**Internal Combustion Engine Division of ASME**
**2006 Spring Technical Conference**
**May 7-10, 2006 Aachen, Germany**

# ICES2006-1387

# Performance and Emissions Characteristics Investigation of a Bi-fuel SI Engine Fuelled by CNG and Gasoline

**Abazar Shamekhi**
**Faculty of Mech. Eng.**
**University of Tehran**
**Tehran, IRAN**

**Nima Khatibzadeh**
**Faculty of Mech. Eng.**
**K.N.Toosi University of Technology**
**Tehran, IRAN**

**Amir H. Shamekhi**
**Faculty of Mech. Eng.**
**K.N.Toosi University of Technology**
**Tehran, IRAN**

## ABSTRACT

Nowadays, increased attention has been focused on internal combustion engine fuels. Regarding environmental effects of internal combustion engines particularly as pollutant sources and depletion of fossil fuel resources, compressed natural gas (CNG) has been introduced as an effective alternative to gasoline and diesel fuel in many applications. A high research octane number allows combustion at higher compression ratios without knocking and good emission characteristics of HC and CO are major benefits of CNG as an engine fuel.

In this paper, CNG as an alternative fuel in a spark ignition engine has been considered. Engine performance and exhaust emissions have been experimentally studied for CNG and gasoline in a wide range of the engine operating conditions.

**KEY WORDS:** Alternative Fuel, CNG, Emission, Gasoline, Performance, SI Engine.

## INTRODUCTION

Alternative fuels are of much importance because of strict emission regulations, lowering fuel cost and increasing depletion of crude oil resources. Therefore, car manufacturers have decided to use alternative fuels [1]. Compressed natural gas (CNG) has been introduced as an alternative fuel. Using CNG has some advantages over gasoline such as:

- Better mixture formation and more uniform combustion.
- Possibility of using higher compression ratios without knocking due to high research octane number (RON>130) of the CNG.
- Lean burning capability of CNG and lowering exhaust emissions.
- Lower fuel cost due to no refinery process.
- Higher durability of engine lubricant.

Abundant resources of natural gas and widespread gas pipe network in some countries have encouraged their governments to use CNG as vehicles' fuel.

Many studies and experimental works have been done on CNG fuelled engines. Lapetz *et al.* [2] developed a Ford CNG bi-fuel pickup truck. To control emissions and insure safety, they modified the base vehicle's configuration for conversion to bi-fuel CNG operation. Natural gas has a lower flame speed than gasoline. This causes the total combustion duration prolonged compared with gasoline fuel [3]. In designing a turbulent effect in order to increase the natural gas flame speed, Johansson and Olsson [4-5] developed ten different geometries of combustion chamber. The results show a high correlation between in cylinder turbulence and rate of heat release in combustion process. However, the results also showed that geometries that gave the fastest combustion would also gave the higher $NO_x$ concentrations. R.L. Evans *et al* [6] investigated combustion chamber design for fast burning of natural gas. Their studies based on the principle of using squish motion to generate a series of jets directed towards the center of the chamber just prior to ignition. The chamber in this study referred to as the UBC squish jet. The faster burning rate of UBC chamber lead to an average 3 percent reduction in brake-specific fuel consumption, 5 percent increase in BMEP, and an increase in the lean limit of combustion. The exhaust emissions were lower for the UBC chamber than those for a conventional Bowl-in-piston (BIP) chamber: brake-specific total unburned hydrocarbon (BSTHC) and $BSNO_x$ were lower by 20 to 50 percent and BSCO were 15 percent lower. Swain *et al* [7] have been studied the effects of hydrogen addition on the natural gas engine operation. According to their results, adding hydrogen into the CNG/air mixture had adverse effect on the combustion delay and increased the burning rate.

Zuo and Zhao [8] developed a quasi-dimensional model for analysis of combustion processes in SI prechamber natural gas engine. They have used two submodels to simulate turbulence intensity in cylinder and modeling of jet orifices in prechamber. They verified their simulation code with experimental data. Performance and emission characteristics of a bi-fuel Ricardo single cylinder SI research engine have been comparatively studied by Evans and Blaszczyk [9]. Their results show 12 percent reduction of power and 5-50 percent reduction of emissions when the engine fuelled by natural gas. Sun *et al.* [1] developed GM 2.2L CNG bi-fuel passenger car. They used a computer engine simulation model able to predict engine performance, fuel consumption and emissions to reduce system calibration time as well as the cost of testing. According to the results non-methane organic gases (NMOG) and carbon monoxide (CO) on CNG was significantly lower than those on gasoline. Manivannan *et al.* [10] studied lean burn strategy for reducing emissions of natural gas spark ignition engines. They considered performance and emissions characteristics of a SI lean burn natural gas engine. Also, they studied effects of fuel composition, combustion chamber geometry, combustion modeling, burning rate models, pre-chamber and after-treatment on these engines. Chiodi *et al.* [11] have investigated mixture formation and combustion process in a CNG engine by using a fast response 3D CFD simulation. An improved mathematical model of SI engines was developed by Shamekhi and Ghaffari [12] for simulation of engine performance and emissions fuelled by different fuels such as CNG, gasoline and LPG. This model is based on a combination of thermodynamics relations and dynamical characteristics of the engine during the four stroke. Volpato *et al*. [13] studied engine management for multi-fuel plus compressed natural gas vehicles. Aslam *et al*. [14] have retrofitted a conventional 1.5L, 4-cylinder Proton Magma gasoline engine for running with CNG. They tested the bi-fuel engine for CNG and gasoline fuels and measured brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC) and fuel conversion efficiency (FCE) in steady state condition with WOT and variable load of 25-65% of engine full load. Also, a comparative study of emissions has been made for both fuels.

The purpose of the present study is the experimental analysis of performance and emissions characteristics of a Mazda bi-fuel (gasoline + CNG) four stroke SI engine of a pick up vehicle over a wide range of engine operations. All of tests have been done under steady state conditions for both gasoline and CNG fuels and detailed comparison has been made between results.

The engine is equipped with a catalyst converter but presented results measured before the catalyst converter and it is set up only for providing tests with more real conditions like back pressure produced by catalyst. A common rail fuel injection system is used for CNG in order to have precise air-fuel ratio control.

## EXPERIMENTAL IMPLEMENTATION

Emissions and performance characteristics of the bi-fuel engine are measured in full load conditions over a wide range of engine speeds according to ISO-1585 testing procedure. Test facilities consist of:

- Four cylinder SI engine
- Eddy current dynamometer, Ricardo FE 760-S
- Exhaust gas analyzer, Pierburg HGA 400
- Fuel temperature control device, AVL 753
- CNG mass flow meter, Emerson micro motion elite sensor
- Gasoline mass flow meters, AVL 753
- Fuel consumption device, AVL 733S
- Mazda on-board diagnostics (OBD II) device
- Data acquisition system, Ricardo
- CNG kit, PRINS (VSI)
- CNG storage

The engine and dynamometer specifications are listed in Tables 1 and 2.

**Table 1- Mazda B2000i engine specifications**

| | |
|---|---|
| Engine Type | Four stroke, Spark ignition |
| Induction | Naturally aspirated |
| Number of cylinders | 4 cylinder- In line |
| Bore (mm) | 86 |
| Stroke (mm) | 86 |
| Connecting rod length (mm) | 153 |
| Displacement volume ($cm^3$) | 1998 |
| Compression ratio | 8.6 |
| Max. power | 70 kw @ 5000 rpm |
| Max. torque | 151 N.m @ 2500 rpm |
| Valve per cylinder | 3 |
| Intake valve opening | $10^{\circ}$ BTDC |
| Intake valve closing | 49° ATDC |
| Exhaust valve opening | 55° BBDC |
| Exhaust valve closing | 12° ATDC |

**Table 2- Ricardo dynamometer specifications**

| | |
|---|---|
| Dyno. type | Ricardo FE 760-S |
| Max. torque (N.m) | 610 |
| Max speed (rpm) | 12000 |
| Max power (kw) | 191.17 |
| Inertia ($kg/m^2$) | 0.176 |
| Torsional spring (N.m/rad)*1000 | 239 |
| Weight (kg) | 474 |

In order to achieve desired data, sensors were mounted in suitable positions. Applied sensors were angle encoder, lambda, MAF (air mass flow rate), intake manifold temperature, oil temperature and pressure, fuel temperature and pressure, exhaust manifold temperature and outlet water temperature. Data were collected simultaneously from sensors and sent to a data acquisition system. Also engine torque and exhaust gases data were recorded. Exhaust gases data included the concentration of $NO_x$, HC, CO, $CO_2$ and $O_2$. ECU data such as: injection time, injection duration and spark advance were monitored by Mazda OBD II device.

Tests have been done for both CNG and gasoline fuels under engine steady state conditions. When CNG kit was installed on the engine, calibration was done for CNG operation. CNG kit consisted of: pressure regulator, common rail injector, CNG ECU, spark advancer, emulator, CNG filter and fuel exchange switch.

The composition and properties of CNG and gasoline used in these tests were obtained from Iran's Research Institute of Petroleum Industry (RIPI). The lower heating value of CNG also checked by gravimetric analysis as proposed by Evans and Blaszczyk [9].

Gasoline properties are shown in Tables 3 and 4.

**Table 3- Gasoline composition (source: RIPI)**

| component | symbol | Mass Fraction*100 |
|---|---|---|
| Carbon | C | 85.65 |
| Hydrogen | H | 12.94 |
| Oxygen | O | 1.39 |
| Sulphur | S | 0.0003 |

**Table 4- Thermodynamic properties of gasoline (source: RIPI)**

| | |
|---|---|
| Stoichiometric ratio | 14.19 |
| Octane number | 95.8 |
| Higher heating value (MJ/kg) | 45.03 |
| Lower heating value (MJ/kg) | 42.23 |
| Density @ 25ºC (kg/m$^3$) (DIN 51757) | 749 |
| Molecular weight (kg/kmol) | 106.22 |

Natural gas properties and composition are shown in Tables 5 and 6 (test method: ASTM D-1945-03)

**Table 5- Thermodynamic properties of natural gas (source: RIPI)**

| | |
|---|---|
| Stoichiometric ratio | 16.5 |
| Higher heating value (MJ/kg) | 50.29 |
| Lower heating value (MJ/kg) | 45.71 |
| Molecular weight (kg/kmol) | 17.74 |

**Table 6- Natural gas composition (source: RIPI)**

| Component | Symbol | Volumetric % |
|---|---|---|
| Methane | $CH_4$ | 89.1 |
| Ethane | $C_2H_6$ | 4.4 |
| Propane | $C_3H_8$ | 1.1 |
| Butane | $C_4H_{10}$ | 0.3 |
| Pentane | $C_5H_{12}$ | 0.1 |
| Hexane | $C_6H_{14}$ | 0 |
| Carbon dioxide | $CO_2$ | 0 |
| Nitrogen | $N_2$ | 5 |
| Oxygen | $O_2$ | 0 |

## TEST RESULTS AND DISCUSSION

The engine has been tested for CNG and gasoline over a range of 1500-5500 rpm engine speeds. The tests have been done in full load condition. Various data such as: engine performance parameters, exhaust emissions, pressures and temperatures in some critical points and ECU data have been measured. Experimental results are illustrated in Figures 1-6 versus engine speed. For simplification of comparison between results, each figure contains two individual curves.

Figure 1 shows the engine volumetric efficiency (the actual air mass per swept volume mass at ambient conditions [15]) for both fuels. According to the figure, volumetric efficiency of CNG fuelled engine is lower than gasoline fuelled engine. This decrease is due to the larger volume of inlet air occupied by CNG. Using ideal gas state equation it can be easily shown that the volume occupied by natural gas is larger than that by gasoline in a stoichiometric air-fuel mixture. There are several ways for improvement of engine volumetric efficiency while operating with natural gas such as: increasing the number of intake valves per cylinder, valve timing and lifting optimization [16], using turbocharged engine [17-18] and designing a modified intake manifold, however these all affect cost and reliability.

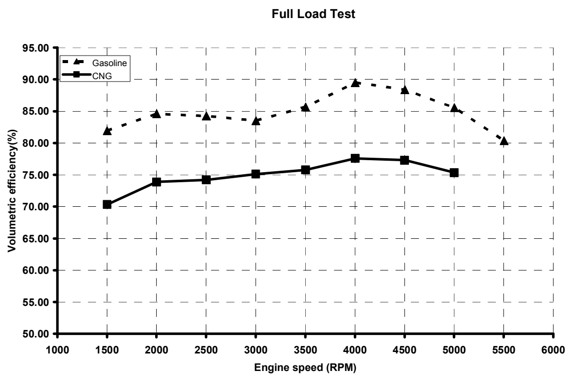


**Fig.1 Engine volumetric efficiency versus engine speed in full load condition for both fuels**

Maximum decrease of volumetric efficiency for CNG is about 13.3% and occurs at engine speed 4000 rpm and its average value is about 12.3% through out the engine speed range.

Figures 2 and 3 compare the engine torque and power for operation with CNG and gasoline. According to the experimental results, these parameters are decreased in CNG fuelled engine. The major reason for lower torque and power of CNG fuelled engine is lower volumetric efficiency. Decrease of volumetric efficiency in CNG operation causes reduction in amount of fuel injected into each cylinder per a cycle and decrease of the engine torque and power consequently.

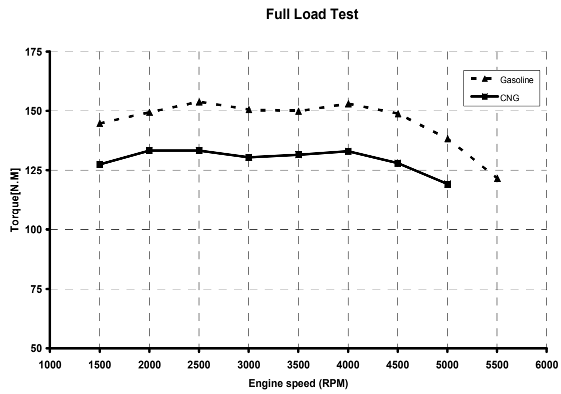


**Fig.2 Engine torque versus engine speed in full load condition for both fuels.**

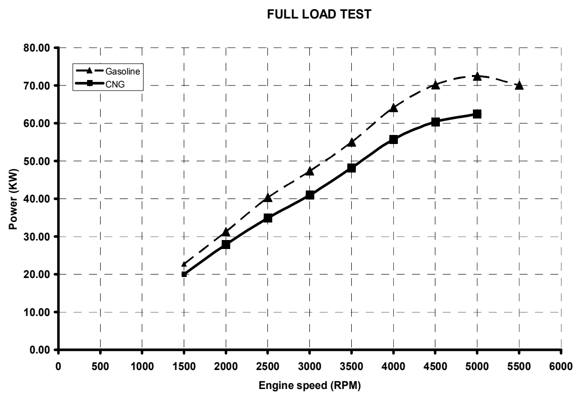


**Fig.3 Engine Power versus engine speed in full load condition for both fuels**

Figure 4 shows break mean effective pressure (BMEP) for CNG and gasoline. It can be observed that CNG BMEP curve is lower than gasoline BMEP curve.

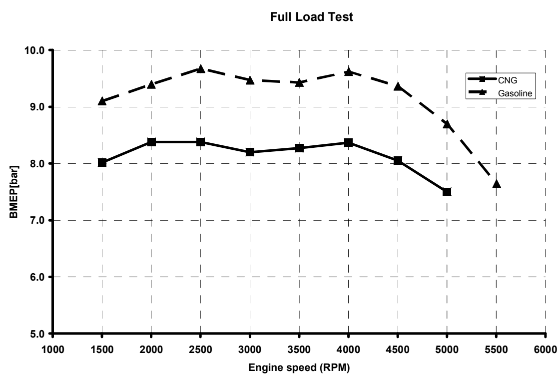


**Fig.4 BMEP versus engine speed in full load condition for both fuels**

The relationship between engine break specific fuel consumption (BSFC) and engine speed is depicted in Fig. 5 for both fuels. The maximum difference of BSFC is 23.8% and it occurs at 2000 rpm. In average, CNG showed around 19.1% lower BSFC than gasoline through out the engine speed range.

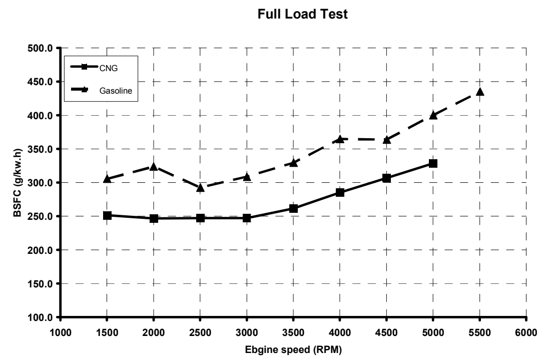


**Fig.5 BSFC versus engine speed in full load condition for both fuels**

BSFC of natural gas has been measured lower than that of gasoline. Because natural gas heating value is higher than gasoline. Therefore specified amount of heat can be released with less amount of CNG than with gasoline.

Variation of engine air-fuel ratio with engine speed is shown in Fig. 6 for both fuels. The air-fuel ratio is determined by ECU strategy. In this work, two individual ECU are used, one for gasoline and the other for natural gas. The CNG ECU itself has the high level integration into the gasoline management system, they are master- slave. Natural gas ECU gets some data from gasoline ECU to determine the air-fuel ratio, injection timing and injection pulse width. It can be observed that the mixture is rich in gasoline operation and the minimum air-fuel ratio is 0.726 at 5500 rpm. Rich burning strongly affects the fuel consumption and emissions such as HC and CO. Also, the CNG fuelled engine burns rich in the majority of operation range and the minimum air-fuel ratio is 0.837 at 5000 rpm.

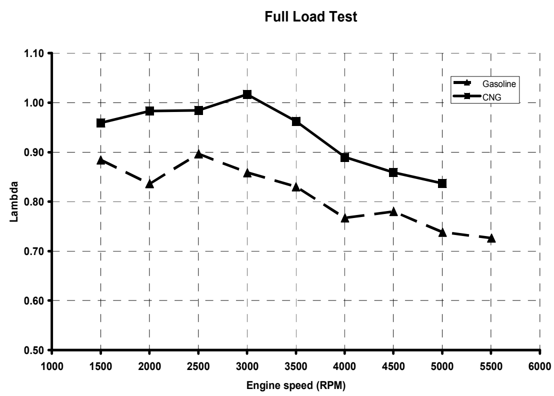


**Fig.6 Lambda versus engine speed in full load condition for both fuels**

According to the obtained results, it can be concluded that calibration of gasoline ECU has not been done for Tehran's climate has 860 mbar atmospheric pressure and it seems to be done for 1000 mbar pressure (at sea level). This difference of pressure causes lower density of air induced to engine and consequently rich burning. In this work, there was no possibility of gasoline ECU calibration and the calibration was done only for CNG one. The engine air-fuel ratio was optimized for CNG ECU. At engine speeds of 1500-3500 rpm which is the most engine operation range of this pick up vehicle, in average the air-fuel ratio is about 0.98 for the CNG fuelled engine. In higher engine speeds, the engine burns rich for attaining sufficient torque and power with CNG.

## INVESTIGATION OF ENGINE PERFORMANCE CHARACTERISTICS VARIATION

Figure 7 shows variation percentage of some engine performance parameters such as: torque, power, break mean effective pressure and volumetric efficiency over a wide range of engine speeds. For engine torque, power and brake mean effective pressure, the maximum decrease of about 14% occurs at 4500 rpm. Around 13.3% decrease of these parameters is observed at 2500 rpm. It is important because the maximum engine torque occurs at this point. Volumetric efficiency shows maximum decrease of 13.3% at 4000 rpm (except 14.2% decrease at 1500 rpm which is a low engine speed).

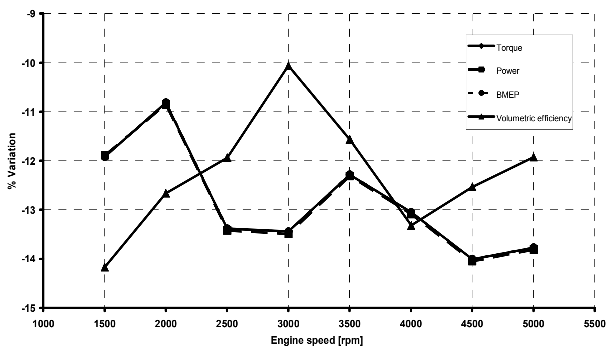


**Fig.7 Variation of engine torque, BMEP, power and volumetric efficiency for CNG compared with gasoline**

The variations of maximum values of engine performance characteristics have been listed in Table 7.

Figure 8 shows the variation percentage of the thermal efficiency and BSFC for both fuels. Maximum decrease of engine BSFC for CNG fuel compared with gasoline is about 24% at 2000 rpm. Thermal efficiency increases in CNG fuelled engine due to higher CNG calorific value and it causes lower engine fuel consumption. This increase shows maximum value of 32% at 2000 rpm.

**Table 7- Variations of engine performance parameters**

| | Gasoline | CNG | Deviation % |
|---|---|---|---|
| Max. power (kw) | 72.44@ 5000 rpm | 62.44@ 5000 rpm | 13.8 |
| Max. torque (N.m) | 153.81@ 2500 rpm | 133.23@ 2500 rpm | 13.3 |
| Max. volumetric efficiency | 89.51%@ 4000 rpm | 77.59%@ 4000 rpm | 13.3 |
| Max. BSFC (g/kw.h) | 434.9@ 5500 rpm | 328.5@ 5000 rpm | ______ |
| Max. BMEP (bar) | 9.67@ 2500 rpm | 8.38@ 2500 rpm | 13.3 |
| Max. thermal efficiency % | 27.34@ 2500 rpm | 34.76@ 2000 rpm | ______ |

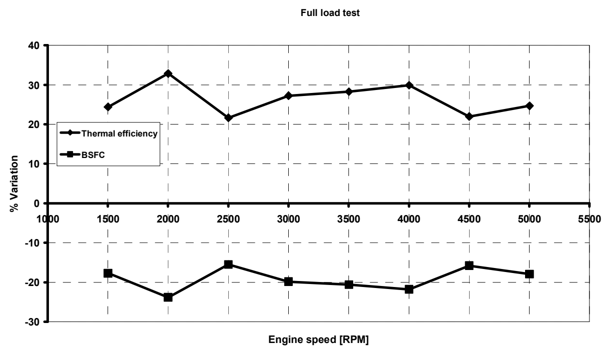


**Fig.8 Variation of thermal efficiency and BSFC for CNG compared with gasoline**

## INVESTIGATION OF ENGINE EMISSIONS CHARACTERISTICS VARIATION

In this section, the effect of fuel type on engine exhaust gases has been considered. The presented results show emissions before catalyst converter. The HC, CO and $NO_x$ emissions data are reported on a brake-specific mass basis. Figures 9 and 10 show relationship of $CO_2$ and brake-specific CO (BSCO) emissions with engine speed for the CNG and gasoline fuels.

 

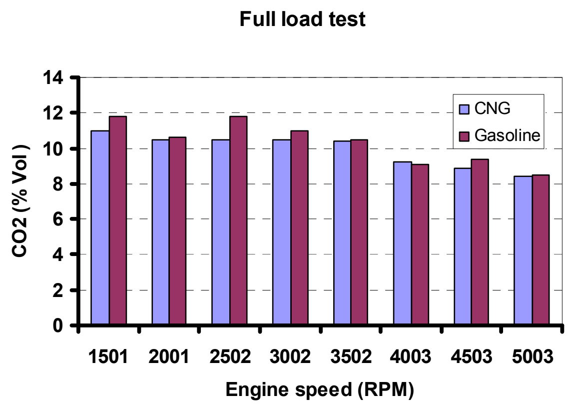


**Fig.9 Comparison of carbon dioxide in exhaust gases for CNG and gasoline fuels**

The amount of $CO_2$ in hydrocarbons combustion is proportional to carbon to hydrogen ratio. The main component of natural gas is methane which has the lowest carbon to hydrogen ratio compared with other hydrocarbons. Therefore, the produced $CO_2$ in CNG combustion is less than gasoline.

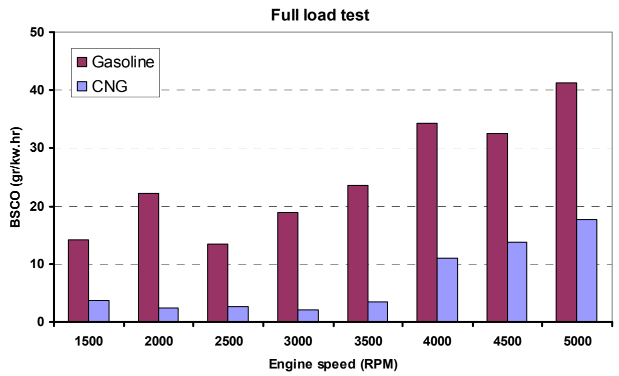


**Fig.10 Comparison of brake-specific carbon monoxide (BSCO) in exhaust gases for CNG and gasoline fuels**

The amount of CO is a function of the mixture air-fuel ratio. In fact, as mixture air-fuel ratio becomes closer to stoichiometric condition, the amount of CO emissions becomes less. As shown in Fig. 6 the air-fuel ratio of CNG fuelled engine is closer to stoichiomertric condition, consequently CO emissions are decreased with CNG.

Figure 11 compares the brake-specific total hydrocarbon (BSTHC) emissions for operation with both fuels. There is some reduction in the HC emissions with CNG operation. This reduction is due to: leaner mixture, higher temperatures of combustion and exhaust gases and lower fuel trapping phenomenon in crevices while engine operates with CNG.

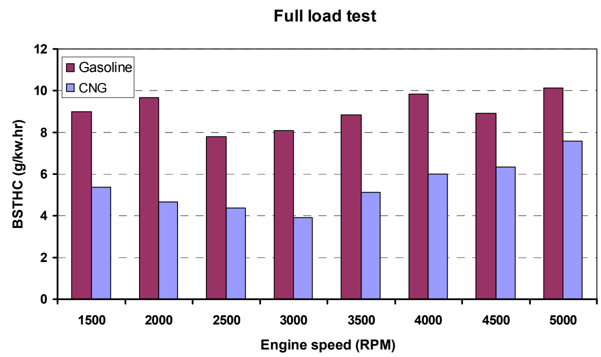


**Fig.11. Comparison of brake-specific total hydrocarbons (BSTHC) in exhaust gases for CNG and gasoline fuels**

Figure 12 presents the brake-specific $NO_x$ ($BSNO_x$) emissions for both fuels. According to the obtained results, the $NO_x$ emissions are increased with CNG fuel. The formation process of the $NO_x$ emissions is severely temperature dependent and this increase is partly duo to the higher natural gas combustion temperature. There are two main reasons for this increase in temperature. The first one is the elimination of the cooling effect of liquid fuel vaporization and the second is the more spark advance used for compensating lower natural gas flame speed which rises peak of combustion temperature. In this work, the spark is between 7 and 13 crank angle more advanced for natural gas than that for gasoline. Furthermore, lean mixture is another reason for more $NO_x$ emissions in internal combustion engines. According to the Fig. 6, the engine is leaner with CNG than with gasoline in average about 13.7% through out speed range. It has a significant impact on the higher $NO_x$. The simple chemical bond of CNG compare to gasoline is also a reason of producing more $NO_x$ than gasoline [14].

There are many ways for reducing the $NO_x$ emissions such as: lean burning strategy [19], spark retarding, Exhaust gas recirculation (EGR) [20] and using suitable bi-fuel catalyst converter [21]. However, these ways may have negative effects on other emissions.

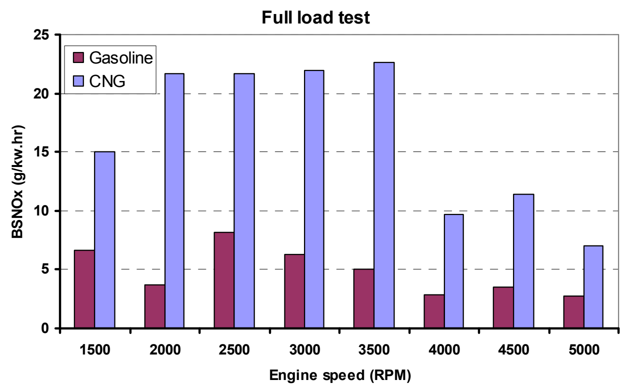


**Fig.12. Comparison of brake-specific nitrogen oxides ($BSNO_x$) in exhaust gases for CNG and gasoline fuels**

## CONCLUSION

Performance and emissions characteristics of a Mazda B2000i bi-fuel (CNG + gasoline) SI engine have been experimentally studied. Individual engine tests have been done in steady state and full load conditions for compressed natural gas and gasoline fuels. All results have been measured before catalyst converter over a wide range of engine speeds. Engine operation with CNG has been compared with gasoline and the following findings have been obtained:

**1-** At all engine speeds, volumetric efficiency has been reduced. The volumetric efficiency reduction is between 10 and 14.2 percent.

**2-** BMEP, torque and power have been decreased between 10.8 and 14 percent.

**3-** BSFC is decreased in range of 15 and 24 percent. Thermal efficiency of CNG fuelled engine is increased between 22 and 33 percent.

**4-** Emissions of CO and $CO_2$ are decreased. CO emissions are decreased between 57 and 89 percent and the $CO_2$ between 0 and 11 percent.

**5-** The HC emissions demonstrate reduction between 25 and 57 percent.

**6-** The $NO_x$ emissions are only ones show increase in their amounts. Their increase is between 126 and 492 percent.

## ACKNOWLEDGMENT

The authors would like to thank Bahman Motor Center for their financial support.

## REFERENCES

[1] Sun, X., Lutz, A., Vermiglio, E., Arold, M., Wiedmann, T., 1998, “The Development of the GM 2.2L CNG Bi-Fuel Passenger Cars”, *SAE Paper 982445*.

[2] Lapetz, J., McCarthny, D., Greenfield, N., Czapski, R., Geftos, T., Rosson, J., 1996, “Development of the Ford QVM CNG Bi-Fuel 4.9L F-Series Pickup Truck”, *SAE Paper 960850*.

[3] Duan, S.Y., 1996, "Using Natural Gas in Engines: Laboratory experience with the use of natural gas fuel in IC engines", *IMechE Seminar Publication, p.39-46.*

[4] Johansson, B., and Olsson, K., 1995, "Combustion Chambers for Natural gas SI Engines part 1: Fluid Flow and Combustion", *SAE Paper No.950469, SAE Trans.*

[5] Johansson, B., and Olsson, K., 1995, "Combustion Chambers for Natural gas SI Engines part 2: Fluid Flow and Combustion", *SAE Paper No. 950517, SAE Trans.*

[6] Evans, R.L., Blaszczyk, J., 1998, "Fast-Burn Combustion Chamber Design for Natural Gas Engines", *Transactions of the ASME (Journal of engineering for gas Turbines and power), Vol.120.*

[7] Swain, M.R., Yusuf, M.J., Dulger, Z., and Swain, M.N., 1993, " The Effect of Hydrogen Addition on Natural Gas Engine Operation", *Society of Automotive Engineers, SAE Paper No.932775.*

[8] Zuo, C., Zhao, K., 1997, “A Quasi-dimensional Model of SI Natural Gas Engines with Prechamber”, *SAE Paper No.972994.*

[9] Evans, R. L., Blaszczyk, J., 1997, “A Comparative Study of The Performance and Exhaust Emissions of a Spark Ignition Engine Fuelled by Natural Gas and Gasoline”, *Proc. Inst. Mech. Engrs. Vol. 211 Part D. D00295.*

[10] Manivannan, A., Tamil porai, P., Chandrasekaran, S., Ramprabhu, R., 2003, “Lean Burn Natural gas Spark Ignition Engines-An Overview”, *SAE Technical Paper Series 2003-01-0638*.

[11] Chiodi, M., Jurgen berner, H., Baragende, M., 2004, "Investigation on Mixture Formation and Combustion Process in a CNG Engine Using a Fast Response 3d cfd Simulation", *SAE Technical Paper Series 2004-01-3004.*

[12] Shamekhi, A. H., and Ghaffari, A., 2004, "An Improved Model for SI Engines", *ASME, ICEF- 2004-818, 2004.*

[13] Volpato, O., Theunissen, F., Mazara, R., 2005, "Engine Management for Multifuel Plus Compressed Natural Gas Vehicles", *SAE Technical Paper Series 2005-01-3777.*

[14] Aslam, M.U., Masjuki, H.H., Kalam, M.A., Abdessalam, H., Mahlia, T.M.I, Amalina, M.A., 2006, "An experimental investigation of CNG as an alternative fuel for a retrofitted gasoline vehicle", *Journal of fuel research, Fuel 85 (2006) 717-724.*

[15] Heywood J.B., "Internal Combustion Engine Fundamentals",*McGraw-Hill Co.,1988.*

[16] Kato, K., Igrahashi, K., Masuda, M., Otsubo, K., Yasuda, A., Takeda, K., and sato, T., 1999, "Developement of engine for natural gas vehicle", *Society of Automotive Engineers, SAE paper No.01-0574.*

[17] Tilagone, R., Monnier, G., Chaouche, A., Baguelin, Y., Chauveron, D.S., 1996, "Development of a High Efficiency, low Emission SI-CNG Bus Engine", *Society of Automotive Engineers, SAE Paper No.961080.*

[18] Kubesh, J.T., Igarashi, D.J., Gugliemo, K.H., and McaCaw ,D. 1995, "Development of an Electronically-Controlled Natural Gas-Fueled John Deere power Tech 8.1L Engine", *Society of Automotive engineers, SAE 951940, p. 788-795.*

[19] Goto, S., Itoh, Y., Higuchi, Y., 1990, "NIGATA Ultra Lean Burn SI Gas Engines-Achieving High Efficiency and Low $NO_x$ Emissions", *SAE Paper No.901608, SAE Trans.*

[20] Bhargava, S., Clark, N., Hildebrand, W., 1998, "Exhaust gas recirculation in a lean burn natural-gas SI engines*", SAE Paper No.981385, SAE Trans.*

[21] Chi-Burn, I., Sang-Ho, K., 1997, "Catalyst technology satisfying low emissions of natural gas vehicle", *SAE Paper No.970744, SAE Trans.*