A Comparative Evaluation of the Performance and Emissions of a Retrofitted Spark Ignition Car Engine

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Abstract

The potentials of using compressed natural gas (CNG) as the main fuel instead of gasoline in a 1.5 litre, 4-cylinder, retrofitted spark ignition car engine at different loading conditions have been investigated experimentally. The engine was converted to computer integrated bi-fueling system from a gasoline engine, and operated separately either with gasoline or CNG using an electronically controlled solenoid actuated valve system. A personal computer (PC) based data acquisition and control system was used for controlling all the operation. A detailed comparative analysis of the engine performance and exhaust emissions using gasoline and CNG has been made. It is observed that the CNG shows low power, low brake specific fuel consumptions, higher efficiency and lower emissions of CO, CO2, HC but more NOx compared to gasoline.

Nomenclature

CNG	compressed natural gas
PC	personal computer
ICE	internal combustion engine
NG	natural gas
Tscf	trillion standard cubic feet
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
WOT	wide open throttle
NGV	natural gas vehicle
λ	relative air-fuel ratio
AFR	air-fuel ratio
CNG/DI	direct injection compressed natural gas engine
ICU	ignition control unit
BTDC	before top dead centre
FCE	fuel conversion efficiency
EGR	exhaust gas recirculation
SI	spark ignition
TWC	three way catalytic

Introduction

A shortage of crude oil is expected at the early decades of the 21st century. In addition to this, the deteriorating quality of the air is becoming another great public concern. So tighter regulations on the emissions from engines are anticipated. In view of the versatility of internal combustion engine (ICE), 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 is much more than that of the battery powered or fuel cell operated vehicles [1]. These factors have led scientists and researchers to develop environment-friendly technologies, and to introduce more clean fuels like natural gas (NG) to power ICE for ensuring the safe survival of the existing engine technology. The world's total reserve of NG as of January 1, 2004 was 6,076 trillion standard cubic feet (Tscf) and on the basis of current consumption rates, it is adequate for almost 65 years [2]. There are many merits of compressed natural gas (CNG) as an automotive fuel over conventional fuels [3-4]. Due to some of the favourable physio-chemical properties [5] of CNG, the gasoline run spark ignition (SI) engines can be retrofitted to CNG operation quite easily with the addition of a second fueling system.

Manufacturers are also converting gasoline engine into bi-fuel engine in order to satisfy customer demand as presently happening in Malaysia [6].But, retrofitted natural gas vehicle (NGV) engine produces about 10-15 % less power than the same engine fuelled by gasoline [7-10]. Another main drawback is that the required fuel storage tank is heavier so that the vehicle range is compromised for avoiding very large storage tank. However, CNG has the potential for increasing engine efficiency if the engine is designed for dedicated CNG operation. Numerous reliable researches on CNG fuelled engines have been done, and are still going on worldwide. Jones and Evans [11] showed a total power loss of approximately 15% and, an efficiency drop of 5% when changing from gasoline to CNG. Loss of 10% power was attributed to reduction in the inhaled energy and the remaining 5% to the lower burning velocity of CNG compared with gasoline. Evans and Blaszczyk [12] have done another comparative study of performance and exhaust emissions of a spark ignited engine fuelled with CNG and gasoline. They found both break mean effective pressure (BMEP) and break specific fuel consumption (BSFC) 12% lower with CNG at wide open throttle (WOT) condition with same λ (relative air fuel ratio) value than gasoline. Efficiency for both the fuels are about the same up to $\lambda = 1.3$, and with increasing λ, CNG shows higher efficiency than gasoline. Hamid and Ahmad [13] presented a comparison of the NGV and gasoline based engine performance where they have found the volumetric efficiency of the NGV engine is reduced by about 15%, and the 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 rotation per minute (rpm), for the same air fuel ration (AFR).

A recent paper by Kalam et al. [14-15] presented 15% power loss, 15-18% less BSFC and 10% higher efficiency using CNG in comparison with gasoline. However, Kalam et al. [14-15] performed tests at lean operating conditions of the engine and did not conduct part load performance tests. In general, today's SI gasoline engines and automotive SI natural gas (NG) engines are controlled to operate near a stoichiometric air-fuel ratio to allow the three way catalytic (TWC) system to be highly effective [10]. Therefore, an attempt has been made in the present study to practically evaluate the comparative performance, and emissions characteristics of a retrofitted spark ignition car engine fuelled with gasoline and CNG near the stoichiometric condition. Though the same 4-cylinder Proton Magma engine studied by Kalam et al. [14-15] was also used in this study, the CNG composition (mainly methane, ethane and carbon dioxide) was different in the present study. Moreover, part load performance tests were also included in the present study.

Experimental Setup and Test Procedure

The layout of the experimental setup is shown in Fig. 1. The test engine was 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 1. An AG 150 (Froude Consine) eddy-current dynamometer was used for testing the engine. The load imposed on the engine by the dynamometer is governed by the amount of exciting current passing through the field coil. The method by which the coil current is controlled gives the dynamometer varying types of power/speed characteristics, such as constant torque and constant speed. All the electronic equipment, along with its manipulative controls and indicators, etc., was mounted on "CP Cadet10" control unit. The fuel system was so designed that the engine can run on gasoline and natural gas.

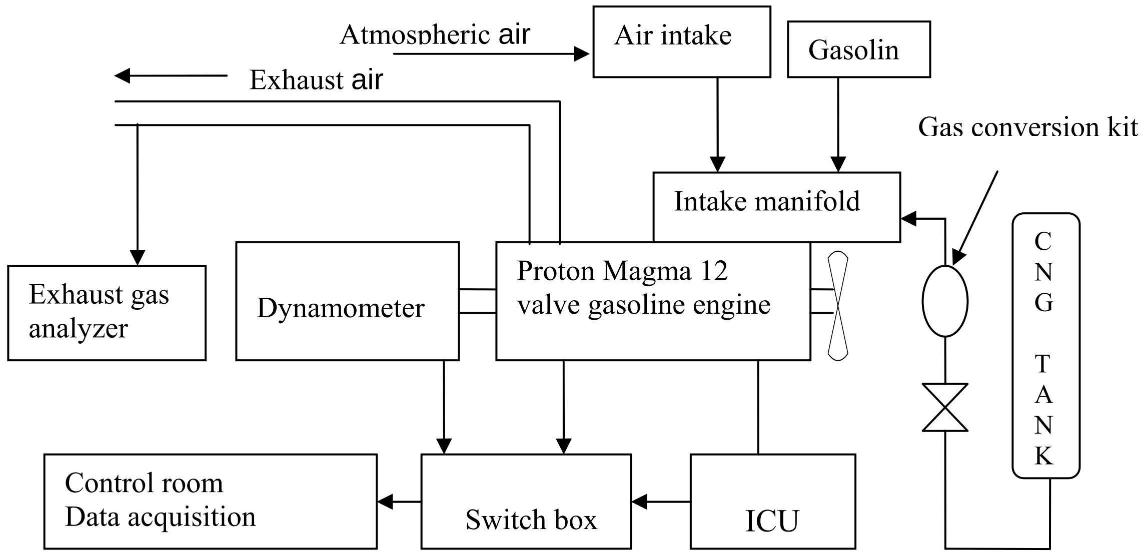

Fig. 1 Layout of the experimental setup

Table 1 Specifications of test engine

Characteristic	Proton Magma12-Valve
Displacement	1,468 cc
Compression ratio	9.2: 1
Bore	75.5 mm
Stroke	82 mm
Max output (DIN) PS/rpm net (Kw/rpm)	87/6000 64/6000 (KW/rpm)
Max torque (DIN) Kg-m/rpm net (Nm/rpm)	12.5/3500(122/3500)
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

The engine was operated in two different modes such as:

- Steady state condition with WOT and variable speed range from 1500 rpm to 5500 rpm, where the engine satisfied an average λ value of 1.01 and 1.06 for gasoline and CNG respectively.
- And at the constant speed of 2500, 3000, 3500 rpm with variable load of 25% to 65% of engine full load (122 N-m), where the average value of λ was maintained at 0.83 for gasoline and 0.91 for CNG.

The gasoline consumption was measured with fuel flow meter (load cell arrangement) and natural gas was measured with Kobold gas flow meter (Model WFM 2705). Exhaust emissions were measured by BOSCH and BACHARACH gas analyzer. All the flow meters were incorporated with engine control system through interface cards. Gasoline and Malaysian CNG (composition shown in Table 2) 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 5-6 minutes with updating data in every 30 seconds. Every test was done at least three times for avoiding errors.

Table 2 Typical composition (% vol.) of Malaysian CNG [source PRSS]

Component	Leanest	Richest
Methane	94.42	89.04
Ethane	2.29	5.85
Propane	0.03	1.28
Isobutane	0.23	0.14
Normal-butane	0.02	0.10
Isopentane	n/a	n/a
Normal-pentane	n/a	n/a
n-Hexane	n/a	n/a
Carbon dioxide	0.57	0.47
Nitrogen	0.44	3.09
Condensate	0.00	0.02
Others	2.00	0.01

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 higher minimum ignition energy than gasoline. Thus when CNG is used in a gasoline fuelled engine, the combustion duration becomes relatively longer, and it requires more advance spark timing. So, retrofitting is necessary for the conventional gasoline fuelled engine to run with CNG. The CNG is stored under a maximum pressure of 200 bars. Before entering into carburetor CNG passed through a three-stage conversion kit of model Tartarini RP/76-M. 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 was included to prevent gas flow when the engine was not operating or operating on gasoline. A down draft 2-barrel carburetor was used for gas-air mixture. The ignition timing for gasoline and CNG fuels was selected by an external auto ICU at 10 and approximately 18 degrees crank angle before top dead centre (BTDC) respectively for ensuring a similar cylinder peak pressure after top dead centre from both the fuels.

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. In Table 3 some important differences between gasoline and CNG are summarized.

Table 3 Combustion related properties of gasoline and CNG [5]

Properties	Gasoline	CNG
Motor octane number	80-90	120
Molar mass (kg/mol)	110	16.04
Carbon weight fraction [mass-%]	87	75
$(A/F)_s$	14.6	14.5
Stoichiometry mixture density (Kg/m^3)	1.38	1.24
Lower heating value (MJ/Kg)	44	50
Lower heating value of stoic. mixture (MJ/kg)	2.83	2.72
Maximum burning velocity (cm/sec)	30	38
Flammability limits (% vol in air)	1.3 ~7.1	5 ~15
Spontaneous ignition temperature (^{O}C)	480~550	645

$(A/F)_s$ = Stoichiometric Air Fuel Ratio

Results and Discussions

All the tests and data analysis were performed for gasoline and CNG running Proton Magma-12 valve presently vast used retrofitted bi-fuel engine in the Thermal Engine Laboratory, Department of Mechanical Engineering, University of Malaya. The test results were used to serve as a basis for the comparison of the engine performance and emissions of the two different fuels and it will be also useful for the Malaysian new CNG/DI engine in future.

Engine performance

The performance of an engine running on natural gas mainly depends on the composition of NG, λ value, sophistication of the engine and whether the engine is dedicated for natural gas or not. In the present study the performance tests were done in two different conditions as mentioned earlier.

Brake power

Referring to Fig. 2, it can be seen that the brake power developed by the engine running with CNG was always lower than gasoline fuel throughout the speed range. CNG produced nearly an average of 16% less brake power compared to gasoline fuel. This happened due to the lower volumetric benefits and less energy density of CNG in comparison with gasoline per power stroke of the engine. In case of liquid fuels, it is considered that the fuel does not reduce the amount of air captured in the cylinder. Hence, a gasoline-fuel-designed engine converted to CNG will be capable of significantly lessening peak power. The curve's trend is nearly same for both the fuels due to the fact that every operating condition was the same; while the only change was fuel itself. It is seen that the maximum brake power occurs at around 5000 rpm (Fig. 2) for both fuels and it were 46.6KW and 38.5 KW for gasoline and CNG respectively.

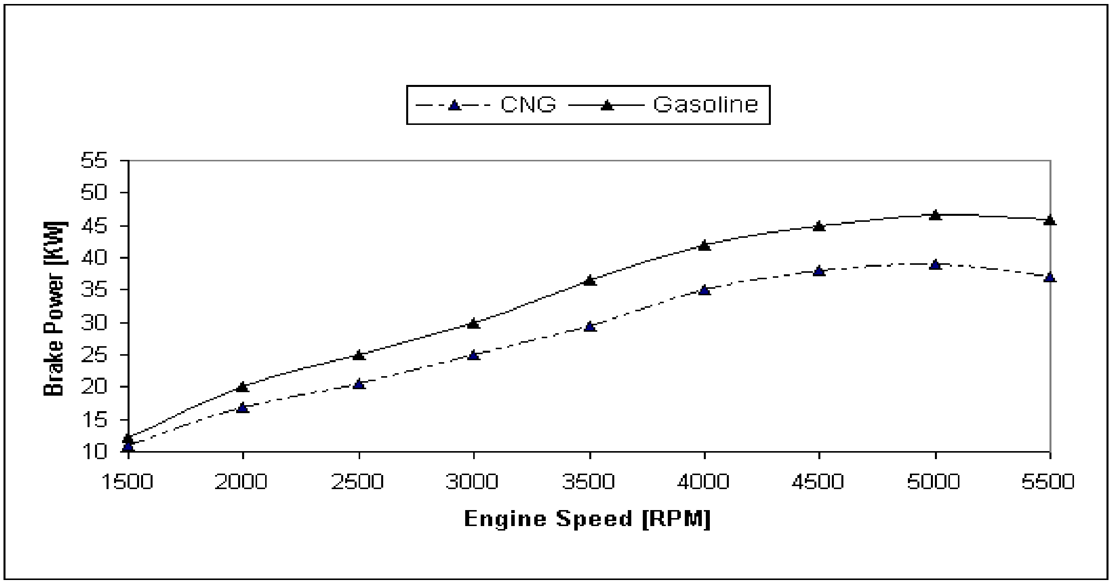

Fig. 2 Brake power vs. engine speed at WOT

Brake specific fuel consumption

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.

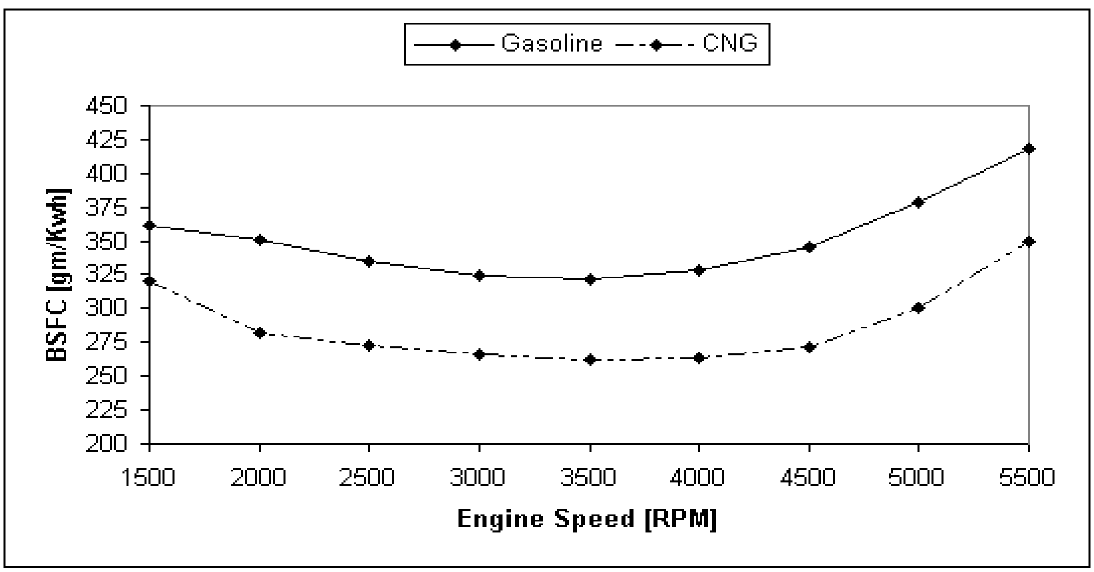

Fig. 3 BSFC vs. engine speed at WOT

It is seen (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 of this, 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 increases at a rapid rate, resulting in a slower increase in brake power than in fuel consumption with a consequent increase in BSFC. It is seen 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 12% more, and the lean burning of CNG compared to gasoline. The lowest BSFC occurs at 3500 rpm for both the fuels, and it was 323 gm/kWh and 264 gm/kWh for gasoline and CNG respectively, and on average, BSFC of CNG was near about 18% lower than that of gasoline.

Figs. 4-6 show the variation of BSFC with constant speed of 2500, 3000 and 3500 rpm respectively with the variable engine load of 25% to 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. So, the brake power drops more rapidly than fuel consumption, and thereby the BSFC rises. The lowest BSFC was attained at 65% of engine full load for both gasoline and CNG, and there were 331, 336 and 348 gm/kWh for gasoline and 282, 285 and 285 gm/kWh for CNG. It is found that BSFC for both the fuels was increased slightly with increasing speed. As the load is fixed, the rate of increase of friction power with speed was more than that of indicated power in this condition, which results in more BSFC. The difference of BSFC for gasoline and CNG at three different speeds varied a little bit and shows an average difference of 17.3%.

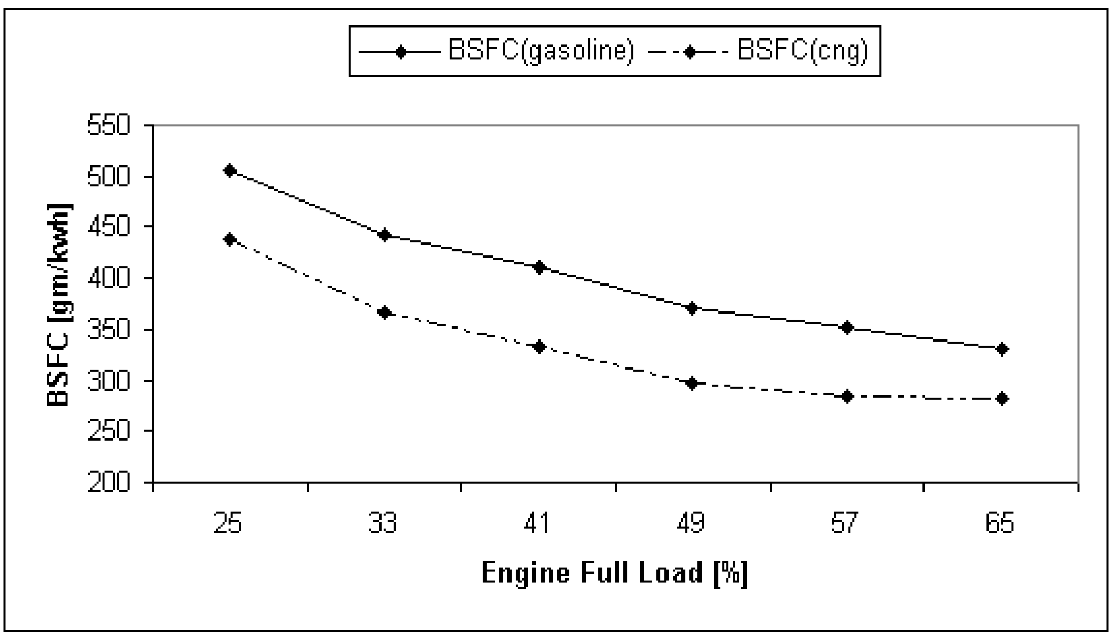

Fig. 4 BSFC vs. engine load at 2500 RPM

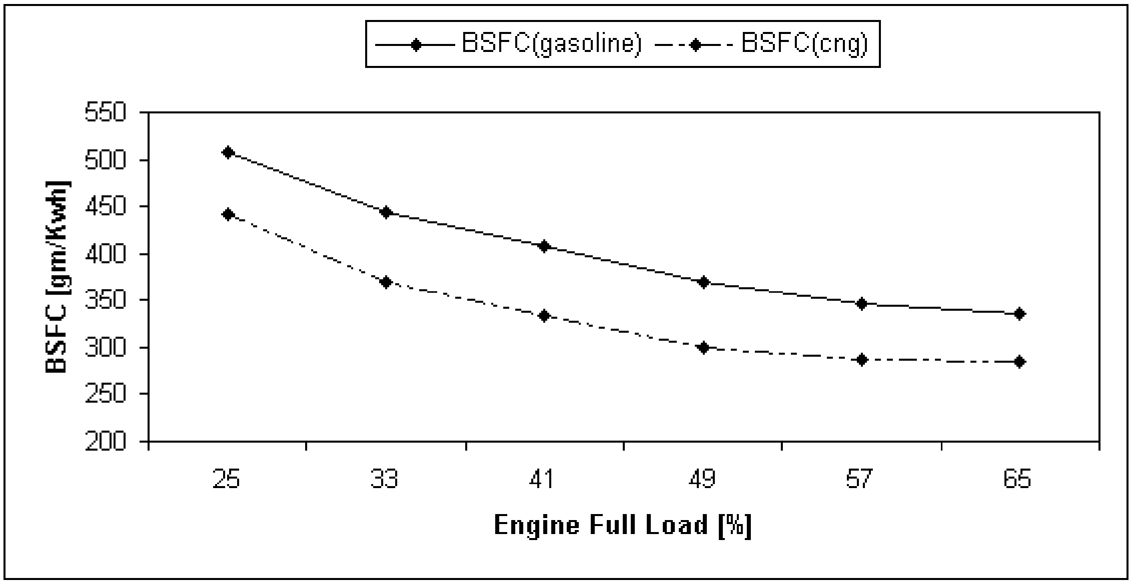

Fig. 5 SFC vs. engine load at 3000 RPM

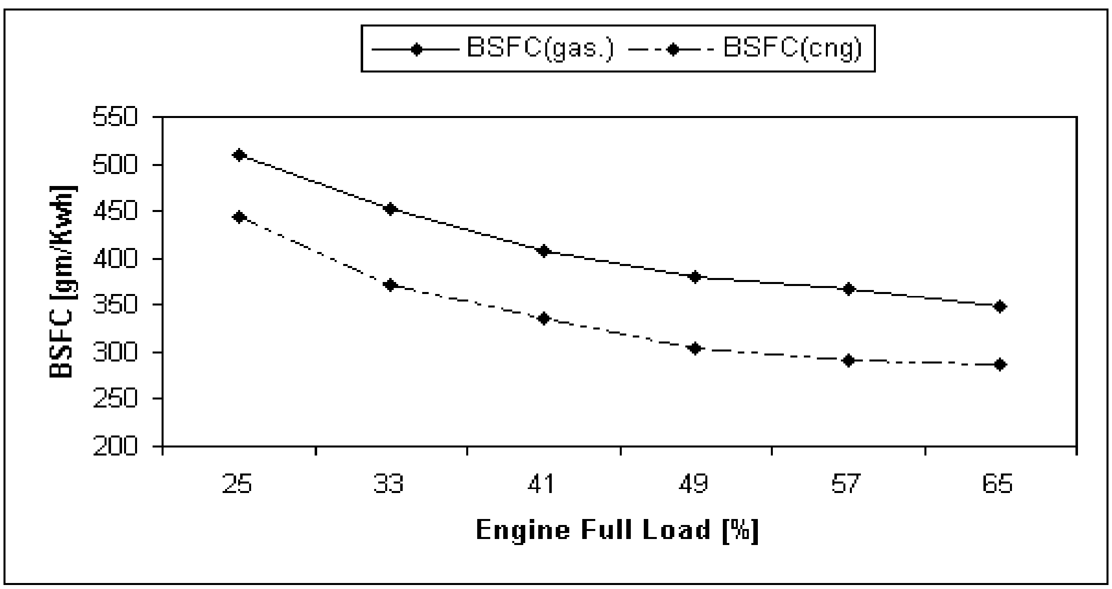

Fig. 6 BSFC vs. engine load at 3500 RPM

Fuel conversion efficiency

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 [16]. 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. The difference in fuel conversion efficiency (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 to 5500 rpm. It is seen that CNG showed higher efficiency throughout the speed range, and on the average CNG showed around 2% higher efficiency than gasoline. This is due to the comparative lean operation of the engine for CNG (λ=1.06) than gasoline (λ=1.01). Jones and Evans [11] did not mention λ values. Evans and Blaszczyk [12] maintained same λ for both the fuels and hence FCE were same for both the fuels up to certain λ value. Kalam et al. [14] mentioned an average λ value of 1.391 and 1.374 for CNG and gasoline, and found the efficiency difference of 10%.

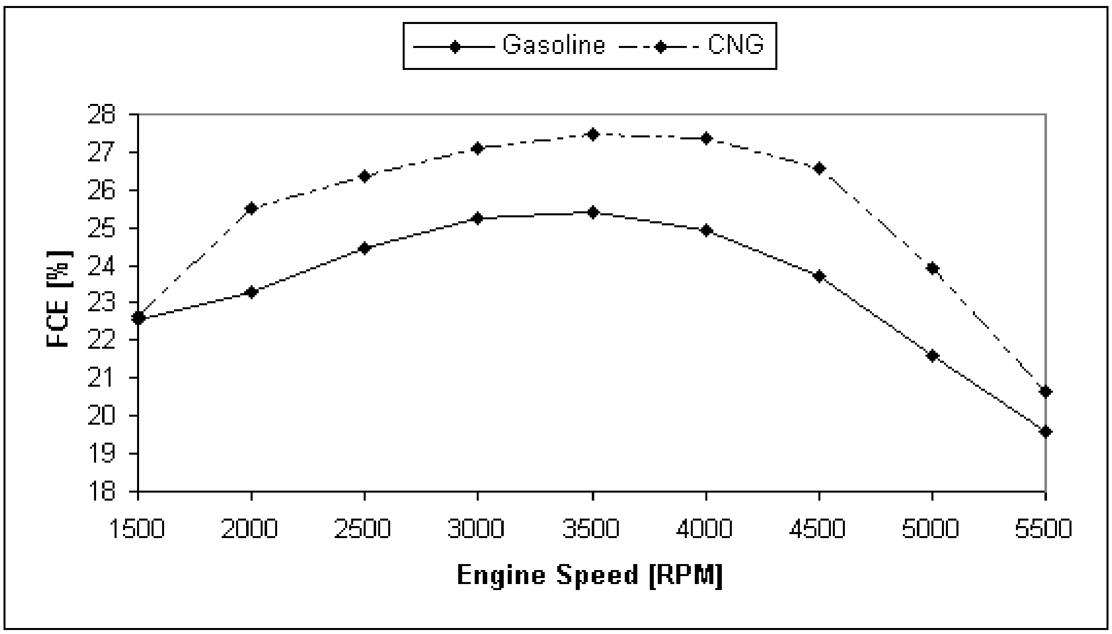

Fig. 7 FCE vs. engine speed at WOT

Figs. 8-10 reveal the FCE comparison at constant engine speeds of 2500, 3000 and 3500 rpm respectively with variable load range of 25% to 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 1.3 % more. Here, the average λ value was 0.91 and 0.83 for CNG and gasoline respectively.

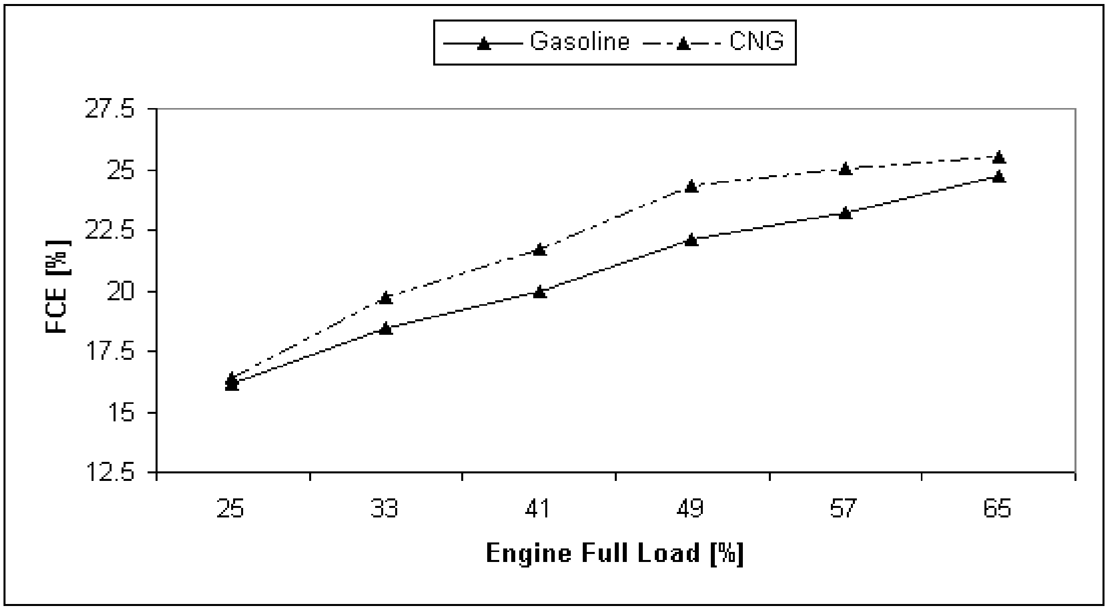

Fig. 8 FCE vs. load at 2500 RPM

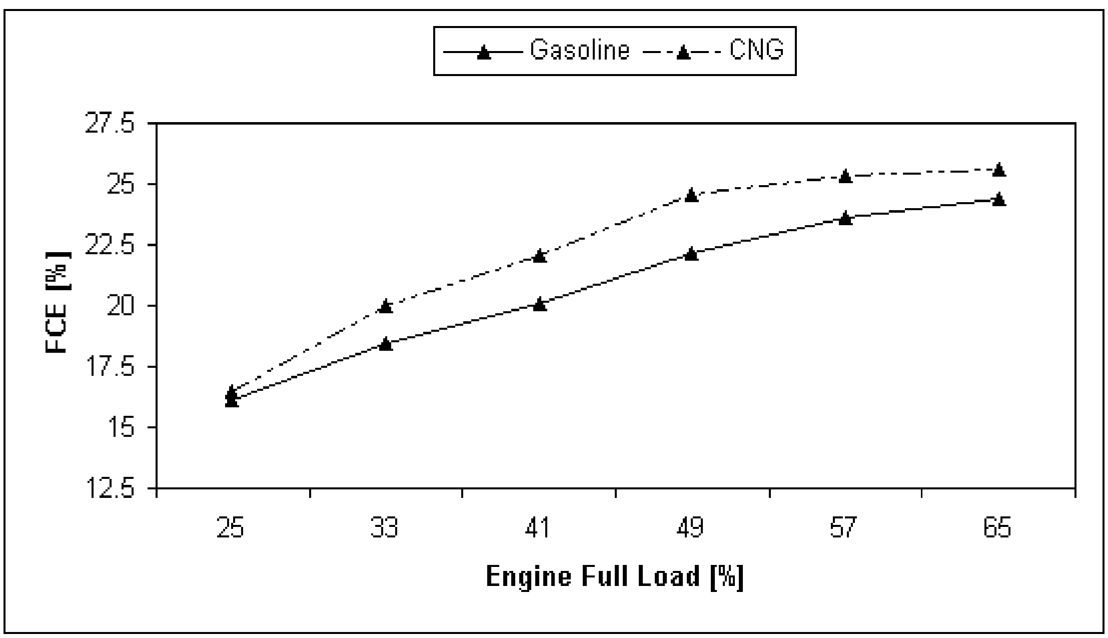

Fig. 9 Efficiency vs. load at 3000 RPM

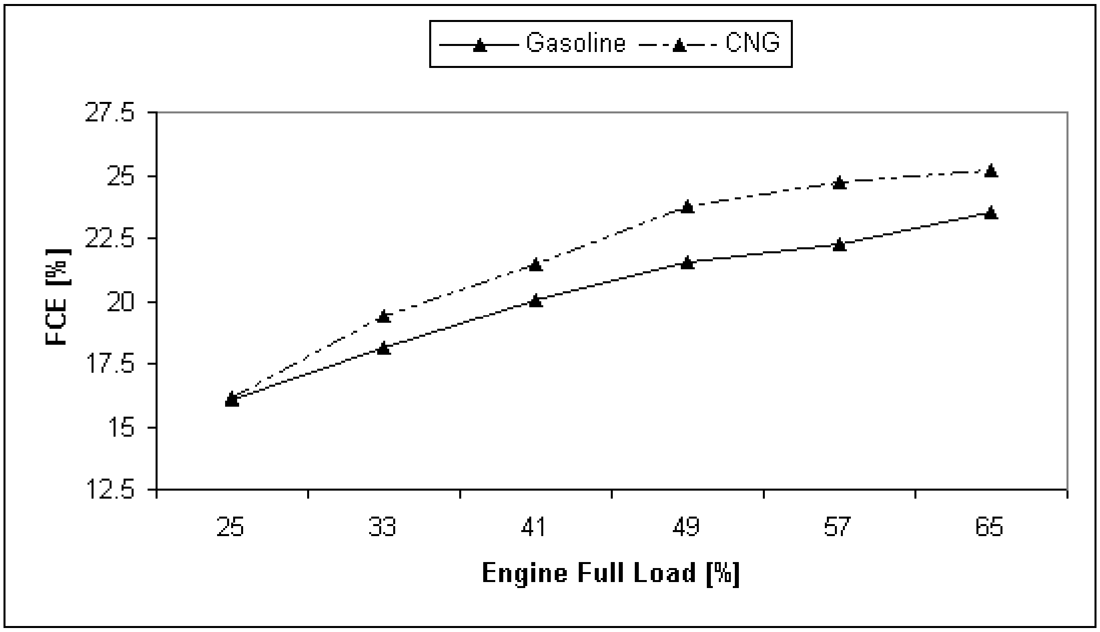

Fig. 10 Efficiency vs. load at 3500 RPM

Engine emissions

Exhaust emissions of a CNG operated SI engine vary strongly with air-fuel ratio. However, NO_x emissions is higher in the region of λ=1 to λ=1.28 and maximum at around λ=1.2 [3]. Figs. 11-12 show graphs correlating the emission test results for engine speed from 1500 to 5500 rpm with WOT position. In comparison to gasoline fuel, CNG produced less emissions of HC and more emissions of NOx (Fig. 11). The formation of NOx in internal combustion engines are primarily caused by the oxidation of N_2 in the air within the combustion chamber of the engine and high combustion temperature, pressure and lean mixture are the reasons for more NOx emissions and this is true for the present study because of the lean (λ=1.06) combustion of CNG and high combustion temperature (compared to gasoline). The simple chemical bond of CNG compared to gasoline is also a reason of producing more NOx than gasoline. On average, CNG produced around 33% higher NOx and 50% lower HC than gasoline. The NO_x emissions have similarity with Aslam et al [8] and Kalam et al. [14-15]. They found CNG produced around 29-30% more NO_x compared to gasoline. But, [14] showed 12% less HC and [15] showed more CO_2 produced by CNG compared to gasoline. However, NOx emissions at high engine loads can be effectively reduced by employing exhaust gas recirculation (EGR) without sacrificing thermal efficiency and smoke emission [17].

From Fig. 12, it is observed that CNG produced much less CO (80%) and CO_2 (20%) emission, and more O_2 emission. CO is a product of incomplete combustion in the engine cylinder when λ value is lower than stoichiometric value. Gasoline is basically iso-octane (C_8H_{18}) and CNG is basically (CH_4). From the chemical equilibrium, it is evident that for higher hydrogen to carbon ratio (H/C) of a fuel, the amount of CO and CO_2 will be lower. Hence the above emissions of CO and CO_2 for gasoline and CNG are fairly expected as CNG has the favorable hydrogen/carbon ratio of almost 4:1 (gasoline 2.3: 1).

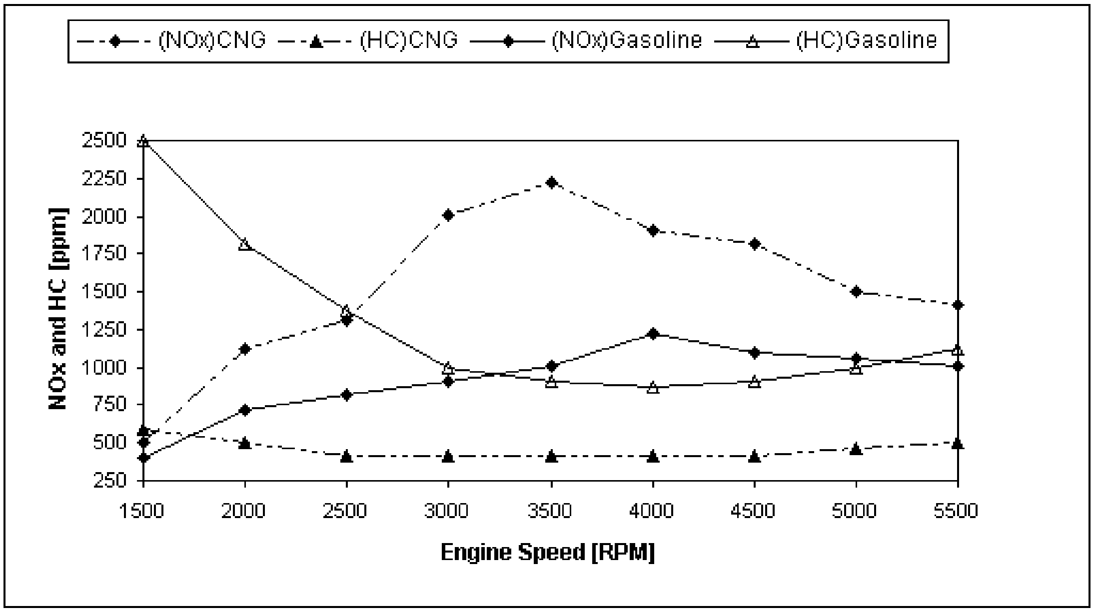

Fig. 11 NOx and HC concentration vs. engine speed at WOT

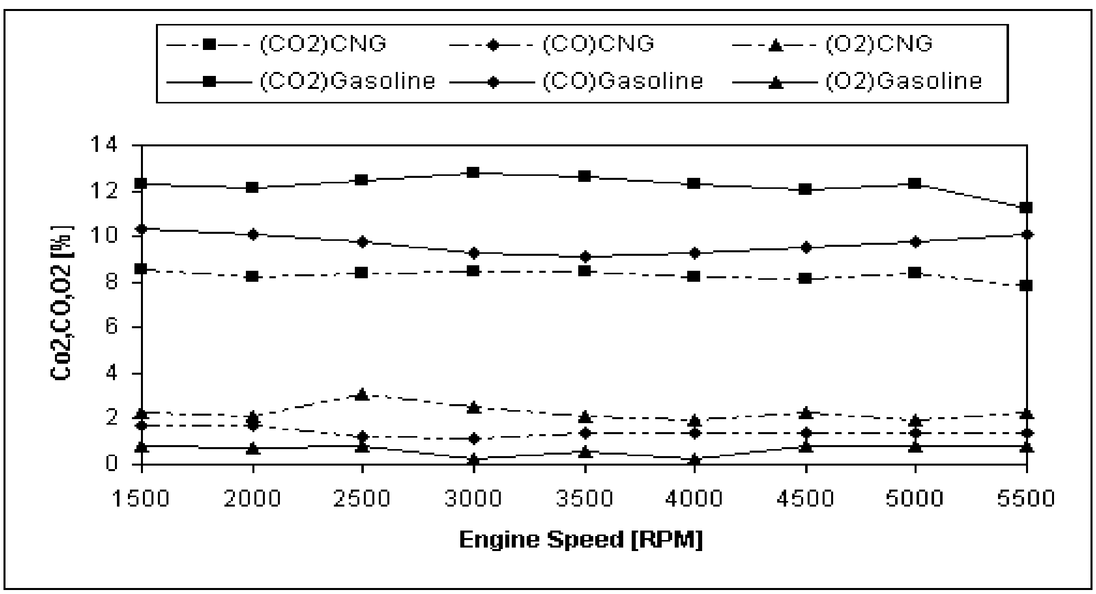

Fig. 12 CO_2, CO, and O2 concentration vs. engine speed at WOT

Conclusion

A comparative study of spark ignition engine performance and exhaust emissions using gasoline and CNG has been made. Measurements were conducted over a range of speed and load. The following inferences can be drawn from the present study.

i) Retrofitted CNG engine produces around 16 % less brake power, and consumes 17%-18% less BSFC as compared to gasoline engine.

ii) CNG engine shows an average of 2% higher FCE at WOT operation with an average λ value of 1.01 and 1.06 for gasoline and CNG respectively.

iii) On average, retrofitted CNG engine reduced CO by around 80%, CO_2 by 20% and HC by 50% and increases NOx emissions by around 33% in comparison with gasoline engine.

iv) 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 network of CNG supply stations at convenient locations throughout the country.

v) CNG does have its shortcomings like less power, heavier fuel storage tank, etc., but its advantages are far too favorable to avoid it as an alternative clean fuel. However, retrofitted CNG fuelled engine can be used at this moment for economic, environmental and energy security reasons.

The results obtained in the present study can be used as a basis to compare the performance of Malaysian new mono fuelled CNG/direct injection (DI) engine.

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