Journal of the Korean Society of Marine Engineering, Vol. 34, No. 3, pp. 351~359, 2010(ISSN 1226-9549)

Performance Analysis and Emission Characteristics of a Bi-fuel Using Spark Ignition Engine

Md. Iqbal Mahmud[1] · Haeng-Muk Cho†

(Received January 5, 2010; Revised March 8, 2010; Accepted May 4, 2010)

Abstract : Bi-fuel system in a spark ignition engine (SIE) is a rising phenomena in today's automobile technology. In a gasoline driven vehicle, alternatively adoption of compressed natural gas (CNG) could be used as a potential substitute to meet the energy requirement and this is possible by some minor changes in the hardware of the existing engine. Gasoline engine is widely used in the passenger cars, light, medium and heavy duty vehicles but the consumption status of the petroleum is decreasing worldwide and at the same time environmental pollution from automobiles is seriously establishes as a threat for every nation in respect to global warming and climate changes. Now-a-days most vehicles operate using CNG for its popularity stems, clean burning properties and cost effective solution compared to other alternative fuels. It refers as a good gaseous fuel because of its high octane number and self ignition temperature. Though the power output is slightly lesser than the gasoline fuel; its thermal efficiency is better than the gasoline for the same SIE. The research paper highlights the reduction of CO, reasonable outcomes of HC emissions with minor increase in NO_x emissions compared with the gasoline fuel to bi-fuel mode in the SIE that meets the emission challenges.

Key words : Spark Ignition Engine (SIE), Compressed Natural Gas (CNG), Gasoline, Bi-fuel, Emissions

1. Introduction

Emissions from automobiles are a serious issue in today's world. Considering the issue, auto manufacturers are developing the technologies for minimizing the vehicular exhaust. International and governmental regulations of specifying exhaust limit led to researchers and scientists to invent advanced technology to reduce such emissions. Environmental protection and energy conservation have become a major issue at present. In this regard, Kyotoprotocolwas initially adopted on 11 December 1997 in Kyoto,Japantothe United Nations Framework Convention on Climate Change(UNFCCCorFCCC). In 2012 the Kyoto Protocol to prevent climate

* Corresponding author (Department of Mechanical Engineering, Kongju National University, Email : Phone: +82-41-521-9287; Fax: +82-41-551-0376)
1 Department of Mechanical Engineering Kongju National University

cchanges and global warming runs out. To keep the process on the line and effective, at Copenhagen 2009, the parties of the UNFCCC meet to renew the climate agreement and adapt new climate protocol urgently.

At present, in automobile sectors, alternative fuels have great potentials. In this consideration, compressed natural gas (CNG) is a good alternative for traditional vehicle fuels. CNG as a vehicle fuel is very popular to the end user's because of its clean burning properties and cost effective solution compared to other alternative fuels. U.S. Department of Energy (DOE) analyzed that over 6 million vehicles on U.S. highways are flexible fuel vehicles(FFV's). A FFV has the flexibility of running on more than one type of fuel mainly fueled with unleaded gasoline, E85 or any combination of the two [1]. U.S. DOE also supports natural gas vehicle (NGV) research and development to help the United States reach its goal of reducing dependence on imported petroleum as outlined in the Energy Policy Act of 1992. Another benefit of NGV is that it can reduce emissions of regulated pollutants compared to other vehicles [2].

Engines fuelled by CNG emit less Carbon monoxide (CO) and reactive hydrocarbons (non-methane HC) compared to gasoline. But the Oxides of Nitrogen (NO_x) emission may be still not low enough to meet the increasingly stringent emission regulations [3]. Increasing interest in CNG, which is regarded as one of the most promising alternative fuels due to environmental benefits (high H/C ratio and high research octane number)x and HC emissions[5]. The increasing needs in terms of emission control have been requiring both the use of more sophisticated thermodynamic combustion models for spark ignition and diesel engines and the modeling of reacting flows in the exhaust ducts, in order to be able to correctly evaluate the pollutants discharged into the atmosphere [6]. Thus, use of CNG as alternative fuel in a SIE (as bi-fuel mode), could play an important role in achieving global energy security, climate change mitigation and sustainable development in the automotive field.

2. Fuel Characteristic in IC engine

2.1 Fuel properties

CNG contains Figure 70-90% methane with 10-20% ethane, 2-8% propane, and decreasing quantities of the higher HC's up to pentane. The major disadvantage of CNG is the reduced range. Vehicles may have between one to three cylinders (25 MPa, 90-120 liter capacity), and they usually provide Figure 50% of the gasoline range. Gasoline on the other hand contains over 500 hydrocarbons that may have between 3 to 12 carbons, and gasoline used to have a boiling range from 30°C to 220°C at atmospheric pressure. The boiling range is narrowing as the initial boiling point is increasing, and the final boiling point is decreasing, both changes are for environmental reasons [7]. Table 1 shows the ignition and combustion properties of gasoline and CNG fuels [8].

Table 1: The ignition and combustion properties of Gasoline and CNG fuels

Properties	Gasoline	CNG
Motor Octane number	80-90	120
Molar mass (kg/mol)	110	16.04
Carbon weight fraction (mass %)	87	75
Stoichiometric air fuel ratio $(A/F)_s$	14.6	16.79
Stoichiometric mixture density (kg/m^3)	1.38	1.24
Lower heating value (MJ/kg)	43.6	47.377
Lower heating value of stoichiometric mixture (MJ/kg)	2.83	2.72
Flammability limits (vol% in air)	1.3-7.1	5-15
Spontaneous ignition temperature (°C)	480-550	645

2.2 Fuel efficiency

Un-regulated emission components for CNG and gasoline fuel and vehicle technologies listed in Table 2 that shows the efficiency of gasoline and CNG fuels [9].

Table 2: Efficiency of the gasoline and CNG fuels

Fuels	1, 3-butadine in mg/km	C_6H_6inm g/kg	Formaldehyde in mg/kg	Methanol in mg/kg
Gasoline (without catalyst)	11.8	55	43	0
Gasoline	0.6	4.7	2.5	0
CNG	<0.5	0.6	<2	0

Table 3: Effect of fuels on human health

Items	Gasoline	CNG
Toxic to skin	Moderate	No
Toxic to lungs	Moderate	No
Source/feed stock	Petroleum	CNG

About the effect of the petroleum fuels in automobile vehicles, Table 3 shows the characteristics of gasoline and CNG for human health. It is seen that the gasoline has some effect on human health as the CNG has none.

2.3 Fuel Cycle Analysis

The fuel cycle for a given transportation fuel includes some processes such as energy feedstock (or primary energy) production, feedstock transportation and storage (T&S), fuel production, fuel transportation, storage and distribution (T&S&D) and vehicle operations that involves fuel combustion or other chemical conversions. The processes that precede vehicle operations are often referred to as upstream activities; vehicle operations are referred to as downstream activities. Figure 1 shows the stages of a fuel cycle [10]. The processes enclosed in rectangles are production or combustion related activities and those enclosed in ovals are distribution related activities. Spreadsheet-based model for estimating the full fuel cycle energy and emission impacts of alternative transportation technologies. GREET 1.5a model incorporates additional fuel cycles and vehicular technologies, revised modeling approaches for upstream fuel production activities. GREET calculates Btu/mile energy use and g/mile emissions by taking into consideration the energy use and emissions of fuel combustions and non combustion sources.

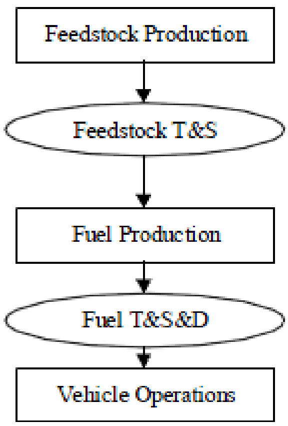

Figure 1: Fuel cycle stages

2.4 NG to CNG pathway

Natural gas can be imported through pipelines or as a cryogenic (super-cold) liquid on special tanker ships, but because this is a lot harder than pouring crude or refined oil into a tanker or a pipeline [11]. Basically, from underground or sub-sea deposits the natural gas is lifting and supplies through the seamless steel pipe to the CNG compressor. Then by the compressor the compression process done and the gas converted into CNG. Figure 2 shows the pathway from NG to CNG may need to be compressed initially to 4000 psi to maintain the 3600 psi tank pressure primarily because the pressure drops during cooling.

CNG compressors can be powered by NG fueled reciprocating engines or electric motor [10]. Figure 2 shows the CNG pathway.

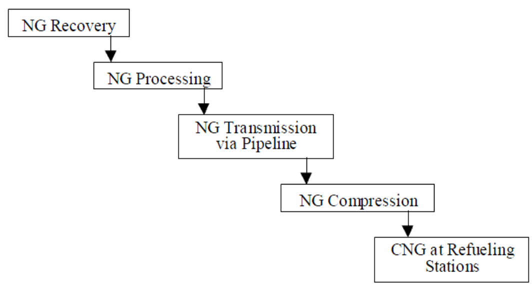

Figure 2: CNG pathway from NG

2.5 Fuel Economy and Emission rate

Several analyses show that NG based fuel in passenger cars also can be used in both light-duty and heavy duty vehicles. The relative changes among the fuels for other vehicle types may be similar to those for passenger cars. Table 4 shows

Table 4: Average emission rates in gasoline vehicle

Parameters	Short term Baseline Vehicle (Gasoline car)	Long term Baseline Vehicle (Gasoline car)
Fuel economy (mpgeg)	22.4	24.0
Exhaust VOC	0.080	0.062
Evaporative VOC	0.127	0.063
CO	5.517	2.759
NO_x	0.275	0.036
Exhaust PM_{10}	0.012	0.010
Brake and Tire wear PM_{10}	0.021	0.021
CH_4	0.084	0.065
N_2O	0.028	0.028

* Values are in miles per gasoline-equivalent gallon (mpgeg) for fuel economy and g/ml for emissions.

Table 5: Fuel economy and emission change rates of NG based fuel in SIE

Option	Fuel economy (mpgeg)	Exhaust VOC	Evaporative VOC	CO	NO_x	Exhaust PM	CH_4	N_2O
Short term options: Relative to NLEV Gasoline Cars Fueled with CG								
SI engine: CNG	-7/0	-40/-80	-90	0/-40	0/-10	-95	900	0/-50
SI engine: LPG	0/5	0/-30	-90	-15/-35	0/-10	-90	60/30	0
SI engine: M85	0/5	0/-15	0/-15	0/-25	0/-10	-60	-50	0
Long term options: Relative to Tier 2 Gasoline Cars Fueled with RFG								
SI engine: CNG/LNG	5/10	-10	-90/-95	-20/-40	0	-80	400	-50
SI engine: LPG	10/15	0	-90/-95	-20/-40	0	-80	10	0
SI engine: M90	10	0	0	0	0	-40	-50	0

* Values are in percent relative to fuel economy and emissions of baseline gasoline vehicles
* A negative number means a reduction and a positive number means an increase. In some cases, two values are presented. The first value represents the incremental scenario. The second value represents the leap-forward scenario.

average emission rates for short term and long term baseline vehicles (gasoline car) and Table 5 shows fuel economy and emission change rates of NG based fuel in the SIE [10].

3. Modification for bi-fuel (CNG) engine

Different technologies and approaches could be applied for the modification of bi-fuel vehicle. Cost, time, performance, fuel ratio, maintenance and emission reductions are the deciding factors for an optimum bi-fuel approach. The ease of adopting a generic bi-fuel conversion system to various SIE is an important consideration for technologist and scientist [9]. Important components that necessary for a bi-fuel system are storage cylinders, three stage gas regulator, gas air mixer, fuel selector switch, solenoid valves, fuel gauge and master shut off valve [12]. Figure 3 shows the bi-fuel system arrangement in a SIE engine.

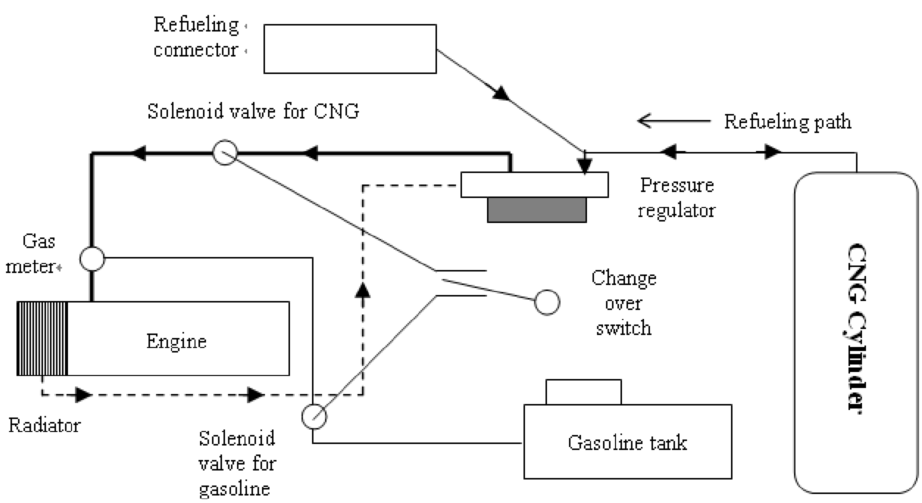

Figure 3: Bi-fuel system arrangement

For the dedication of the CNG engine some parameters need to modify. To take the advantage of higher octane number; higher compression ratio could be obtain, for valve timing, the exhaust valve needs to open lately in power (combustion) stroke. As CNG requires high energy for ignition; therefore strong spark plug is necessary for the ignition system. Also the ignition timing needs to be advanced. Some other modifications/changes are necessary in valve seat head gasket etc. After converting the automobile to CNG fuel, the following steps maintained [13]:

(a) Through the natural gas dispenser, gas is compressed and enters into the vehicle. Therefore, CNG flows into high-pressure cylinders that are located on the vehicle.

(b) When the driver steps on the accelerator, the natural gas leaves the on-board storage cylinder, passes through the high-pressure fuel line and enters the engine compartment.

(c) Gas then enters the regulator which reduces pressure from up to 3500 psi to approximately atmospheric pressure.

(d) The natural gas solenoid valve allows natural gas to pass from the regulator into the gas mixer or fuel injectors.

(e) Natural gas mixed with air flows down through the carburetor or fuel injection system and enters the engine's combustion chambers and finally runs the vehicles

4. Performance and emission analysis

Gaseous fuels are advantageous over gasoline in terms of cold starts. Most of the dedicated engines perform well at low temperature. CNG provides low emissions in the vehicle operating conditions.

These vehicles retain the fuel flexibility (but have limited fuelling infrastructure). The emission data that generally used CNG and gasoline fuels are listed in the Table 6 [9].

Table 6: Emissions from CNG and gasoline fuel

Constitutes (g/km)	Gasoline	CNG
NO_x	0.15	0.13
CO	1.12	0.45
HC	0.15	0.36
Particulates	0.015	0.025

Experimental investigation was performed in order to obtain different analysis with following engine shown in the Table-8 and test is carried out with large range conditions such as in cylinder pressure data analysis with piezoelectric high pressure transducer, crank shaft position measurement with resolution of crank angle etc. The tests have been done for both the fuel under engine's steady state conditions. For engine running on CNG, the set up installed with CNG kits. In Figure 3, necessary kits for CNG set up arrangement have shown (such as solenoid valve, pressure regulator, gas meter, changes over switch etc.) and Table 7 refers typical pipeline quantity gas [12]. Exhaust emission data is taken by exhaust gas analyzer. Data acquisition system recorded the exhaust emissions that received from sensors.

Table 7: Pipeline gas in different sources

Constitute	Source-I	Source-II	Source-III
Methane	84.5	88.24	82.55
Ethane	7.7	8.79	7.67
Propane	2.4	1.59	3.85
I-Butane	0.26	0.29	0.64
N-Butane	0.32	0.28	0.78
I-Pentane	0.18	0.05	0.13
N-Pentane	0.19	0.05	0.14
Hexane	0.17	0.04	0.09
Nitrogen	0.12	0.2	0.07
CO_2	4.23	0.27	0.07

Table 8: Engine specifications

Bore (mm)	84
Stroke (mm)	90
Displacement (cm^3)	1995
Cylinders	4
Compression ratio	8

Performance analysis regarding thermal efficiency and output power is observed. It is seen that in the duel fuel system because of greater heating value and suitable mixing, the higher rate of thermal efficiency is about 10%. In addition, due to low velocity of flame, power output is about 15% less compared to gasoline. And in gaseous state it produces less volumetric efficiency. Figure 4 shows the brake specific fuel consumption (BSFC) with the effect of equivalence ratio at compression ration of 8, RPM 15000 and $^1/_2$ throttle.

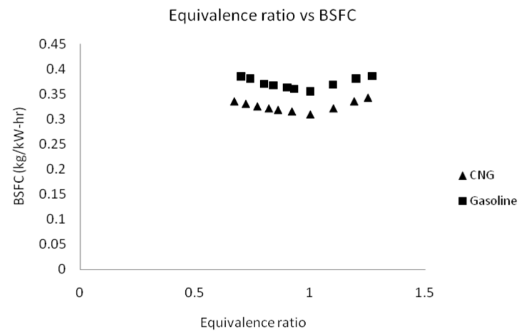

Figure 4: BSFC analysis

On the other hand, analysis of oxides of nitrogen (NO_x), carbon-monoxides (CO) and hydrocarbon (HC) emission are as follows (with the effect of equivalence ratio at compression ration of 8, RPM 15000 and $^1/_2$ throttle):

Experimentally, the NO_x formation rate depends on temperature. Because of low flame temperature of NG and lean air-fuel ration, lower level of NO_x emissions are encountered in SIE. Moreover, if the ignition timing and compression ration is optimized then the NO_x levels are expected to be higher in a dedicated CNG driven vehicle. Figure 5 shows the NO_x emissions for CNG and gasoline fuel in a duel fuel SIE.

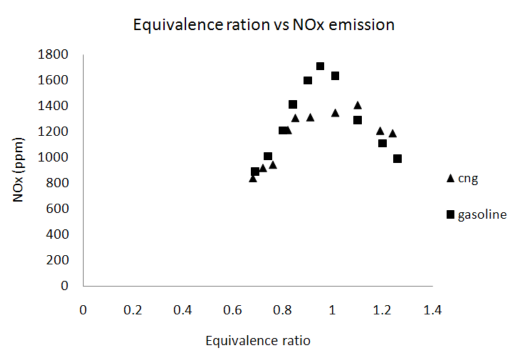

Figure 5: NOx emission analysis

Incomplete combustion inside combustion chamber occurs CO emissions. It depends on the overall mixture strength function and length of time available for combustion. CO emissions with CNG are lower as it can easily form more homogeneous mixture with air and run leaner compared to gasoline engine. In addition, CNG doesn't require cold enrichment so that CO emission is lower during cold start. Figure 6 shows the CO emission for CNG and gasoline fuel in a duel fuel SIE.

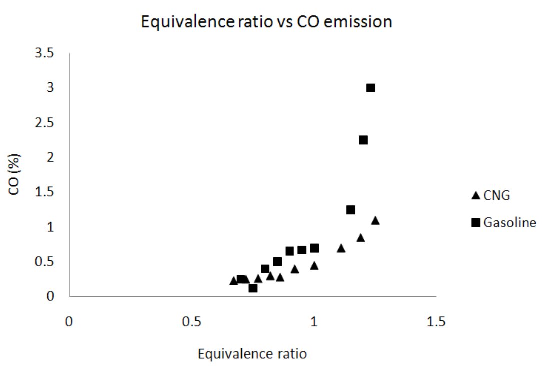

Figure 6: CO emission analysis

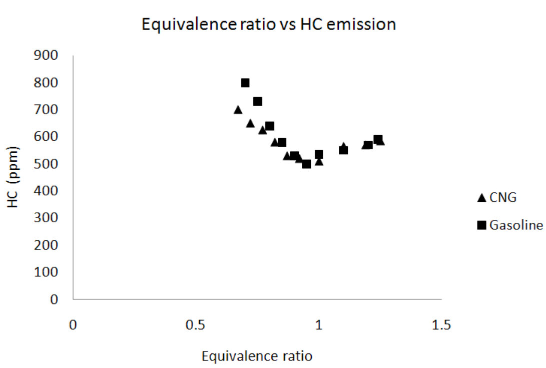

Figure 7: HC emission analysis

As methane is slower to react than other hydrocarbons in lean mixtures and flame speed is low for combustion in the power stroke, total HC emission with CNG tends to high. Besides, non-methane hydrocarbons or reactive HC emissions that are of real concern are considerably lower. It is observed that, the reactive HC emissions are about 18-20% of the total HC emission in case of CNG vehicle. Fig. 7 shows the HC emissions for CNG and gasoline fuel in a bi-fuel SIE.

5. Conclusions

Lean-burn Otto-cycle powered engines can achieve higher thermal efficiencies when compared with stoichiometric. Otto-cycle engines at the expense of higher NO_xandHC emissions. Electronically controlled stoichiometric engines offer the lowest emissions across the board and the highest possible power output especially when combined with exhaust gas recirculation (EGR), turbo charging and inter-cooling and three way catalytic converters. The octane rating of CNG is far greater (more than 120) than gasoline and if handled correctly it can produce same or more power output from an engine provided the CNG is compressed properly and accurate amounts of BTU figures attained. Thus, duel fuel system is reliable for SIE with lower exhaust emission and high efficiency.

References

[1] "Flexible Fuel Vehicles: Providing a Renewable Fuel Choice", Clean Cities Fact Sheet, Energy Efficiency and Renewable Energy, U.S. Department of Energy, 2008.

[2] E. J. Lyford-Pike "An emission and performance comparison of the natural

gas C-Gas plus engine in heavy duty trucks", A Subcontractor Report (contract no. DE-AC36-99-GO10337) by National Renewable Energy Laboratory (NREL), U.S. department of Energy, NREL/SR-540-32863, 2003

[3] Weaver CS. "Natural gas vehicle - A review of the state of art", SAE paper no. 891966, 1989.

[4] H. M. Cho and B.Q. He, "Spark ignition natural gas engines - A review", Energy Conversion and Management 48, pp. 608-618, 2007.

[5] U. Kesgin, "Study on the design of inlet and exhaust system of a stationary internal combustion engine", Energy Conversion and Management 46, pp. 2258-2287, 2005.

[6] Gianluca D'Errico, "Prediction of the combustion process and emission formation of a bi-fuel s.i. engine", Energy Conversion and Management 49, pp. 3116-3128, 2008.

[7] http://stason.org/TULARC/science-engineering/chemistry/27-2-What-are-CNG-LPG-gasoline-kerosine-diesel.html

[8] J.B. Heywood, "Internal Combustion Engine Fundamentals", McGraw-Hill, Singapore, pp. 915, 1988.

[9] Suresh, K. P., Mahanta, P., and Saha, U. K., "Emissions Characteristics of CNG in Automobiles", Proceedings of All India Seminar on Application of Compressed Natural Gas (CNG) as an Automotive Fuel, Guwahati, India, pp. 23-30, 2002.

[10] M. Q. Wang and H. S. Huang "A full fuel-cycle analysis of energy and emission impacts of transportation fuels produced from natural gas", Center for Transportation Research, Energy System Division, Argonne National Laboratory, operated by The university of Chicago (contract no. W-31-109-Eng-38), sponsored by the U.S.department of Energy, 1999.

[11] http://www.altfuels.org/backgrnd/altftype/cng.html

[12] Bhupendra and Haeng Muk Cho "A comparative study of gasoline and CNG as potential fuel in Korea", Proceedings of the Korean Society of Mechanical Engineers(KSME), 2008 fall Annual Meeting, South Korea, 2008.

[13] Haeng Muk Cho and Md. Iqbal Mahmud, "Benefit analysis of CNG as an automobile fuel". Journal of the Korean Society of Clean Technology, vol. 15 no. 1, pp. 1-8, 2009.

Author Profile

Md. Iqbal Mahmud

2002: B.Sc. Engg. (Mech.), Islamic University of Technology (IUT), Bangladesh. 2010: M.Sc. Engg. (Mech.), Kongju National University, South Korea. 2006 till to date: Faculty, Mawlana Bhashani Science and Technology University, Bangladesh.

Haeng-Muk Cho

1991: M.Sc. Engg. (Automotive), Yonsei University, South Korea. 1997: PhD, Hanyang University, South Korea. 1984-1993: Hyundai Motor Company, 1993-1999: Catholic Sangji University, South Korea,1999 till to date: Faculty, Kongju National University, South Korea.