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Full Length Research Paper

Power boosting of a modified natural gas engine

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This paper presents the experimental results on brake power enhancement of a modified natural gas engine. Conventional natural gas engine produces 15 to 20% less brake power than that of gasoline fired engine. This lacking in compressed natural gas (CNG) engine needs to be recovered through modifications and optimization of fuel injection system to provide complete gas combustion in the engine cylinder. A multi-cylinder gasoline engine was modified to bi-fuel engine for operating in several test conditions, such as constant full and half throttle condition. Variation in power production with corresponding fuel flow rate and emission gases (such as carbon monoxides, CO; unburnt hydrocarbon, HC and nitrogen oxides, NO_x) were studied by using two fuels (gasoline and CNG). Engine tune up information like variation in air fuel ratio (AFR) for lean burn operation can be known from those tests. Performance of engine was studied with both the fuels at fixed load and the corresponding fuel flow rate and emissions were measured for evaluation and optimization. The engine produced 10% higher brake power with CNG fuel as compared to that produced with gasoline fuel at full load, but at partial load gasoline fuel produced more brake power than CNG. Emission results revealed that CNG fuelled engine emits less CO and HC, showing more complete combustion than gasoline fuel. On the contrary, higher combustion temperature of CNG fuel produced more NO_x than gasoline. The results of these investigations can be used to develop a new compressed natural gas (CNG), direct injection (DI) and higher efficiency engine in the near future to build an environment friendly fuel economic clean burning automotive vehicle with less emission and similar power rating like gasoline engine.

Key words: Brake power, compressed natural gas-direct injection (CNG-DI), bi-fuel engine, fuel consumption, emission.

INTRODUCTION

Vehemently, the growing number of automotive vehicles is the primary source of urban pollution. Moreover, energy is secured in getting similar importance in today's petro-diplomacy like environmental protection. Automotive moved up to the 2nd position in 2010 from 4th in 2009 based on overall volume of patent activity, surpassing the Telecommunications and Semiconductors industries. In the automotive sector, "Alternative Powered Vehicles" research contributed much (16%) and jumped to 21% higher than that of 2009 according to Thomson Reuters Derwent World Patents Index (DWPI) shown in Figure 1.

Alternative powered vehicles are mostly concentrated on hydrogen fuel cell, solar car, biofuel driven vehicles and hybrid electric cars. All are from the concept of producing greener car. So far, the most successful was Brazil's flexible-fuel vehicles which runs in petrol and ethanol (up to 85%) and sold 22.6 million (Sperling and Gordon, 2009). But food versus fuel debate has raised consensuses about the use of vegetable oil based biofuels as a probable cause of food crisis worldwide (Pimentel et al., 1988; Escobar et al., 2008). Hydrogen fuel cell have been introduced in transport sectors of advanced countries, but it has some difficulties in overcoming backfire (Lucas and Morris, 1980) and cold weather starting problems, but shows significantly clean combustion with no deposit formation (Verhelst and Wallner, 2009). On the other hand, compressed natural gas is similarly, clean burning fuel in spark-ignition engines but more popular for more availability than hydrogen fuel and easier conversion technique. CNG is

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	SUBSECTORS	2010 Volume	2009 Volume	% Change
16%	Alternative Powered Vehicles	15,913	13,118	21%
13%	Navigation Systems	12,060	12,414	-3%
12%	Transmission	11,577	11,520	0%
11%	Safety	10,263	10,589	-3%
9%	Pollution Control	8,376	8,567	-2%
8%	Seats, Seatbelts and Airbags	7,769	7,657	3%
7%	Steering Systems	6,327	6,610	-4%
6%	Suspension Systems	5,924	5,975	-1%
6%	Security Systems	5,752	5,817	-1%
5%	Engine Design and Systems	5,336	5,552	-4%
4%	Braking Systems	3,908	4,067	-4%
3%	Entertainment Systems	3,052	3,230	-6%

Figure 1. Automotive sector in Thomson Reuters Derwent world patents index (DWPI), 2011.

been used in many countries now, but it requires some modification in injection system and best performance of it can be harnessed by using it in a bi-fuel system.

Engine performance refers to generation of useful energy by an engine in comparison to other comparable engines. It attributes to comparable parameters like speed, inlet pressure, temperature output, air fuel ratio (AFR), etc. The useful ranges of all these parameters are limited by various factors, like mechanical stresses, knocking, overheating, etc. Thus, there is a practical limit of maximum power and efficiency obtainable from an engine. The performance of an engine is judged from two main factors, such as engine power and engine efficiency. The overall engine efficiency related to other efficiencies is encountered when dealing with the theory, design and operation of engines. The energy output of an engine is expressed in three distinct terms, such as indicated power (ip), friction power (fp) and brake power (bp). Indicated power was computed from the measurement of forces in the cylinder and brake power is computed from the measurement of forces at the crankshaft of the engine. The friction power was estimated by motorizing the engine. Figure 2 shows the fuel energy distribution in an integrated circuit (IC) engine system. From this, it is comprehended that by reducing fuel energy losses, the fuel conversion efficiency as well as brake power could be increased.

There are two areas in which efforts can improve engine performance, such as (1) increasing fuel energy input into cylinder and/or (2) increasing fuel energy conversion to mechanical energy. Fuel energy can be increased into engine cylinder in many ways, such as (1) supercharging, (2) larger piston displacement which is limited by engine weight and cooling problems, (3) improvement in volumetric efficiency that increases the mass of charge, (4) higher engine speeds which results in increased friction losses at a certain point and lowered volumetric efficiency, and (5) improvements in fuels quality with usable energy content would help to produce higher power. The use of higher compression ratios would increase the efficiency of conversion of the energy of fuel into useful mechanical energy. This requires the development of economically feasible higher antiknock quality fuels. Even with such fuels, there appears to be a limit to the advantage in increasing the compression ratio. Another solution would be to reduce the losses between the air cycle and the actual cycle, and thereby increases the proportion of energy which can be mechanically utilized. In this investigation, a computer controlled engine test bed was used (Kalam et al., 2004) with a provision to setup engine dynamometer at any load/speed condition. The test bed engine brake power had increased by using CNG fuel while other corresponding results were collected for evaluation.

EXPERIMENTAL SETUP AND PROCEDURES

A proton magma-12 valve 4-cylinder spark ignition engine was installed on a test bed. The engine had a bore of 75.5 mm, stroke 82 mm, capacity 1,468 cc and a compression ratio of 9.2. An eddy current dynamometer, model Froude Consine (model AG150) was connected to the engine. The load imposed on the engine by the dynamometer was governed by the amount of excitation current passing through the field coil. The method by which the coil current was controlled provides the dynamometer a variable type of power/speed characteristic, such as constant torque, propeller law or constant speed. All the electronic equipment together with their manipulative controls, indicators, etc., are mounted on a 'CP Cadet10' control unit. Each engine test started with idle running for engine heating up and stability in power generation. The airflow rate was measured with an air flow meter. The fuel system was so designed that the engine could run on gasoline and natural gas. The gasoline consumption was measured with fuel flow meter (load cell arrangement) and natural gas was measured with vortex gas flow transmitter. All the flow meters were incorporated with engine control system through interfacing cards. An Auto-check (Model

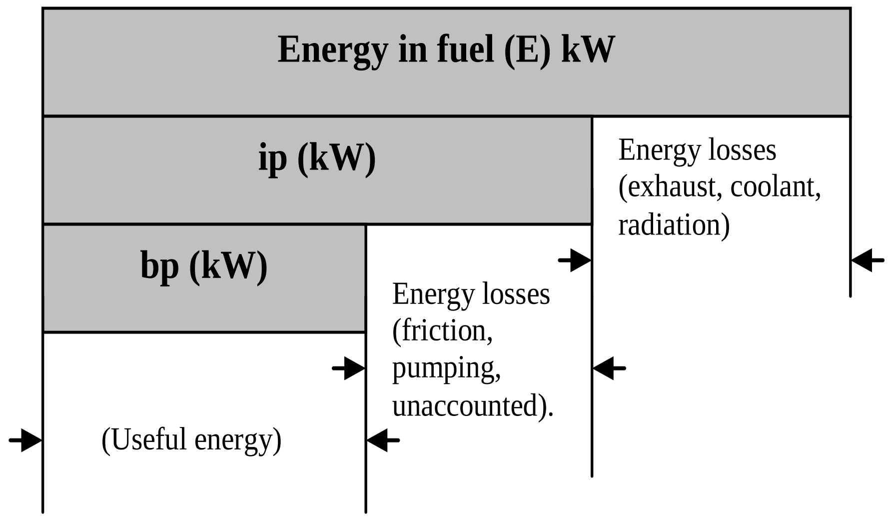

Figure 2. Energy distribution in IC engine (Escobar et al., 2008).

Table 1. Typical natural gas compositions.

Component	Mole (%)
Methane	94.42
Ethane	2.29
Propane	0.03
Isobutane	0.25
Normal-butane	0.07
Isopentane	0.01
Hexane	0.01
Carbon dioxide	2.61
Nitrogen	0.31

Table 2. Physicochemical properties of CNG and gasoline fuels.

Properties	CNG	Gasoline
Density (kg/m^3)	0.81	-
Gross calorific value (MJ/kg)	49.00	45.00
Molecular weight	18.18	114.00
Specific gravity	0.64	0.780

974/5) and a Bacharach model CA300NSX emissions gas analyzers (standard version, k-type probe) were used to measure the concentration of carbon monoxide (CO), unburned hydrocarbon (HC) and oxides of nitrogen (NO_x).

Retrofitting

The ignition and burning characteristics of natural gas are considerably different from those of gasoline. Methane has a much longer ignition delay time than most hydrocarbons and it has got much higher minimum ignition energy than that of gasoline. Thus, when natural gas is used in an internal combustion engine, the combustion duration becomes relatively longer and much more advanced spark timing is needed. Hence, retrofitting is required on conventional gasoline fueled engine for using natural gas as a fuel. Compressed natural gas (CNG) stored under a maximum pressure of 200 bar flows to the engine through a gas regulator kit. The kit supplies CNG to the engine carburetor at an approximately atmospheric pressure (0.8 bar) so that carburetor can effectively use it. The regulator kit is a three stage pressure regulator unit based on 'high pressure conversion kit' model, Tartarini-RP/76M. Specification of test engine, layout of experimental setup, and gas regulator kit are shown elsewhere (Kalam et al., 2004). A shut off solenoid is included to make availability of gas flow when the engine is not operating on gasoline. A downdraft 2-barrel carburetor is used for gas-air mixture. In fact only the top-half body with the venturi mixer is used and fixed upon the gasoline carburetor to make easy switch of the engine to run on gasoline or gas alternatively.

Compressed natural gas and gasoline

CNG used in this experiment is based on the storage and compositions standard maintained by the government of Malaysia. Its chemical compositions are shown in Table 1. From the data of Tables 1 and 2, a chemical formulae for CNG was derived as $C_\alpha H_\beta O_\gamma N_\delta$, where $\alpha = 1.0318, \beta = 3.953, \gamma = 0.0522$ and $\delta = 0.0062.$ The calculated stoichiomatric air fuel $(A/F)_s$ ratio is 15.20 (Zervas et al., 2001). The gross calorific value and specific gravity of the used gasoline fuel (C_8H_{18}) are 45 MJ/kg and 0.692, respectively. The stoichiomatric air fuel $(A/F)_s$ ratio of the gasoline fuel is 15.14. The physicochemical properties of gasoline and CNG are as shown in Table 2.

Equipment uncertainty analysis

All the equipment was verified for their resolutions. Engine dynamometer, emission analyzer, fuel flow meter, air flow meter,

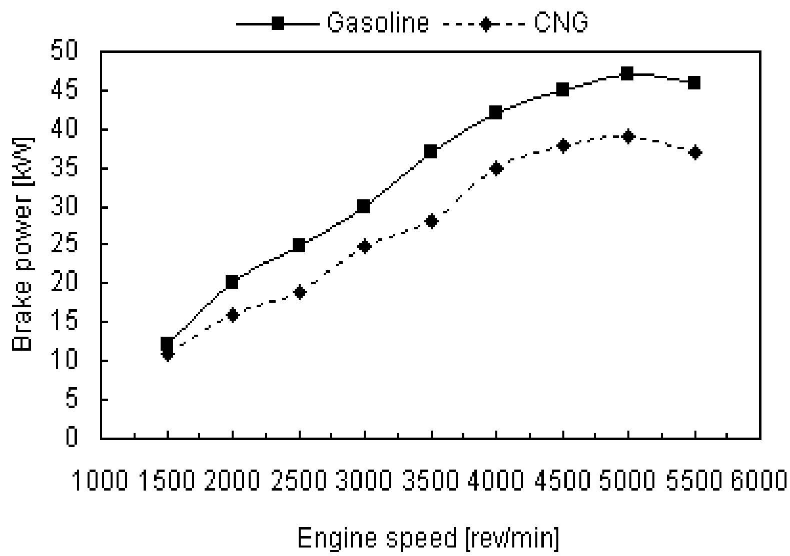

Figure 3. Brake power versus engine speed at WOT.

etc., are properly calibrated. Before data collection for analysis, the engine was operated several times to observe the variation in test results. A new probe of emission analyzer was used and the carbon deposition on it was observed. The emission analyzer was calibrated and the results were verified using another emission analyzer, such as different branded. After correction of all the errors related to equipment, the test was conducted three times to observe the repeatability of the data. The repeatability is matched over 96% for each test. Then, the average of three tests has been used for presentation and discussion.

RESULTS AND DISCUSSION

Engine operated with constant throttle conditions

The brake power output versus engine speed over the range from 1500 to 5500 rpm for both gasoline and CNG fuels is as shown in Figure 3. Maximum brake power was obtained at 5000 rpm by gasoline fuel of 47 kW followed by CNG fuel of 39 kW. The CNG fuel produces an average (over the full length of speed range) of 15% less brake power due to the effect of reduced charge energy density per injection into the engine cylinder as compared to gasoline fuel (Hamzah and Ahmad, 2002). This is mainly due to the gaseous nature of CNG fuel that reduces both the air volumetric efficiency and charge energy density per injection into the engine cylinder. The specific fuel consumption (SFC) and all the emissions result with WOT conditions are shown elsewhere (Kalam et al., 2004).

SFC was lower over the speed range while running on CNG fuel. The SFCs for CNG and gasoline fuels were 300 and 380 g/kWh, respectively at 5000 rpm. On average use of CNG shows 15 to 18% lower SFC than that of gasoline fuel. The minimum SFCs found for CNG and gasoline is 260 and 320 g/kWh, respectively at 3500 rpm. Meanwhile, the emissions result showed that all the polluting gases in the combustion products from CNG fuel were lower except NOx. The maximum lambda (λ) values found from CNG and gasoline fuels were 1.472 and 1.453, respectively at engine speed of 4000 rpm. The average lambda values for CNG and gasoline fuels are 1.391 and 1.374, respectively. It is found that lambda value for CNG fuel is slightly higher than that of gasoline fuel. All these results and discussion are elaborated elsewhere (Zervas et al., 2001).

Figure 4 presents brake power of engine from both the CNG and gasoline fuel operation with half throttle conditions. The maximum brake power (26 kW) is obtained with gasoline fuel followed by CNG fuel (22 kW) at 3000 rpm. In average, engine produces 20% higher brake power by using gasoline fuel than that of using CNG fuel. Figure 5 shows fuel flow rate (kg/h) to engine for both the fuel at half throttle conditions. It is found that increasing speed increases fuel consumption for the development of higher brake power.

However, the fuel consumption rate in using gasoline fuel is higher as compared to that of using CNG fuel at all running speeds of an engine, which is the cause of lower brake power generation by using CNG fuel. The gasoline fuel consumes highest fuel consumption (5 kg/h) at 3000 rpm followed by CNG fuel (4.38 kg/h). In average, the fuel consumption rate in using gasoline is 11% higher than that of using CNG fuel.

Emission results at constant 50 Nm load condition

At a constant load of 50 Nm and over the speed range of 1500 to 3500 rpm, CO and HC emissions are lower by

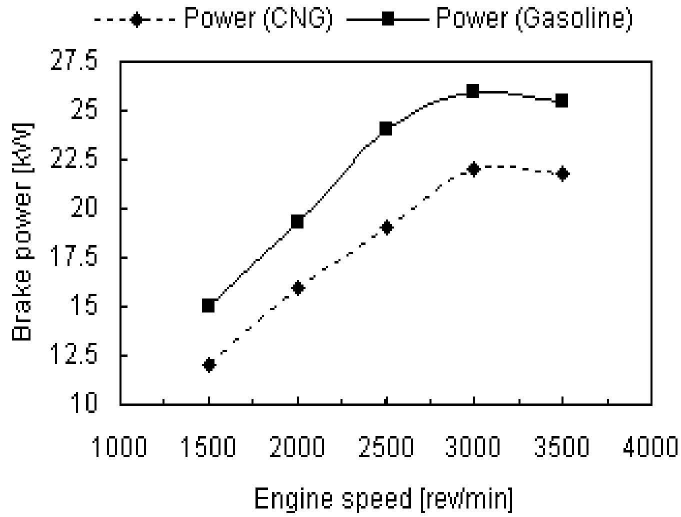

Figure 4. Brake power versus engine speed at half throttle.

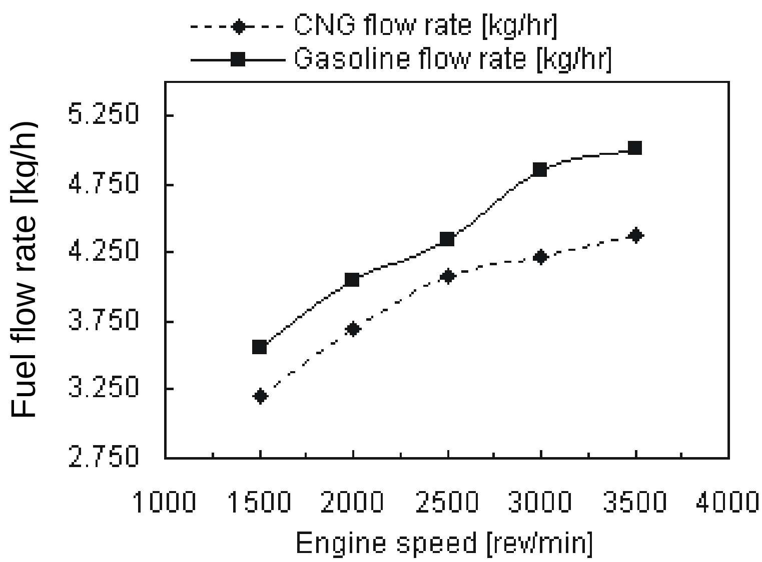

Figure 5. Fuel flow rate versus engine speed at half throttle.

using CNG than that of using gasoline. On average (based on five operating speeds), CNG produces 2.45% CO and 90 ppm HC emissions and gasoline produces 8.5% CO and 350 ppm HC. Comparing the NO_x results on average, CNG produces 383 ppm and gasoline 132 ppm. High combustion temperature of CNG fuel is the reason of higher NO_x product as compared to that from gasoline fuel.

Engine operated with constant load condition

Figures 6 to 9 showed the results of engine operation with constant load (50 Nm, such as constant bmep of 4.27 bar) at each operating speed from 1500 to 3500 rpm with an interval of 500. In this operating condition, engine produced similar brake power at each running speed by using both fuels individually.

Figure 6 shows that increasing brake power increases fuel flow rate for both fuels. It is found that CNG fuel flow rate is lower (average 4.32%) than that of gasoline mainly due to the higher calorific value. Figure 7 presents, CO emission versus engine brake power. It was found that CNG produces lower level of CO emission than gasoline fuel. On average, all over the operating speed range, CO produced by CNG and gasoline are 1.57 and 8%,

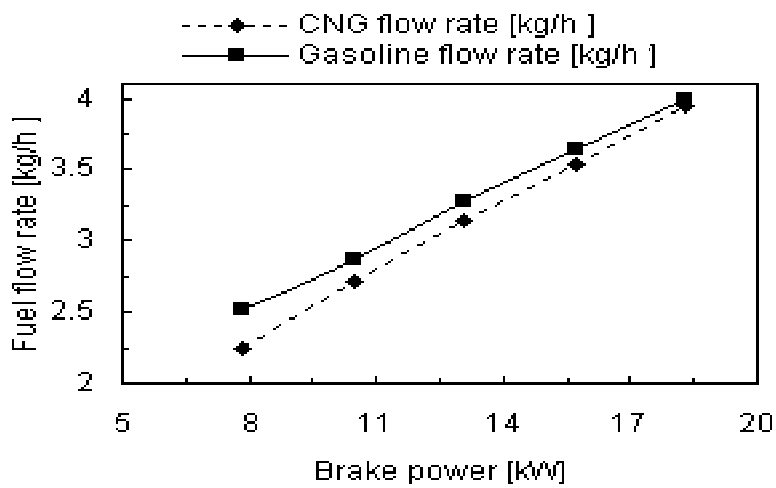

Figure 6. Fuel flow rate versus engine brake power at 50 Nm load.

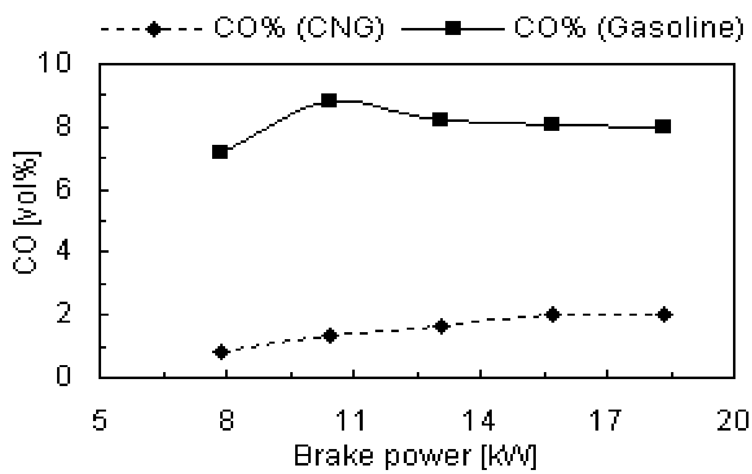

Figure 7. CO emission versus engine brake power at 50 Nm load.

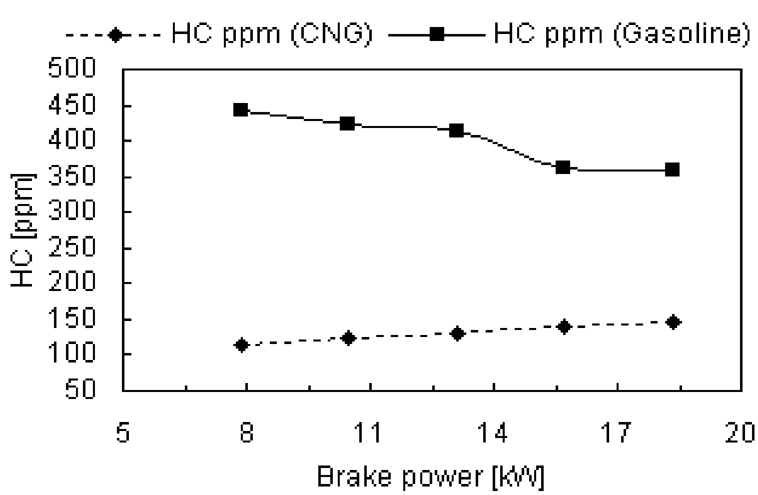

Figure 8. HC emission versus engine brake power at 50 Nm load.

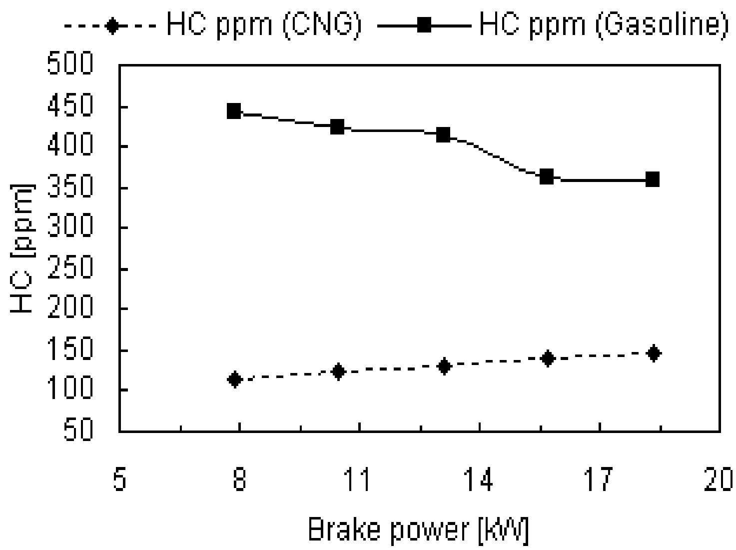

Figure 8. HC emission versus engine brake power at 50 Nm load.

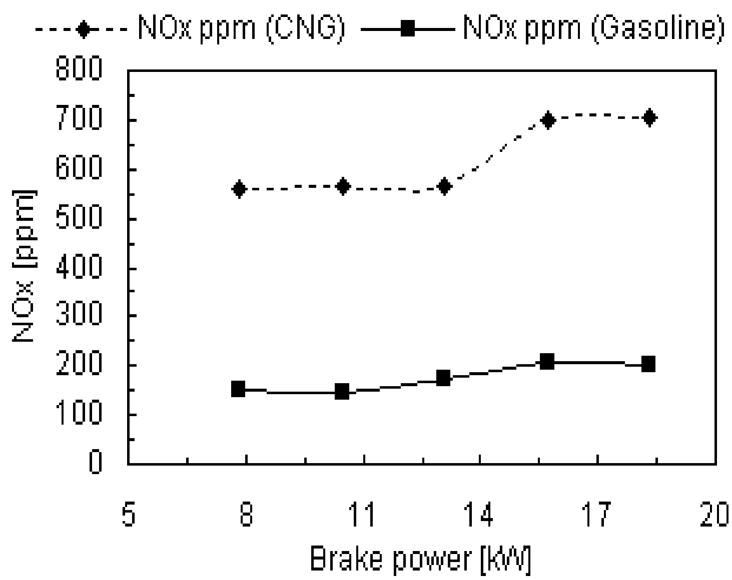

Figure 9. NO_x emission versus engine brake power at 50 Nm load.

respectively. The CNG produces 80% lower CO emission than gasoline fuel. Figure 8 presents unburned hydrocarbon emission versus engine brake power. It is found that gasoline fuel produces higher level of HC emission as compared to that produced by using CNG fuel. Average HC emission from CNG is 130 ppm and that from gasoline is 399 ppm. The lower concentration of HC and CO from CNG fuel is mainly due to more extension to complete combustion as compared to combustion of gasoline fuel. Figure 9 shows the result of oxide of nitrogen versus engine brake power. It is observed that CNG fuel produces higher NO_x concentration as compared to that produced by gasoline fuel. On average, CNG and gasoline fuel produces NO_x 618 and 175 ppm, respectively. Higher combustion temperature of CNG fuel is the reason of increased NO_x concentration.

Engine operated with higher brake power for CNG fuel

Figures 10 to 12 show brake power, emissions and fuel consumption results when the engine was controlled to produce higher brake power by using CNG fuel in comparison to that of gasoline fuel. Figure 10 shows that CNG fuel produces 10% higher brake power than that

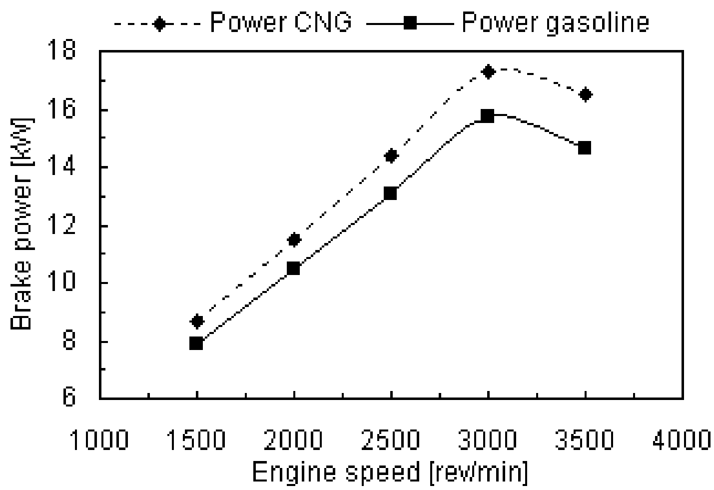

Figure 10. Brake power versus engine speed.

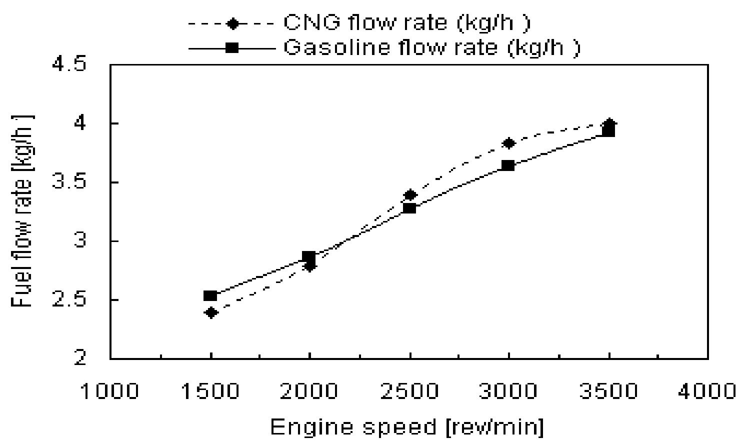

Figure 11. Fuel flow rate versus engine speed at half throttle.

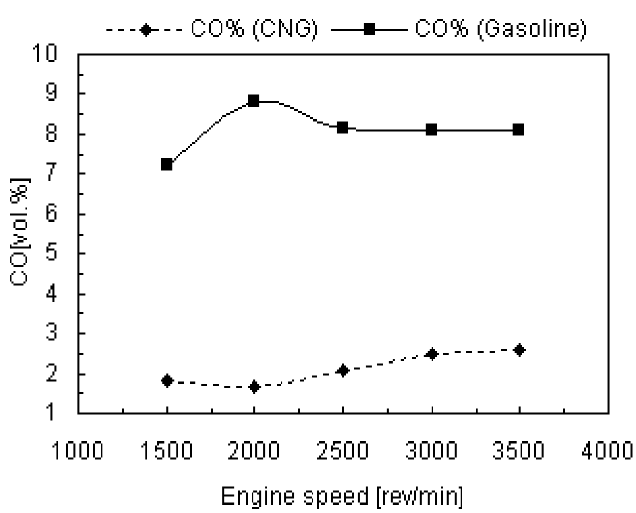

Figure 12. Carbon monoxide versus engine speed.

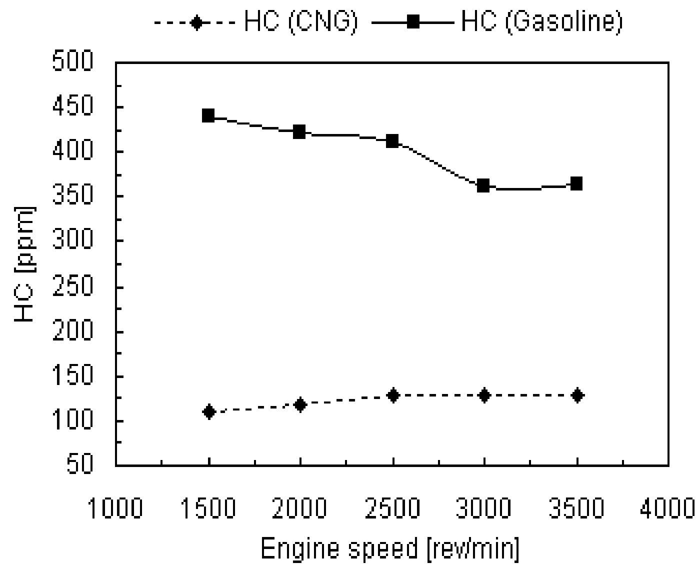

Figure 13. Unburned hydrocarbon versus engine speed.

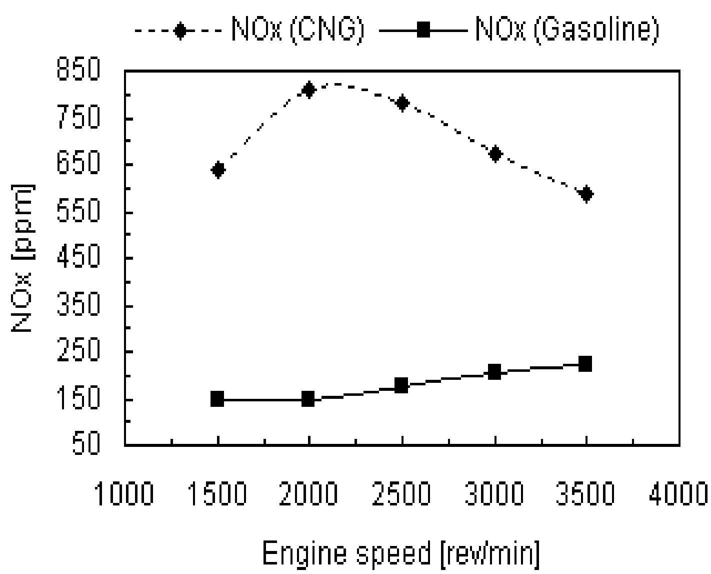

Figure 14. Oxides of nitrogen versus engine speed.

produced by using gasoline fuel at all running speeds and in this running condition, average CNG fuel flow rate was 1.2% higher than that of gasoline fuel as shown in Figure 11.

Similarly, Figures 12 to 14 are showing emission results, where CNG fuel produces average of 1.2% CO and 122 ppm HC, and on the other hand gasoline fuel produces average of 8% CO and 400 ppm HC. Figure 14 shows that CNG and gasoline fuel produces average NO_x as 697 and 179 ppm, respectively. It can be inferred from the analysis presented earlier that it is possible to produce higher brake power by using CNG fuel along with reduced exhaust emissions gases.

Conclusions

The following conclusions were drawn from the present study:

1. Higher brake power was achieved at 100% throttle in CNG fuelled engine. On the contrary, gasoline fuel

produced more brake power than CNG at partial load (50% throttle).

2. CO and HC emission rate are reduced by using CNG fuel instead of gasoline fuel. However, NO_x emission increases by using CNG fuel in comparison to using gasoline.

3. 10% higher brake power along with 1.2% increased fuel consumption and lower emissions (except NO_x) could be obtained by using CNG fuel instead of gasoline fuel.

It was confirmed that CNG fuel can be tuned up to produce higher brake power with reduced emission results (except NO_x emission). Based on the emission results, CNG fuel can be used through designing higher compression ratio engine as well as direct injection engine.

RECOMMENDATIONS

Further reduction in emissions (especially NO_x) can be achieved from CNG fuel by using three-way catalytic converter (TWC). Hence, bi-fuel engine could be useful with TWC to reduce harmful emissions. The results of this experiment could be used to develop new natural gas engine, such as high compression ratio engine as well as new catalytic material to reduce further emissions from CNG fuel.

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