac{A}{F}\right)_S^{\text{Petrol}} = 15.1303$$

$$(2)$$

$$\left(\frac{A}{F}\right)_S^{\text{CNG}} = \frac{4.321\times15.999\times\left[2+(0.5)\times\left(\frac{H}{C}\right)-\left(\frac{O}{C}\right)+1\left(\frac{N}{C}\right)\right]}{\left[(12.011\times1)+(1.0079)\times\left(\frac{H}{C}\right)+(15.999)\times\left(\frac{O}{C}\right)+(14.007)\times\left(\frac{N}{C}\right)\right]}$$

$$\left(\frac{A}{F}\right)_S^{\text{CNG}} = \frac{4.3211\times15.999\times\left[2+(0.5)\times\left(\frac{4.098}{1.136}\right)-\left(\frac{0.0834}{1.136}\right)+1\left(\frac{0.0062}{1.136}\right)\right]}{\left[(12.011\times1)+(1.0079)\times\left(\frac{4.098}{1.136}\right)+(15.999)\times\left(\frac{0.0834}{1.136}\right)+(14.007)\times\left(\frac{0.0062}{1.136}\right)\right]}$$

$$\left(\frac{A}{F}\right)_S^{\text{CNG}} = 14.6858$$

$$(3)$$

## 3.0   RESULTS AND DISCUSSION

The natural gas and petrol consumption at the corresponding engine crankshaft revolutions (rpm) are displayed in Figures 8 and 9 respectively. The engine would draw similar amount of air irrespective of natural gas or petrol operation. The petrol supply system is designed by the engine manufacturer to maintain the desired air fuel ratio to ensure proper power extraction and emission control. The NGV conversion kit does this through the mixer that converts the air flow to the carburettor into vacuum signal that act on the third stage diaphragm of the pressure regulator

to provide corresponding amount of natural gas to maintain the desired air fuel ratio. This validates the similar increment pattern of both the curves indicating the engines intrinsic fuel requirement at the desired engine rpm. Since the fuel is in different phases, comparisons are done by converting the fuel in terms of energy content (similarly done in Appendix A) as shown in Figure 10.
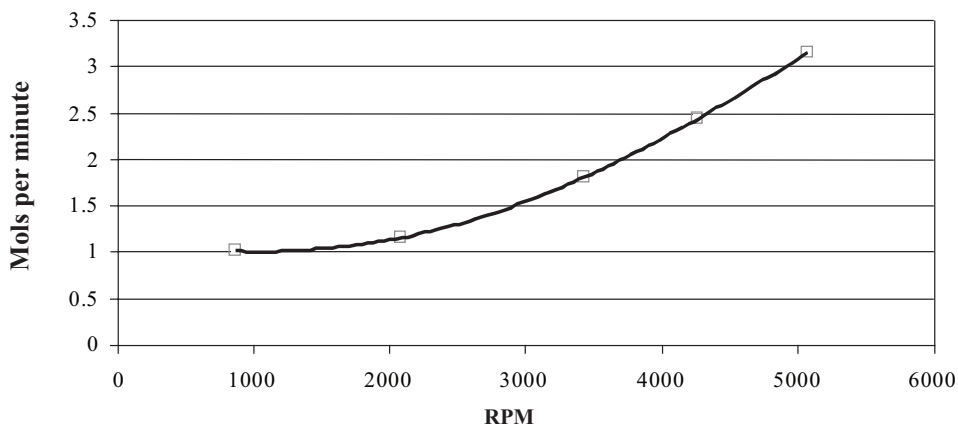
Figure 8   Moles of natural gas consumed by engine at varying rpm
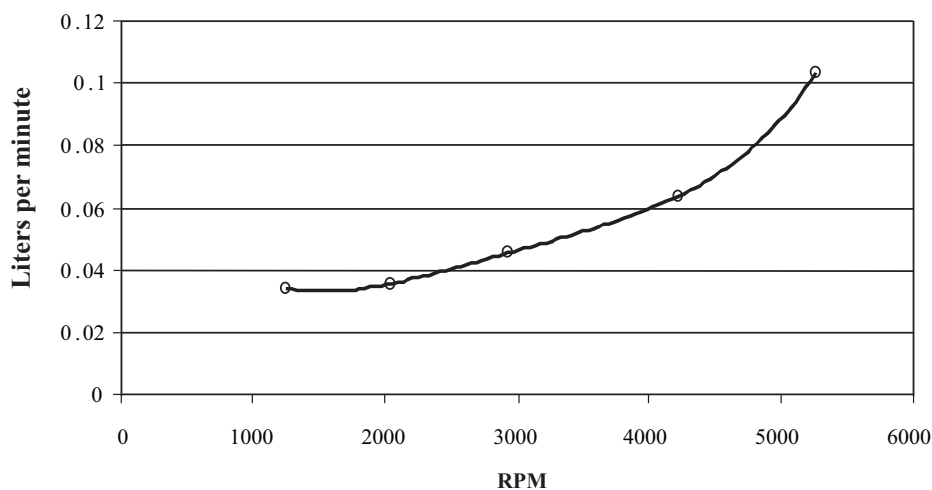
**Figure 9**   Litres of petrol required by engine at varying engine rpm
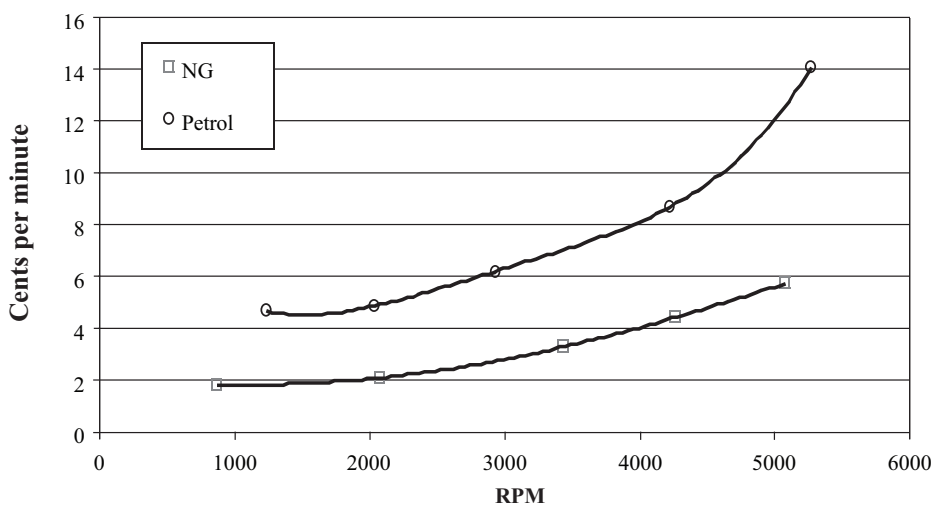
Figure 10   Cost of fuel in cents per minute at varying engine rpm

The fuel consumption rate combined with the price of fuel has lead to the generation of the graph in Figure 10 which compares the cost of fuel in terms of cents per minute at the relevant engine rpm. It clearly shows that the use of natural gas as fuel provides more then 50% savings on fuel cost over petrol operation regardless of the engine rpm.

Table 3   Emission data for gasoline (C_8H_{18}) and CNG fuels

| Fuels	RPM	CO (%)	CO_2 (%)	O_2 (%)	NO_x (ppm)	HC (ppm)
Gasoline	1239	0.7	11.33	3.19	129	142
	2037	1.33	11.86	1.73	159	82
	2928	0.41	13.33	0.48	364	47
	4219	2.3	11.98	0.4	701	174
	5264	0.55	12.37	1.67	1158	388
CNG	863	0.04	4.91	11.48	26	776
	2082	0.11	8.74	4.33	84	62
	3430	0.12	10.03	1.9	194	29
	4257	0.29	10.48	0.59	373	50
	5073	0.44	10	1.1	805	133

The exhaust emission shown in Table 3 for both natural gas and petrol operations are presented in the graphs shown from Figures 11 to 15 to ease analysis of the engines inherent emission pattern during petrol and natural gas operation. It is clear that the use of natural gas is favourable in terms of emission quality as all the polluting components have been reduced throughout the engine rpm value from idle to values above 5000 rpm. These emissions are the result of the engine's intrinsic behaviour coupled with the provided air fuel ratio (Figure 15) by the designated fuel system.
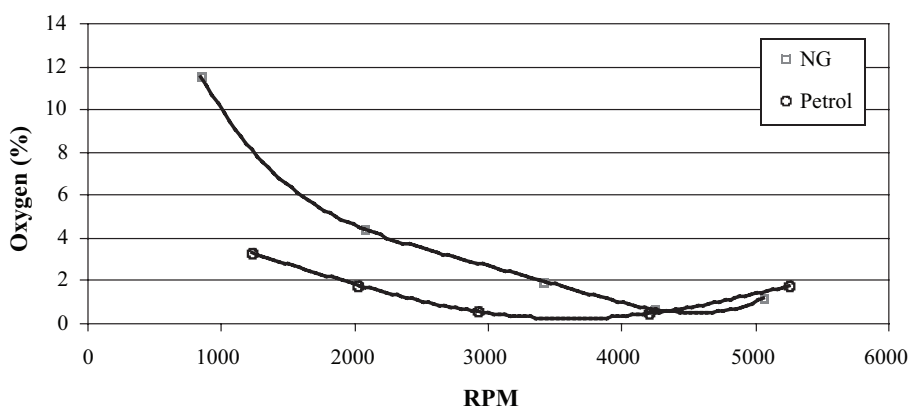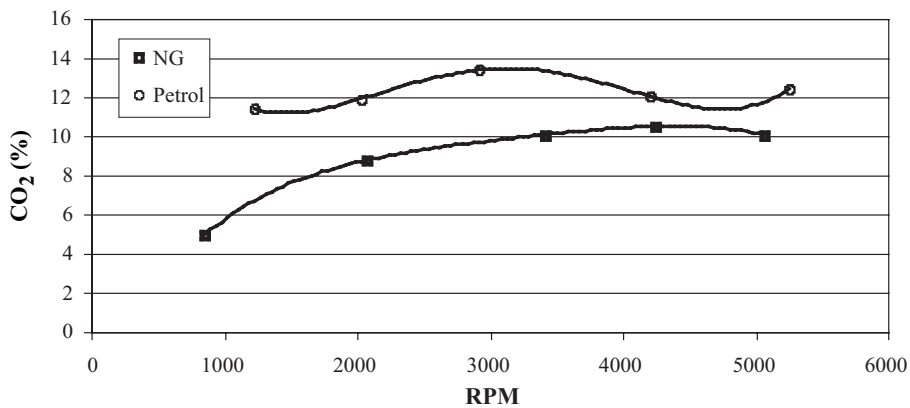
Figure 11   Percentage oxygen content in exhaust gas at varying engine rpm
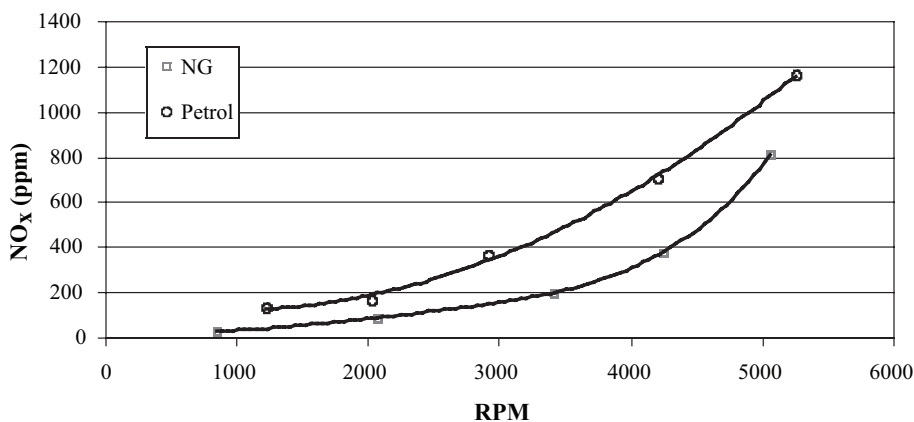
Figure 12 NO_x content in exhaust gas at varying engine rpm
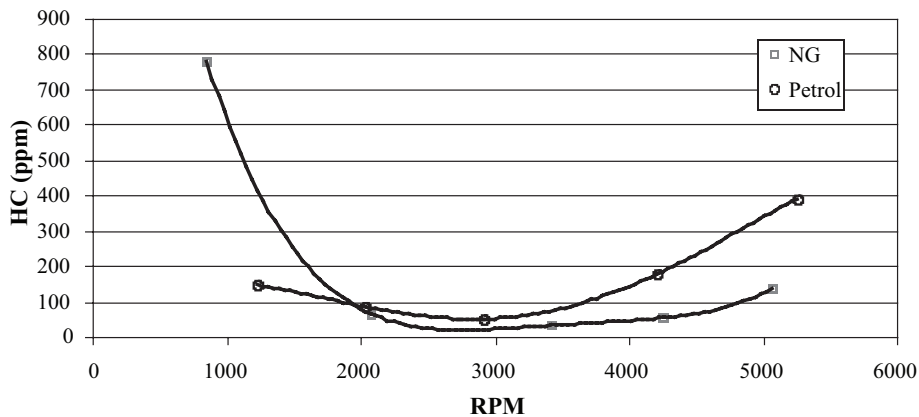
Figure 13   Unburned hydrocarbon content in exhaust gas at varying engine rpm


Figure 14 CO_2 content in exhaust gas at varying engine rpm

As stated in the previous sections, the fuel consumption and emission are used to calculate the air fuel ratio as shown in Figure 15. It is seen that the engine operates with air fuel ratios in the range of 16.2 to 18.8 for petrol operation and 17.0 to 87.3 for natural gas operations. For petrol operations, the air fuel ratio within 16 to 17 provides the highest thermal efficiency [11]. This validates the inherent air fuel ratio of 18.8, designed to save petrol during engine idle while air fuel ratio of 16 to 17 is experienced for engine speeds between 2000 and 5000. This ensures the vehicle will mostly operate at the highest thermal efficiency to obtain the highest attainable work from fuel to minimise fuel consumption which is directly related to cost. As stated earlier, the natural gas operates at very lean air fuel ratio of 87.3

during idle. This is to minimise the use of natural gas as an NGV has limited CNG supply onboard. The inherent natural gas air fuel ratio increases with the engine rpm to provide richer blend that provides the engine with more combustion power. The supplied air fuel ratio is next compared with the stoichiometric air fuel ratio to form lambda value as shown in Figure 16.
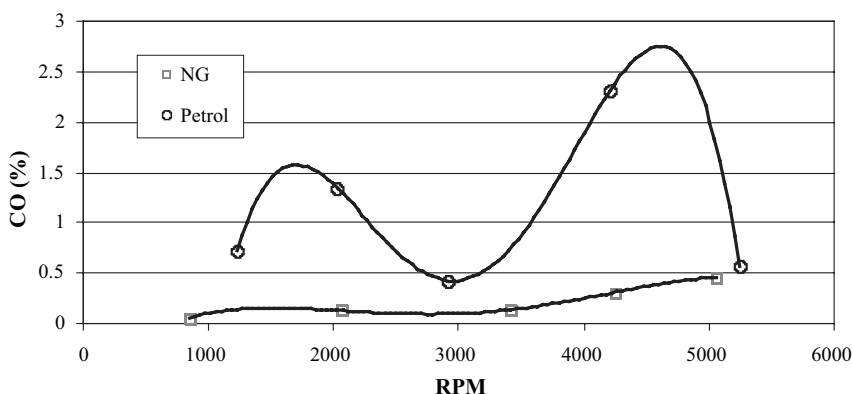
Figure 15   CO content in exhaust gas at varying engine rpm
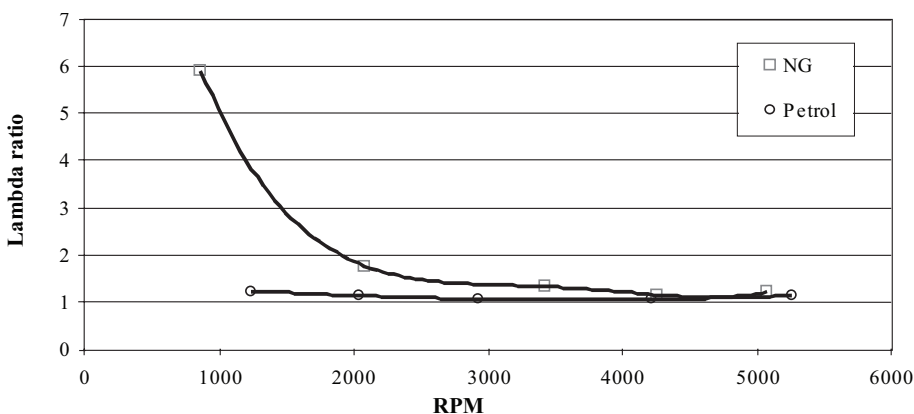
Figure 16   Lambda ratio of the air fuel ratio corresponding to engine rpm

Petrol operated engines in general have air fuel ratio of approximately between $\lambda = 0.85$ and $\lambda = 1.2$ if no lambda control is present [12]. The engine understudy has an inherent design that operates with lambda ratio of 1.2 to 1.0. These values are at the upper limit of the suggested range, provide high thermal efficiency which in return reduces fuel consumption [11].

4.0   CONCLUSION

The bi-fuel engine test rig has successfully provided the inherent behaviour of 1500 cc bi-fuel NGV system in terms of fuel consumption and exhaust emission. Most NGV operating in Malaysia will have similar characteristics with the findings obtained. It is clear that the use of natural gas release less polluting exhaust emission compared to petrol operation. The cost of natural gas operation provides over 50% savings over the use of petrol. All this factors proves the benefits of natural gas over petrol operations.

ACKNOWLEDGEMENTS

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APPENDIX A

i) From the ideal gas law, we know one mole of gas would occupy the following volume at room temperature.

$$v = \frac{RT}{P} = \frac{8.314 \dfrac{\text{kPa} \cdot \text{litre}}{\text{mol} \cdot \text{K}} \times 298\text{K}}{101325\text{Pa}} = 24.45 \, \text{litre}$$

ii) Energy content of natural gas.

$$1053 \frac{\text{Btu}}{\text{cft}} \times \frac{1 \, \text{cft}}{28.317 \, \text{litre}} \times \frac{24.45 \, \text{litre (at 298K)}}{1 \, \text{mol}} \times \frac{1 \, \text{MJ}}{947.817 \, \text{Btu}} = 0.957 \frac{\text{MJ}}{\text{mol}}$$

iii) Energy content of 1 litre of petrol.

$$\frac{0.69 \, \text{kg}}{1 \, \text{litre}} \times \frac{1000 \, \text{g}}{1 \, \text{kg}} \times \frac{1 \, \text{mol}}{114.23 \, \text{g}} \times \frac{5.07 \times 10^6 \, \text{J}}{1 \, \text{mol}} \times \frac{1 \, \text{MJ}}{1 \times 10^6 \, \text{J}} = \frac{30.625 \, \text{MJ}}{1 \, \text{litre}}$$

iv) Energy within a 55 litre NGV cylinder charged for RM 8.43 based on RM 0.68 NGV = RM 1.34 = 30.625 MJ.

$$\frac{\text{RM} 8.43}{\text{cylinder}} \times \frac{30.625 \, \text{MJ}}{\text{RM} 0.68} = \frac{379.660 \, \text{MJ}}{\text{cylinder}}$$

v) Mol content within a cylinder based on energy per mol of natural gas.

$$\frac{379.660 \, \text{MJ}}{\text{cylinder}} \times \frac{1 \, \text{mol}}{0.9573 \, \text{MJ}} = \frac{396.65 \, \text{mol}}{\text{cylinder}}$$