

THE PERFORMANCE OF A SPARK-IGNITION ENGINE FUELLED WITH NATURAL GAS AND GASOLINE

M.U. Aslam, H.H. Masjuki, M.A. Kalam, H. Abdesselam, M. Varman*
T.M.I. Mahlia and M.A. Amalina

Department of Mechanical Engineering
University of Malaya, 50603, Kuala Lumpur, Malaysia.

Abstract

An experimental evaluation has been made of the power output, specific fuel consumption and fuel conversion efficiency from running a 1.5 litre, 4-cylinder Proton Magma retrofitted spark ignition car engine with a dynamometer. Tests have been conducted at wide open throttle (WOT), with varying speeds and at constant speed with varying load. Performance, fuel consumption measurements were recorded under steady state operating conditions for gasoline and CNG (compressed natural gas). The engine was converted to computer integrated bi-fueling system from a gasoline engine and was operated separately either with gasoline or CNG using an electronically controlled solenoid actuated valve system. A PC based data acquisition and control system was used for controlling all the operation. A comparative analysis of the performance has been made for gasoline and CNG. With CNG operation on average, brake mean pressure and brake specific fuel consumption were found to decrease by around 16% and 18% respectively. However, in terms of fuel conversion efficiency, operation with CNG was found to be more efficient than with gasoline. This is due to the comparative lean operation of the engine with CNG compared to gasoline.

Keywords: Air pollution; compressed natural gas; engine performance

1. Introduction

It is well known that fossil fuel reserves all over the world are diminishing at an alarming rate and a shortage of crude oil is expected at the early decades of this century. In addition to this, the deteriorating quality of air we breathe is becoming another great public concern and tighter regulation of both 'local' and 'global' emissions from engines is anticipated. In view of the versatility of ICE (internal combustion engine), it will remain to lead the transportation sector as there is a significant restriction for the battery and fuel cell powered vehicles with respect to range and acceleration. The power to weight ratio of the ICE (including the tank and fuel) is much more than that of the battery powered or fuel cell operated vehicles [1]. These factors have lead scientists and researchers to develop environment-friendly technologies and to introduce more clean fuels alternatives to the conventional fuels used to power ICEs for ensuring the safe survival of the existing engine technology. Apart from limited life period, the other problem with unrestricted combustion of fossil fuels is the level of CO₂ emission into the Earth's atmosphere. On the other hand, the world total NG (natural gas) reserve as of January 1, 2005 was 6,040 Tscf and based on the current consumption rates, the estimated total recoverable gas, including proven reserves is adequate for almost 66.7 years [2]. This has resulted in

* Corresponding author: M. Varman, Tel.: + 6-03-79674448; e-mail: mv7_98@yahoo.com

an increased interest to use CNG as fuel for internal combustion engines. The merits of CNG as an automotive fuel over conventional fuels are many and presented comprehensively by Nylund et al. and Aslam et al. [3-4]. Due to some of its favorable physio-chemical properties, CNG appears to be an excellent fuel for the SI (spark ignition) engine. Moreover, SI engines can be converted to CNG operation quite easily for with the addition of a second fueling system. CNG has been used in vehicles since 1930's and the current worldwide NGV population is more than 4.6 million according to the IANGV (International Association for Natural Gas Vehicle) statistics and this figure is fast increasing everyday. However most of the engines are retrofitted to natural gas engines from gasoline engines and it produces about 10-15 % less power than the same engine fueled by gasoline [5-8]. Another main drawback is the heavier fuel storage tank and vehicle range is compromised for avoiding very large storage tank.

However, CNG has the potential for increased engine efficiency if the engine is designed for dedicated CNG operation. CNG engines also have the potential for extremely low exhaust emissions if they are operated with state-of-the-art engine control systems. The problematic traffic-related pollutants such as particulates, ozone precursors and benzene in particular are significantly lower compared with diesel, gasoline or LPG engines. The substantial advantage that CNG has in anti knock quality is related to the higher auto ignition temperature and higher octane number compared to that of gasoline as shown in Table 1. Due to such antiknock properties, dedicated SI CNG engines could potentially be designed with CR (compression ratio) as high as 13:1 [9].

Numerous reliable researches on CNG fuelled engines have been done and also going on worldwide by the researchers to enhance the benefits of CNG as well as to reduce its difficulties as an engine fuel. Jones and Evans [10] measured a total power loss of approximately 15% and efficiency drop of 5% when changing from gasoline to CNG. Ten percent loss of power was attributed due to reduction in the inhaled energy and the remaining 5% to the lower burning velocity of CNG compared to gasoline. Evans and Blaszczyk [11] have done another comparative study of performance and exhaust emissions. They found the MBT (maximum brake-torque) spark timing for CNG was between 2 ° to 10 ° crank angle more advanced than that for gasoline at air-fuel ratios close to stiochiometric. The BMEP (brake mean effective pressure) and BSFC both are 12% lower with CNG at WOT (wide open throttle) condition. Efficiency for both the fuels are about the same up to λ (relative air-fuel ratio) =1.3 and with increasing λ value CNG shows higher efficiency than gasoline. Recently Hamid and Ahmad [12] presented a comparison of the NGV and gasoline base engine performance where they found the volumetric efficiency of the NGV engine is reduced by about 15% and overall performance lowered by circa 9% at maximum torque and maximum power conditions. BSFC of NGV engine is reduced from 15-22% at speeds 1500 to 3500 rpm, for the same AFR (air-fuel ratio). The objective of this paper is to practically evaluate the comparative performance characteristics of gasoline and CNG fuels in a 1.5 litre, 4-cylinder retrofitted spark ignition car engine.

| Properties | Gasoline | CNG |
|--|----------|---------|
| Motor octane number | 80-90 | 120-130 |
| Molar mass (kg/mol) | 110 | 16.726 |
| Stoichiometric air-fuel ratio | 14.6 | 16.79 |
| Stoichiometry mixture density (kg/m ³) | 1.38 | 1.24 |
| Lower heating value (MJ/kg) | 44 | 47.669 |
| Lower heating value of stoic. mixture (MJ/kg) | 2.83 | 2.72 |
| Minimum ignition energy required in air (MJ) | 0.25 | 0.29 |
| Flammability limits (% vol. in air) | 1.3 ~7.1 | 5 ~15 |
| Spontaneous ignition temperature (° K) | 753~823 | 918 |

Table 1: Combustion related properties of gasoline & CNG [13]

2. Experimental

2.1 Setup and test procedure

The layout of the experimental setup is shown in Fig. 1. The test engine is converted from a gasoline (Proton Magma) engine and is equipped with a bi-fuelling system. The main specifications of the test engine are listed in Table 2. An AG 150 (Froude Consine) eddy-current dynamometer was used for testing the engine. All the electronic equipment, together with its manipulative controls and indicators, etc. is mounted on “CP Cadet10” control unit. The engine was operated in two different modes such as-

- Steady state condition with WOT and variable speed range of 1500-5500 rpm where the engine satisfy an average λ value of .89 and 1.01 for gasoline and CNG respectively.
- And at constant speed of 2500, 3000, 3500 rpm with variable load of 25-65% of engine full load (122 N-m) where the average value of λ for gasoline and CNG were 0.84 and 0.95 respectively.

Gasoline consumption was measured on a volumetric basis using a pipette. The gasoline delivery system was configured so that spillback from the carburetor was returned to a position downstream of the measuring pipette. CNG was measured with Kobold gas flow meter (Model WFM 2705). The CNG flow meter was incorporated with engine control system through interface cards. Gasoline and CNG (composition shown in Table 3) were used as fuel. A PC-based data acquisition and control system was used for controlling all the operation regarding the test where every stage was allowed to run around 6-8 minutes with data updated every 30 seconds. Measurements were taken of torque, power and fuel consumption from which calculations were made of BMEP, BSFC, BSEC (brake specific energy consumption) and FCE (fuel conversion efficiency). The standard deviation of the gasoline time measurements ranged from 0.4 to 4.0%, depending on the engine operating point. All measurements were repeated at least three times at each test setting and the test sequences were repeated four times.

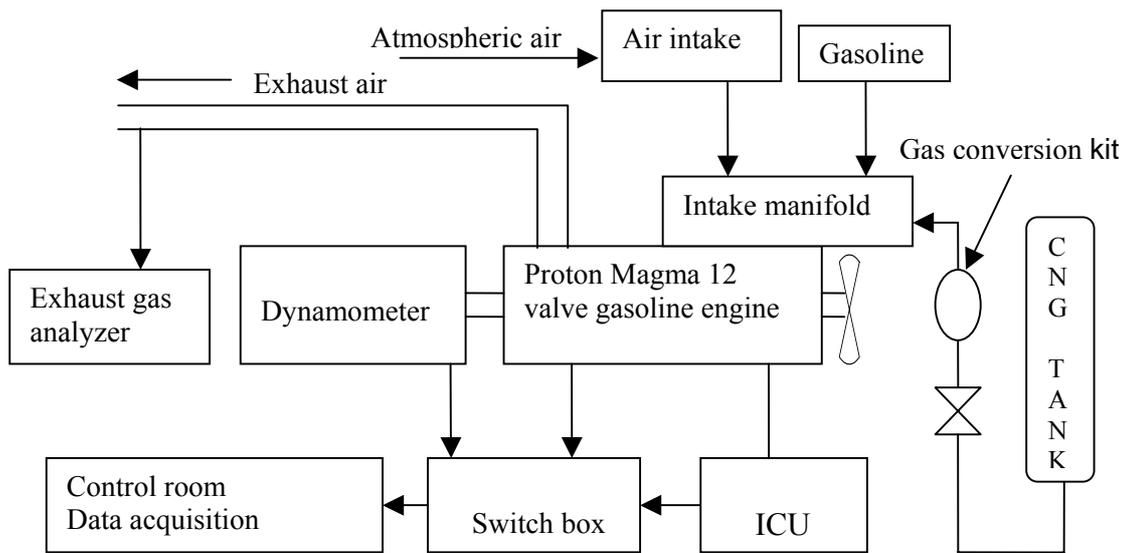


Fig. 1: Layout of the experimental setup

| | |
|--|--|
| Characteristic | Proton Magma12-Valve |
| Displacement | $1.468 \times 10^{-3} m^3$ |
| Compression ratio | 9.2: 1 |
| Bore | 0.075.5 m |
| Stroke | 0.082 m |
| Max output | 64/6000 (kW/rpm) |
| Max torque | 122/3500 (N-m/rpm) |
| Carburetor | Down-draft 2-barrel |
| Specification of NGV carburetion system tested | Proton 12 – Valve 1.5S |
| Stage | 1 st Stage – 3.4 Bar 2 nd Stage – 0.8 Bar 3 rd Stage (–ve) pressure |
| Regulator | Tartarini model RP/76-M |
| Mixer | Remote extractor |
| Control | Time advance processor Model 529 |

Table 2: Specifications of test engine

| Component | Symbol | Volumetric % |
|----------------|--------------------------------|--------------|
| Methane | CH ₄ | 94.42 |
| Ethane | C ₂ H ₆ | 2.29 |
| Propane | C ₃ H ₈ | 0.03 |
| Butane | C ₄ H ₁₀ | 0.25 |
| Carbon dioxide | CO ₂ | 0.57 |
| Nitrogen | N ₂ | 0.44 |
| Others | (H ₂ O+) | 2.0 |

Table 3: Typical composition (% vol.) of CNG (source: PRSS, 2002)

2.2 Retrofitting

The ignition and burning characteristics of CNG are considerably different from that of gasoline. CNG has a longer ignition delay time than most hydrocarbons, and has higher minimum ignition energy than gasoline. Thus when CNG is used in a gasoline fuelled engine, the combustion duration becomes relatively long and more advance spark timing is required. So, retrofitting is needed on conventional gasoline fuelled engine for running with CNG. An after-market CNG conversion kit of model Tartarini RP/76-M, manufactured in Italy, was installed on the test bed engine by the local agent. The CNG was stored under a maximum pressure of 200 bars. Before entering into the carburetor CNG passes through the three-stage conversion kit. The conversion kit supplied CNG to the engine carburetor at approximately atmospheric pressure (~0.8 bar) so that the carburetor can effectively use it. A shut off solenoid valve is included to prevent gas flow when the engine is not operating or operating on gasoline. The ignition timing for gasoline and CNG fuels were selected by an external auto ignition control unit ICU (ignition control unit).

2.3 Comparison of test fuel properties

The differences in basic fuel properties between gasoline and CNG are defining issues for the barriers to commercialization for CNG vehicles. These fuel property differences are also pertinent to CNG engine and vehicle efficiency issues. However, as the composition of CNG varies from well to well, therefore, its heating value also varies. Knowledge of exact composition and heating value of CNG is essential before using it as an automotive fuel. The lower heating value of CNG was calculated from gravimetric analysis as proposed by Evans and Blaszczyk [11]. The stoichiometric air-fuel ratio of CNG was also calculated from its compositions. In Table 1 some important differences between gasoline and CNG are summarized.

3. Results and discussions

All the tests and data analysis for gasoline and CNG were performed on a Proton Magma 12 valve retrofitted bi-fuel engine in the Thermal Engine Laboratory, Department of Mechanical Engineering, University of Malaya. The performance of an engine running on CNG with respect to power output, fuel consumption and

efficiency depends very much on the composition of CNG, relative air-fuel ratio, sophistication of the engine, and whether the engine is dedicated for natural gas or not. The test results obtained were used to serve as a basis for comparison of the engine performance for the two different fuels.

3.1 Brake mean effective pressure (BMEP)

Fig. 2 illustrates the BMEP with engine speed at WOT. The reduction in BMEP with CNG operation is seen throughout the speed range. Part of this BMEP loss is due to longer ignition delay and lower flame speed of CNG. As combustion starts earlier with respect to TDC, there is a greater amount of negative work done on the piston before TDC compared to gasoline. The remainder of the BMEP loss is due to the displacement of air by CNG. On average there is around 1.25 bars or 16% BMEP dropped with CNG operation compared to gasoline.

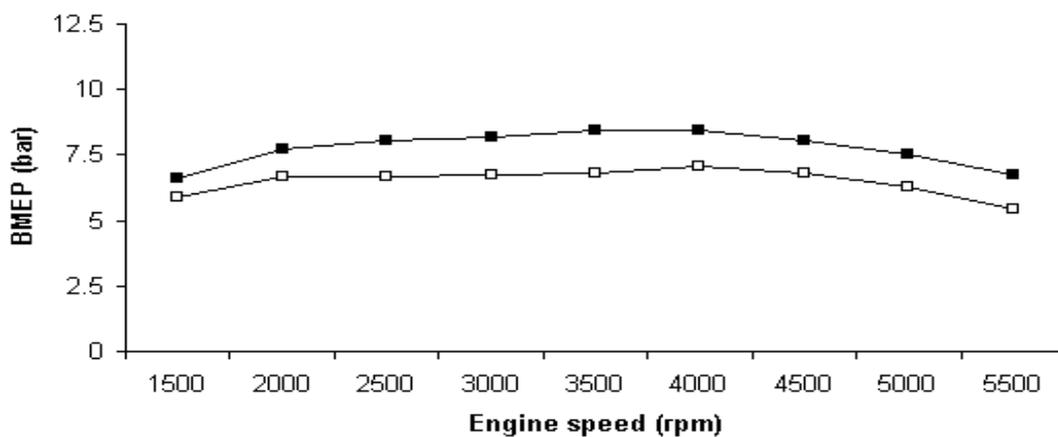


Fig. 2: BMEP vs. engine speed at WOT. ■, gasoline; □, CNG.

3.2 Brake specific fuel consumption (BSFC)

The BSFC curve of Fig. 3 is for full throttle, variable speed operation. At any speed, it represents the BSFC which will result when the engine is carrying its maximum load at that speed. It is observed (Fig. 3) that BSFC drops as the speed is increased in the low speed range, nearly levels off at medium speeds, and increases in the high speed range. This is because, at low speeds, the heat loss to the combustion chamber walls is proportionately greater, resulting in higher fuel consumption for the power produced. At high speeds, the friction power is increasing at a rapid rate, resulting in a slower increase in brake power than in fuel consumption, with a consequent increase in BSFC. It is observed that BSFC for CNG was always less than gasoline throughout the speed range. This can be attributed to the fact that the heating value of CNG is around 9% more and lean burning of CNG compared to gasoline. The lowest BSFC occurred at 3500 rpm for both the fuels and it is 0.323 kg/kWh for gasoline and 0.264 kg/kWh for CNG and on average BSFC of CNG are near about 18% lower than that of gasoline. However the average BSEC of the engine at WOT condition for gasoline and CNG were calculated and found to be 15.26 MJ/kWh and 13.61 MJ/kWh

respectively. On average the engine consumed around 1.65 MJ less energy per kWh power production with CNG compared to gasoline.

Fig. 4-6 present the variation of BSFC with constant speed of 2500, 3000 and 3500 rpm respectively with the variable engine load of 25-65% of engine full load. The reason for the rapid increase in BSFC with the reduction of load is that the friction power remains essentially constant, while the indicated power is being reduced. As a result, the brake power drops more rapidly than fuel consumption, and thereby the BSFC rises. The lowest BSFC is attained at 65% of engine full load for both gasoline and CNG and it were 0.331, 0.336 and 0.348 kg/kWh for gasoline and 0.282, 0.285 and 0.285 kg/kWh for CNG. It is found that BSFC for both the fuels increased slightly with increasing speed. As the load is fixed, the rate of increase of friction power with speed is more than that of indicated power in this condition which results less brake power and hence more BSFC. The difference of BSFC for gasoline and CNG at three different speeds varies a little bit and shows an average difference of 17.15%.

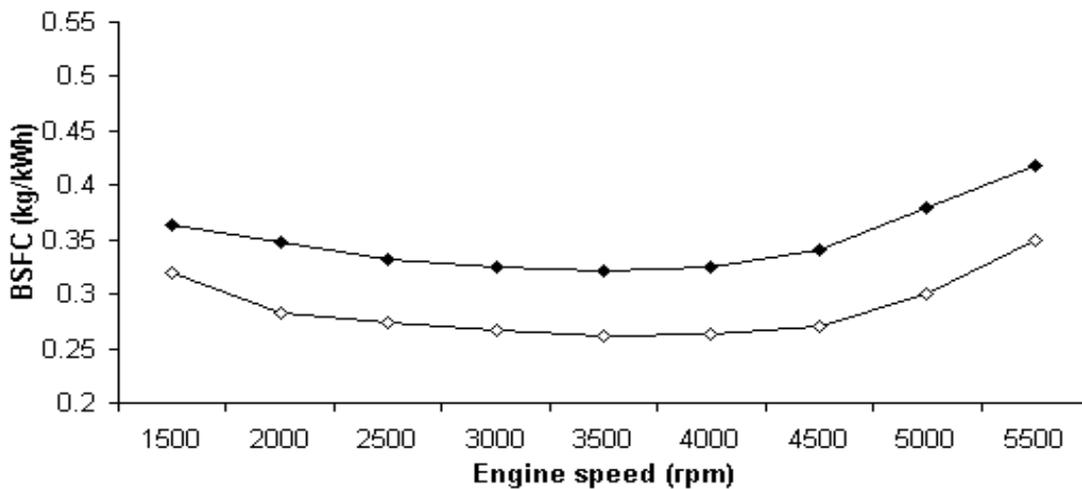


Fig. 3: BSFC vs. engine speed at WOT. ♦, Gasoline; ◻, CNG.

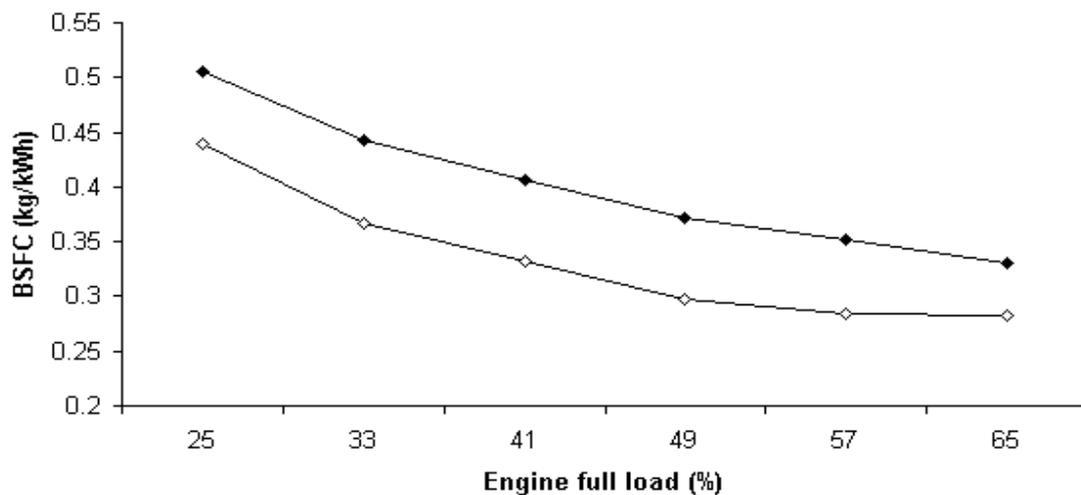


Fig. 4: BSFC vs. engine load at 2500 rpm. ♦, Gasoline; ◻, CNG.

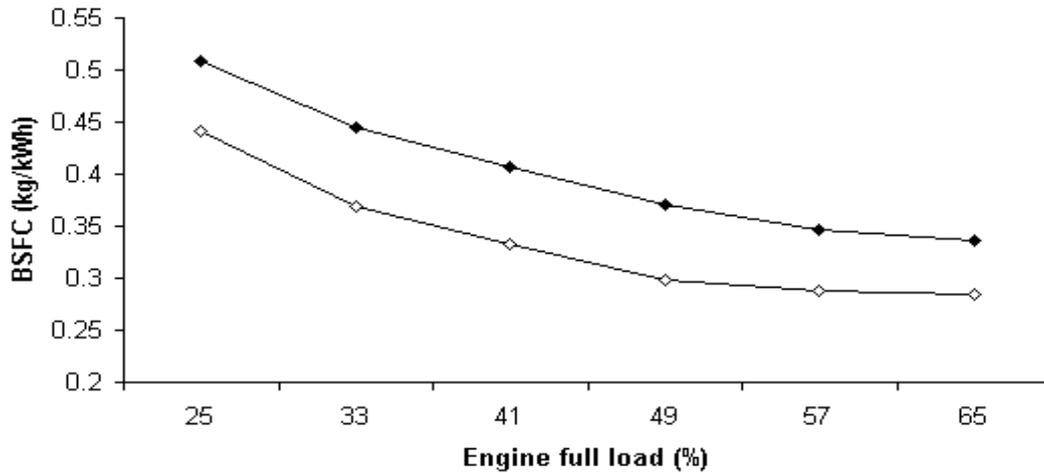


Fig. 5: BSFC vs. engine load at 3000 rpm. ♦, Gasoline; ◇, CNG.

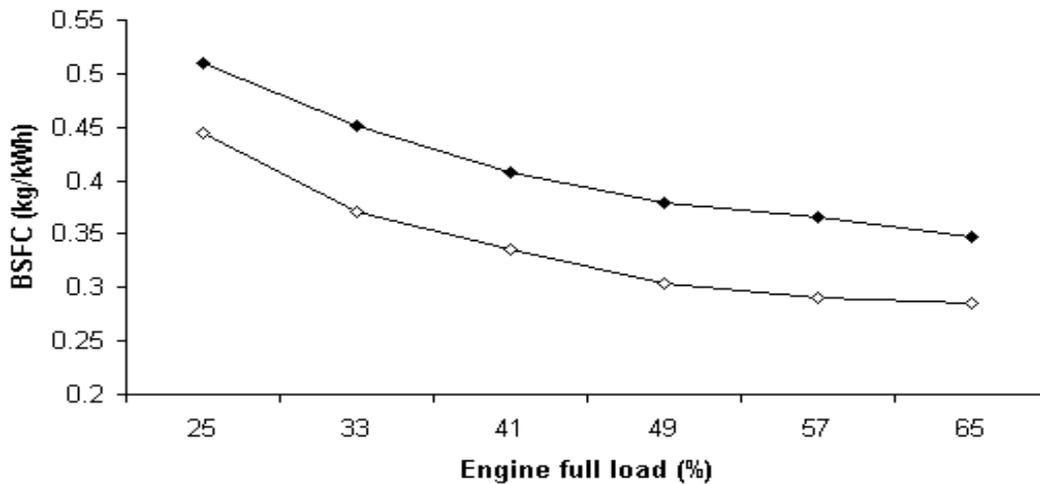


Fig. 6: BSFC vs. engine load at 3500 rpm. ♦, Gasoline; ◇, CNG.

3.3 Fuel Conversion Efficiency (FCE)

Internal combustion engines operate by burning fuel in, rather than by adding heat to, the working medium, which is never returned to its original state. So, its efficiency is defined based on a characteristic quantity of heat relating to the fuel. The method of determining this value, which is called the heat of combustion of the fuel, is somewhat arbitrary, but it is accepted in work with heat engine [15]. The measured efficiency is called fuel conversion efficiency and is defined as the ratio of energy in the power to the required input fuel energy to achieve that power in appropriate units. This empirically defined engine efficiency has previously been called thermal efficiency or enthalpy efficiency. The term fuel conversion efficiency is preferred because it describes this quantity more precisely, and distinguishes it clearly from other definitions of engine efficiency [14].

The difference in FCE of a retrofitted engine for CNG and gasoline depends mainly on the compositions of CNG (heating value) and operating condition (lean/rich and same/different λ value for gasoline and CNG). Fig. 7 illustrates the FCE at WOT condition with a variable speed range of 1500-5500 rpm. It is observed that CNG showed higher efficiency through out the speed range and in average CNG showed around 2.95% higher efficiency than gasoline.

Fig. 8-10 revealed the FCE comparison at constant engine speed of 2500, 3000 and 3500 rpm respectively with variable load range of 25-65% of engine full load. It is seen that FCE for CNG is always higher than that of gasoline throughout the load range and on average it is around 2.41% more. One added point to be mentioned here is that for a given power output (in this case 25-65% of 122 Nm) CNG requires a greater throttle opening than does gasoline. The larger throttle opening then results in reduced pumping losses and a higher overall FCE for CNG. This has important implications for CNG automotive conversions, since nearly all of the engine operation will be at substantially less than full-load operation. Over a complete driving cycle, therefore, the efficiency of operation with CNG can be expected to be higher than with gasoline.

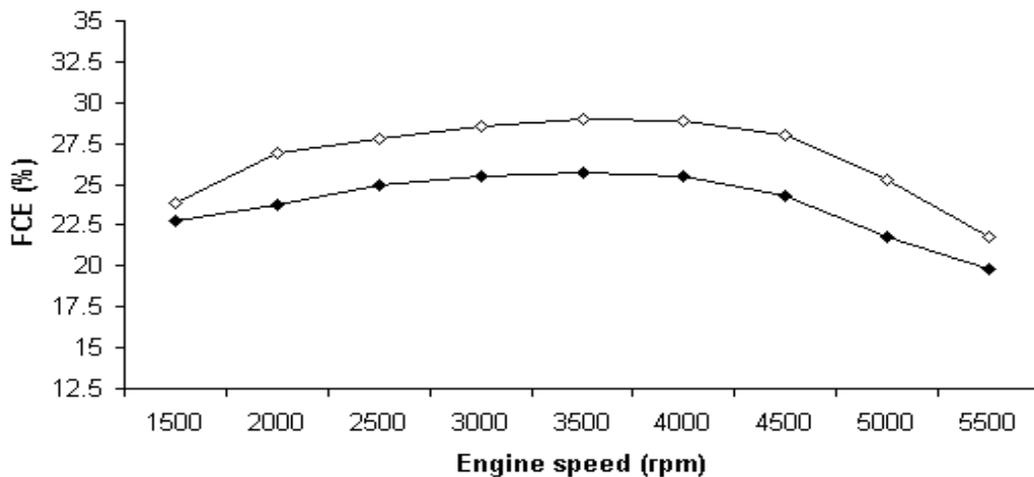


Fig. 7: FCE vs. engine speed at WOT. ♦, Gasoline; ◊, CNG.

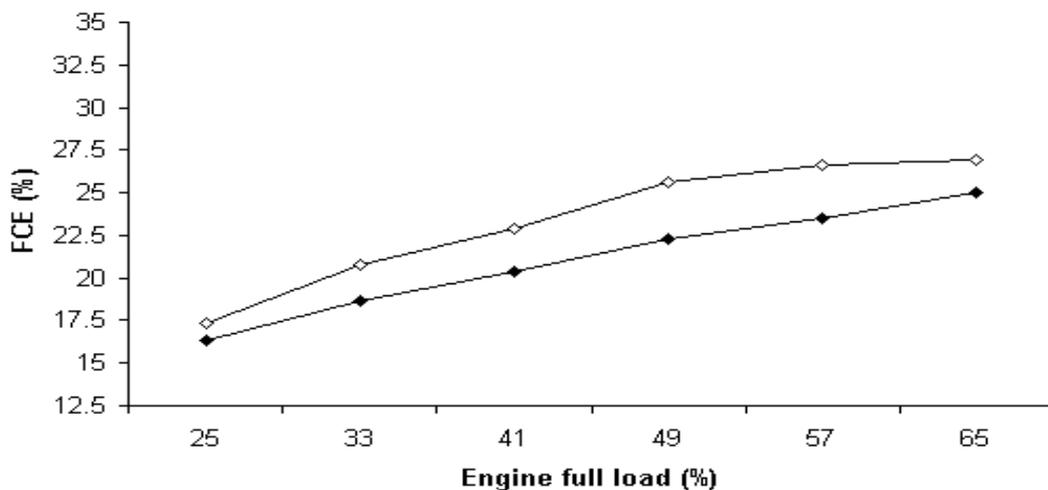


Fig. 8: FCE vs. engine speed at 2500 rpm. ♦, Gasoline; ◊, CNG.

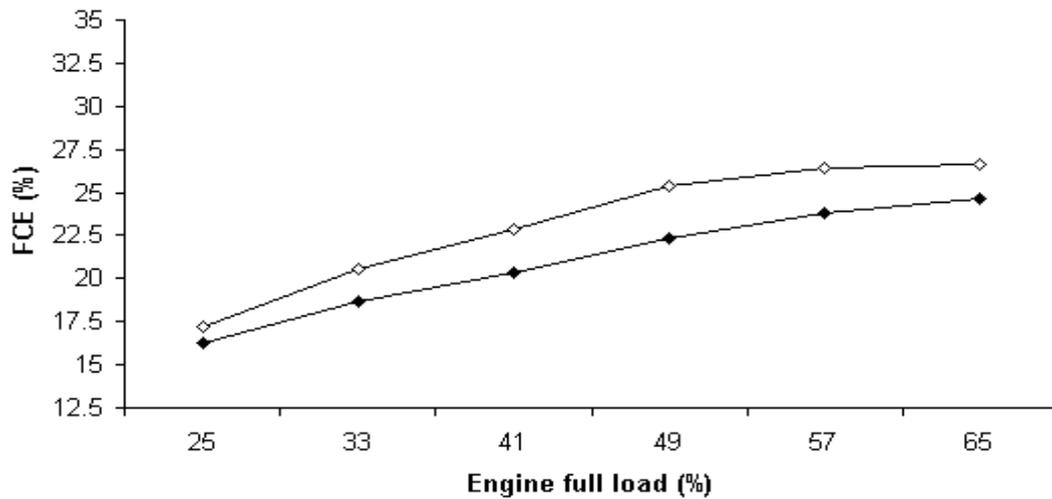


Fig. 9: FCE vs. engine speed at 3000 rpm. ♦, Gasoline; ◇, CNG.

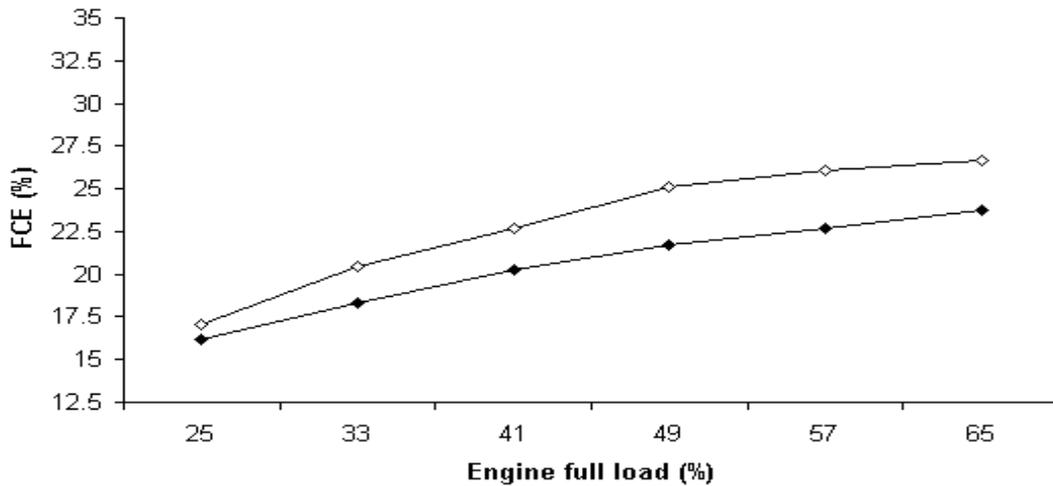


Fig. 10: FCE vs. engine speed at 3500 rpm. ♦, Gasoline; ◇, CNG.

4. Conclusions

The present study has demonstrated that retrofitted CNG fuelled engines have a potential for higher FCE and significant reduction of specific fuel consumption. The following concluding remarks can be drawn from the present study-

- Retrofitted CNG engine produces around 16% less BMEP and consumes 17%-18% less BSFC, or consumes an average of 1.65 MJ less energy per kWh at WOT condition with CNG compared to gasoline.
- The engine shows an average of 2.95% and 2.41% higher FCE with CNG at full and part load conditions respectively.
- For reducing CNG vehicles efficiency penalty due to heavier CNG storage tank and for providing easy refueling it is required to develop lighter CNG storage tank

(400+ km) and extensive networks of CNG supply stations at convenient locations through out the country.

- Retrofitted CNG fuelled engines can be used for the moment for economic, environment and energy security reasons.

Acknowledgements

The authors would like to thank Mr. Hassan Md Saad (Lab Assistance) for his helpful technical assistance during the test. The authors would also like to acknowledge the Ministry of Science, Technology and Innovation for providing financial support through Vote- IRPA No: 33-02-03-3011 and The University of Malaya, Kuala Lumpur, Malaysia, which made this study possible.

References

- [1] Das L.M, Gulati R. & Gupta P.K., *Int J of Hydrogen Energy*, **25**(2000) 783-793.
- [2] International Energy Outlook. Energy information administration, (Washington, DC: Department of Energy, 2005), EIA-0484 38-39.
- [3] Nylund N.O., Laurikko J. & Ikonen M., “ Pathways for Natural Gas into Advanced Vehicles”, (International Association for Natural Gas Vehicle, IANGV Edited Draft Report 2002), Version 30.8.2002.
- [4] Aslam M.U., Masjuki H.H., Maleque M.A., Kalam M.A., Mahlia T.M.I., Zainon Z., Amalina M.A., Abdesselam H., “Introduction of Natural Gas Fueled Automotive in Malaysia”, *Proc. TECHPOS'03*, (UM, Malaysia 2003) 156-161.
- [5] Beck N.J., Barkhimer R.L., Johnson W.P., Wong H.C. and Gebert K., *SAE Technical paper Series* **972665**.
- [6] Aslam M.U., Masjuki H.H., Maleque M.A., Kalam M.A., “Prospect of CNG as an Automotive Fuel Instead of Gasoline”, *Proc. 7th Asia-Pacific International Symposium on Combustion and Energy Utilization*, (Hong Kong 2004), Paper No.C1-170.
- [7] Bach C., Lammler C., Bill R., Soltic P., Dyntar D., Janner P., Boulouchos K., Onder C., Landefeld T., Kercher L., Seel O., Baronick J.D., *SAE Technical Paper Series* **2004-01-0645**.
- [8] Kalam M.A, Masjuki H.H, Mahlia T.M.I.&Shioji M., “Exhaust Emission and Performance Evaluation of a Modified Spark Ignited Natural Gas Engine”, *Proc. Natural Resources & Energy Environment*, JSPS-VCC Program, (Japan 2004) 164-174.
- [9] Thomas J.F.& Staunton R.H., *SAE Technical Paper Series* **1999-01-1511**.
- [10] Jones A.L & Evans R.L., *J Engineering for Gas Turbine and Power* **107**(1985) 908.
- [11] Evans R.L & Blaszczyk, “A comparative study of the performance and exhaust emissions of a spark ignition engine fuelled by natural gas and gasoline”, *Proc. Institute of Mechanical Engineers* **211D**(1997) 39-47.
- [12] Hamid H.A, Ahmad A.S., “Development of Monofuelled Natural Gas Vehicles: A Malaysian Experience”, *Special Project of Petronas Research Co. Ltd.*, (Malaysia 2002) 10.
- [13] Heywood J.B., *Internal Combustion Engine Fundamentals*, McGraw-Hill, Singapore (1988) 915.
- [14] Taylor C.F., *The Internal-Combustion Engine in Theory and Practice*, Halliday Lithograph Corporation, . USA, (1985) 1-9.