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Evaluation of the exhaust emissions of bi-fuel spark engine

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Abstract: *A computer based data acquisition and control system was used for controlling all variables like revolution per minute RPM and relative air fuel ratio AFR. Exhaust emissions of both of the fuels were analyzed and compared using the DesignExpert 8.0. The analysis of exhaust gases was done by means ofone of the top notch crypton gasanalyzer. Resultswere recorded under steady state operating conditionsby controllingthe revolution per minute (RPM)and relative air fuel ratio (AFR) of the engine. Equipment was assembled to carry out different exhaust emission testsfor simple spark ignition (SI) enginemodified to run on Bi-fuel (Compressed natural gas/ Gasoline) for the required data.*

Keywords: compressed natural gas-direct injection, *gasoline, design expert, gas analyzer,* emission, *eco-friendly* , fuel consumption,

1. Introduction:

" The growing concerns about the harmful effects of conventional fossil fuel (diesel & petrol) emissions have made natural gas a very attractive alternative fuel for the internal combustion engine with advantages of being environmentally friendly, clean burning economical as a fuel and safety properties." [1]. Fossil fuel reserves are annihilating at an alarming rate as a result, the prices of petroleum based fuels are increasing at a rocketing speed. Moreover, their combustion results in emission of very harmful pollutants which ultimately lead to global warming and ozone depletion issues. The role of existing internal combustion engines needs to be reviewed now in the context of these two major issues. The tool used for design and analysis of the experiment was Design expert 8.0.The rest of the paper is organized as follows. In Section 3, a literature review about the origin of CNG and its different aspects are briefly covered. Also the various statistics regarding the usage of CNG around the globe are stated. The data that has been analyzed in this paperis in special perspective of the country which has the second most NGVs around the globe i.e. Pakistan [2] .Section 4 and 5 presents the experimental procedures adopted for the acquisition of data which is then further analyzed usingDesign Expert. On the basis of the statistical data obtained,some conclusion are also drawn and discussed regarding the CNG which conclude this study.

Literature survey

Compressed Natural Gas (CNG) is composed primarily of methane (CH_4), and other Hydrocarbons such as ethane, propane and butane, etc. CNG is produced by compressing natural gas, by about 75% of its volume. It is then stored and distributed in high pressurized vessels, at a pressure range of 200–248 bar (2,900–3,600 psi), usually in cylindrical or spherical shapes. Compressed Natural Gas is one of the alternative fuels found that can be used as a vehicle fuel as a replacement for the gasoline (petrol), diesel, or propane.

According to the NGV Global statistics survey 2012,There are currently more than 17 million natural gas vehicles (NGVs) worldwide), moreover the International Association for Natural Gas Vehicles (IANGV)has projected that thenumber of NGVs will riseat least five-

fold, to more than 65 million natural gas vehicles by the end of 2020 [2][3].however contrary to the facts about NGV fuels being eco-friendly, safe and economical, these remarkable attributes might be marred by the fact that CNG gives slightly inferior road vehicle performance as compared to the equivalent gasoline-fueled vehicles (16 % lower power output) [16, 20].

Natural gas is colorless, shapeless, and odorless in its pure form and is formed deep underground trapped between layers of rock and sand in reservoirs underneath the Earth, like other fossil fuels. Due to its lower density characteristics, natural gas floats above other trapped substances such as crude oil and water. A drilling rig is used to penetrate the Earth surface to draw out the natural gas. The extract is then refined to remove impurities and transmitted through a series of pipelines to processing plants and then sent to transmission companies before reaching the end-user (NaturalGas.org, 2004) [5].

As compared to other fossil fuels, the natural gas is a clean burning fuel and emits lower levels of potentially harmful byproducts into the air [4].

According to the NGV Global Statistics 2012, [3] Worldwide, there were more than 17 million Natural Gas Vehicles by the end of 2012, led by Iran with 3.3 million, Pakistan on second having a 3.10 million , Argentina with 2.2 million NGVs,Brazil possessing about 1.74 million, and India taking the fifth position by having 1.5 million natural gas running vehicles. In Pakistan, CNG vehicleswere initiated in 1992. Currently Pakistan has about 3.70 million NGVs (natural gas vehicles) and about 3600 refueling stations (NGV Communication Group, 2013 December. In Pakistan majority of light duty vehicles have been converted to CNG with bi-fuel spark ignition CNG/gasoline engine.

The potential of natural gas to fuel our cars has not gone unnoticed by the U.S. government [14]. In February 2012, the U.S. Department of Energy announced a $30 million competition aimed at finding ways to "harness our abundant supplies of domestic natural gas for vehicles". The money has since been awarded to 13 research firms, which are working on breakthrough technologies to bring NGVs to the general public.An increasing number of vehicles worldwide are being manufactured to run on CNG. The Honda Civic GX is the only NGV commercially available in the US market [9] but ford has been working on CNG powered pickups and will be releasing these vehicles by the end of 2012. Kojima (2001) [12] had shown that the use of natural gas in buses produces less noise and vibrations compared to conventional fuel. This will lead to longer service life and reduced maintenance costs. Fleet operators also reported a 40% savings on maintenance costs since interval between vehicle check-ups is lengthened (Barbotti CNG, 2002) [11]. Engine performance are also claimed to be superior to gasoline engines since NGVs encounter less knocking and has a wide range of temperature tolerances (Barbotti CNG, 2002) [11].

Properties of Natural Gas. [16, 17, 18, 19]

Stoichiometric air/fuel ratio (mass)	15.7
Octane number	120-130
Lower heating calorific value (MJ/kg)	38-50
Lower heating value Stoichiometric	2.75
Molecular weight (kg/kmol)	16
Minimum Ignition Energy(MJ)	0.26
Laminar flame speed(cm/sec)	37.5
Flammability limits(Vol% in air)	5-15
Adiabatic Flame Temp (K)	2266
Spontaneous ignition temperature(˚C)	633
Auto/self-ignition temperature (°C)	540-560
Molar mass(kg/mol)	17.2
Stoichiometry mixture density (Kg/m3)	1.24
Maximum burning velocity (cm/sec)	38
Carbon weight fraction (mass %)	73.3
Boiling point (Atm press) ˚C	- 162

Current research on the natural gas vehicles found that the engine performance and emission are greatly affected by varying compositions of natural gas. It was also reported that the heating value, efficiency, and concentration of unburnt hydrocarbon and other emission particles would highly depend on the source of supply of natural gas as the main fuel. Also Natural gas vehicles, when designed to run on natural gas alone, are among the cleanest vehicles in the world in terms of emissions [10].

Table 2: Comparison of Thermodynamic Properties Gasoline & CNG [16, 17, 18, 19]

Properties	Gasoline	CNG
Stoichiometric ratio	14.2	15.7
Octane number	96	120-130
Higher heating value (MJ/kg)	45	50.3
Lower heating value (MJ/kg)	42.2	45.9
Density @ 25° C (kg/m3)	749	2.52
Molecular weight (kg/kmol)	106.2	16
Minimum Ignition Energy(MJ)	0.33	0.26

Natural Gas engines suit a wide range of applications which include forklifts, sedans (a car for 4 or more people), light commercial vehicles, heavy duty trucks, buses, marine vessels, even rail locomotives and aircraft.

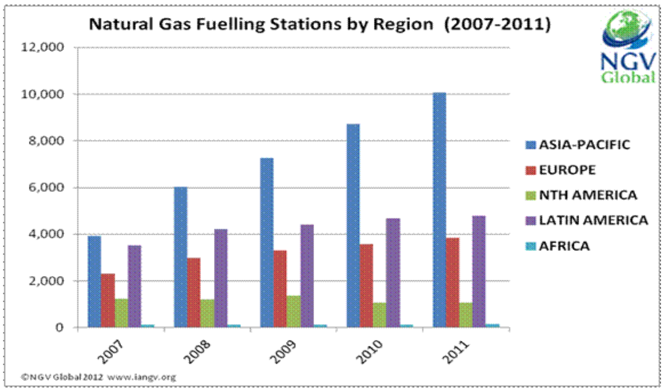
Table 3: Top ten countries with the largest CNG vehicle fleets According to NGV Global Statistics 2012, [3]

Top ten countries with the largest CNG vehicle fleets (millions)					
Rank	**Country**	**fleet**	**Rank**	**Country**	**fleet**
1	Iran	3.3	6	China	1.50
2	Pakistan	3.1	7	Italy	0.74
3	Argentina	2.2	8	Ukraine	0.38
4	Brazil	1.7	9	Colombia	0.40
5	India	1.5	10	Thailand	0.42
World Total = 17.435 million NGV vehicles					

Table 4: NGV regional growth since 2002 (ten years) [3]

Region	**Average % NGV growth since 2002**
Asia-pacific	38.7%
Europe	16.2%
North America	-1.2%
Latin America	14.8%
Africa	16.1%
ALL COUNTRIES	**22.9%**

The above table shows natural Gas Vehicles average growth since 2002, i.e. over a period of ten years in which the Asia-pacific shows the largest growth of NGV's.



www.iangv.org/current-ngv-stats/.

Figure 2: Natural gas refueling stations by region [13] [14]

Statistics of Pakistan's CNG Industry

Due to Government's consumer friendly policy, ample regulatory framework and extensive efforts CNG industry has developed significantly at an unprecedented rate of around 52.5% per annum during the last few years. Currently the country has 3,276,000 total number of register vehicles, out of which there are 3,100,167 (89%) vehicle has been running on CNG. NGV in Pakistan, Currently CNG industry consumes 325 mmscfd natural gas (9% of national gas production**).**

Worldwide various studies have been conducted on the performance and exhaust emission of spark ignition IC engine operated on gasoline but the research in the CNG field is in quite primary stage, and at Pakistan, so far negligible research has been done for detailed comparative analysis of the light dutybi-fuel CNG/Gasoline engine exhaust emissions.This current study compares analytically the exhaust emission of bi-fuel CNG/Gasoline engine.

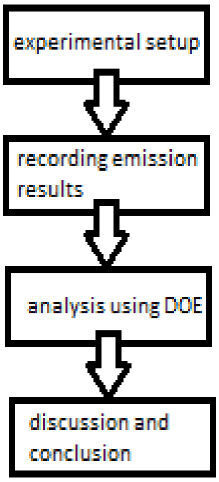


Figure 1.Research Methodology.

Experimental Setup:

Experimental set up consist of various key components. Foremost of them is the Si engine. The engine used is a simple gasoline run IC engine which isD16Z6 (JDMZC), SOHC, VTEC, 16VALVE, 1595CC, 125hp @ 6000 rpm, water cooled and is mass produced by Honda. For the Experiment the same engine was used for gasoline but it was further modified into bi-fuel engine using a CNG kit, RPM meter was also installed on the engine to monitor its RPM and the engine was interfaced with Gas analyzer to monitor the output values of emission, temperature of exhaust gases and engine operating temperature, etc.

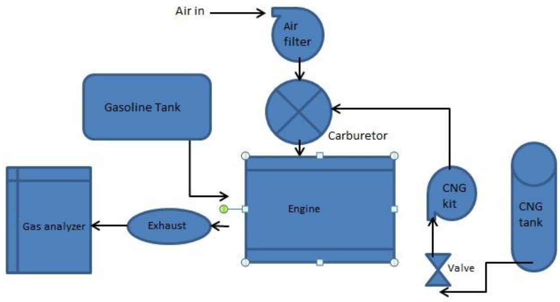


Figure 2 schematic view of the setup.

CNG kit here acts as a regulator.The main function of whichis to reduce the cylinder pressure (about 220 bars) of the gas to engine intake pressure (1 bar), where a High pressure solenoid valve is used for reducing the gas pressure. Engine cannot operate directly on CNG from cylinder without the use of CNG Kit as high pressure of the gas will damage the engine.

The gas analyzer used for this experiment was the top notch Crypton gas analyzer (model: CGP700-C-EN060). It's a computer interfaced analyzer which has different probes and sensors for measuring CO, CO_2, HC, NOx, and other variables and shows all results on a computer screen in tabulated form. A laser printer is also synced with the analyzer and data can be directly collected in such way. It shows values in percentage, parts per million and integers. For exhaust gas analysis, the analyzer has a probe which is inserted in vehicle's silencer and readings are taken at steady RPM and AFR.

- Model:CGP700-C-EN060
- 19" Flat screen monitor
- Battery Tachometer
- Oil Temperature Probe
- Battery life probe
- Ability to find out firing sequence in cylinders, Ignition spark current value in each spark plug, Time belt and cam timing magnitude of vibration in the engine block and other parts etc.
- Laser Printer and wireless mouse.
- Upgradeable for Diesel emission analysis.

The methodology used for acquiring data was that engine required RPM was set and exhaust emissions were recorded against each RPM by keeping temperature and throttle opening constant for both fuels. During experiment engine was in off load conditions i.e. engine shaft was not coupled with dynamometer. On interval of 500 RPM two to three readings were taken for both fuels in stable running condition and average of those readings were used in order to get best optimum emission results. Fig 3 shows the complete layout of experimental setup.

Fig 3 The complete layout of experimental setup.

Results and Discussion

The Composition of CNG we used as a fuel is shown below in table 3. As we now that the Composition of CNG effects exhaust emissions greatly, proper procedures have been implemented to avoid such ordeal.By varying the RPM,different exhaust emissionsare studied for both fuels (CNG & gasoline). Emission of all gases (CO, CO_2, NO_X& HC) will be discussed in detail separately and then results will be concluded from recorded experimental data.

Table 3: Typical composition CNG in Pakistan (SNGPL Composition of CNG)

Composition of CNG at Pakistan	
Component	**Mol %**
Methane	83.96
Ethane	5.72
Nitrogen	6.05
Miscellaneous gases	5.72

1.1 Variation of CO_2 in Exhaust emission against engine speed (RPM):

Fig 4 shows the comparative analysis of emission of CO_2 for both fuels. Results show that emission of CO_2 increases with increasing engine RPM.

The main reason for direct relation of RPM and CO_2 emission is temperature of combustion chamber. In start at lower RPM the temperature of combustion chamber of engine is lower and there is incomplete combustion inside the chamber. As a result less conversion of CO to CO_2 occurs and results in lower emission of CO_2 at lower RPM. By increasing RPM the temperature inside combustion chamberof engine also increases due to complete burning and hence more CO_2 produced at high RPM. (Shown in graph 1.4).It has been shown that CO_2 emission throughout the range of RPM for CNG is 25% lower than that of Gasoline. The reasons for low emission of CO_2 for CNG are that CNG (CH_4) has lower carbon content as compared to gasoline (C_8H_{18}) and in gasoline there is less hydrogen per carbon as compared to CNG.

The ratio of hydrogen to carbon affects the emission of CO_2 in typical combustion. The ratio of carbon to hydrogen atom in CNG (CH_4) is 1: 4 while in gasoline (C_8H_{18}) it is 1: 2.2 which indicate that carbon content in gasoline is much higher than CNG. Therefore, the CO_2 concentration in gasoline is more than that of CNG for full range of speed.so NGV emit very low CO2 (approximately 20-30% lower than a comparable Gasoline vehicle) and volatile organic compounds [16].

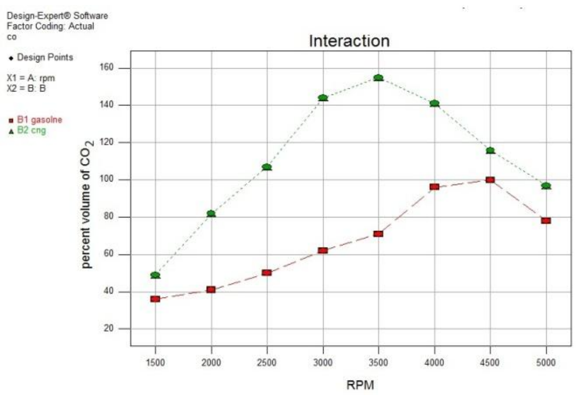


Figure 4 Variation of CO2 in Exhaust emission against engine speed (Rpm)

1.2 Variation of CO (Carbon Monoxide) in Exhaust emission against engine speed (RPM)

When combustion of carbon is incomplete i.e. there is limited supply of air (oxygen) than carbon monoxide is produced as result of combustion. Emissionsof CO_2 and CO are interrelated. At lower RPM the emission of CO_2 is less while emission of CO is more as shown in graph (fig 5) due to lower combustion temperature , incomplete combustion and poor mixing of fuel and Air.

In fig 5 from 1500- 3500 RPM the emission of CO is increasing. Increase in emission of CO for CNG over above RPM rage is due toin complete combustion of fuel in combustion chamber of engine while for gasoline the reason for this increasing behavior is poor mixing of fuel in combustion chamber at lower RPM. Availability of less amount of oxygen (cause low oxidation of carbon) also cause increase in CO emission for both fuels up to 3500 RPM.

Than from 3500 – 5500 RPM in fig 5 the emission of CO gradually decreased. This decline of CO emission is due to increase in combustion temperature, proper burning of fuel, proper mixing of fuel &Air and proper oxidation of carbon.

According to experimental results there is 70-80 percent reduction in % volume of CO for CNG as compared to gasoline. The reason for this reduction is that CNG have higher combustion rate due to proper mixing of Air & natural gas during compression in combustion chamber and also have higher combustion rate which results in lower CO emission as compared to gasoline [23].

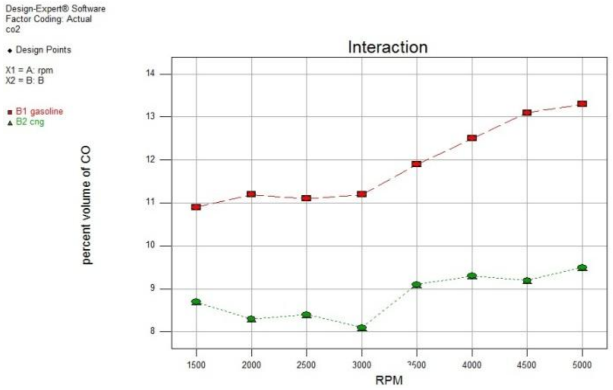


Figure 5 Variation of CO (Carbon Monoxide) in Exhaust emission against engine speed (Rpm)

1.3 Variation of NOx (Nitrogen Oxides) in Exhaust emission against engine speed (RPM)

NOx produce during combustion due to reaction of nitrogen and oxygen at high temperature (endothermic reaction). In Fig6,theemission of NOxincreases up to 4000 RPM and thendecreases onward to 5500 RPM for both fuels.

The reason of this increase in emission of NOx up to 4000 RPM ispeak combustion temperature in chamber, increasingamountof oxygen and nitrogen gas in air intake with increasing RPM and higher temperature and pressure inside the combustion chamber also accelerate the chemical reaction for the formation of NO and NOx.

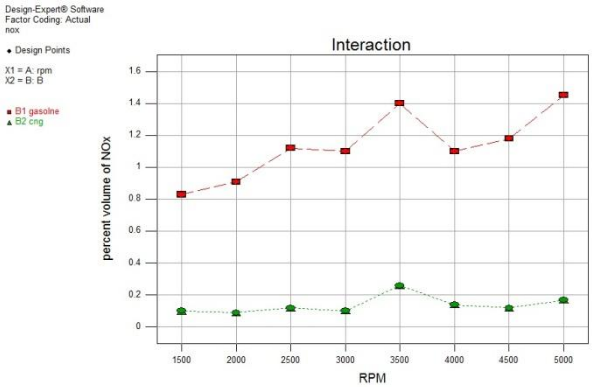


Figure 6 Variation of NOx (Nitrogen Oxides) in Exhaust emission against engine speed (RPM)

The decline in emission of NOx from 4000-5500 RPM is due to low residence time for the fuel in the combustion chamber at such high speed and at high speed the time needed for reaction of NO and NO_2 is shortened and thus decreased the overall NOx emission on high engine speed.

According to our result CNG produce 70% more NOx than Gasoline the reason for this is that CNG has high heat release at premix or have rapid combustion than gasoline which results in more NOx than gasoline. "A fuel that has high heat release at premix or rapid combustion phase and lower heat release rate at mixing control combustion would produce the NOx " [14].

1.4 Variation of HC (Hydrocarbons) in Exhaust emission against engine speed (RPM)

Hydrocarbons (HC) are organic compounds. They emit due to partial burning of fuel. In Fig 7 the emission of HC(Hydrocarbon) gradually decreased with increasing RPM for both fuels. From 1500 to 2500 RPM both fuels have more emission of HC due to incomplete combustion which leads to more emission of unburnt hydrocarbons. Graph (Fig7) depicts that by increase in RPM (from 1500-5500 RPM) cause decrease in HC emission. The reason for this decline of HC at higher engine speed (RPM) is due to proper mixing (during compression stroke) and complete burning of fuel.

According to the data CNG emits 45% less hydrocarbon than gasoline throughout the engine speed. The reasons are that gasoline has complex structure (C_8H_{18}) than CNG (CH_4), so more by-products (organic compound) form during gasoline combustion as compared to CNG and gasoline also has poor mixing as compared to CNG, Which result in incomplete combustion which leads to more HC emission.

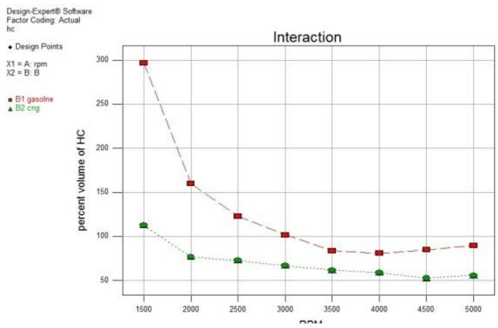


Figure 7 Variation of HC (Hydrocarbons) in Exhaust emission against engine speed (RPM)

<u>Conclusion:</u>

2.1 Achievement of objectives

A comparative study was performed using the emissions tests of engine by converting it into bi-fuel. With CNG as an alternative fuel over Gasoline in terms of exhaust emission of CO, CO_2, HC and NOx by running engine at different speed and Relative Air Fuel Ratio.

The findings of experimentperformed on the basis of RPM arethat there is reduction in emission of percent volume of CO by 88% and one forth in case of CO_2 as compare to gasoline. Emission of hydrocarbon (HC) for CNG is also 45 %(PPM) less as compared to gasoline. The exception is emission of NOx which is 73% (PPM) more in case of CNG as compared to gasoline. On the basis of which, it is concluded that CNG has comparatively less exhaust emission of Carbon monoxide (CO), Carbon dioxide (CO_2)and Hydrocarbons (HC) as compared to gasoline except for the exhaust emission of NO_X which is more in case of CNG as in gasoline. The analyses also lead to the conclusion that CNG can play a vital role as an alternative eco-friendly fuel for IC engines which have comparatively a very small effect on the global warming and ozone depletion as compared to gasoline's.

- NOx is formed by oxidation of molecular nitrogen. During combustion at high flame temperatures, nitrogen and oxygen molecules in the inducted air breakdown into atomic species which react to form NO. Some NO_2 is also formed and NO and NO_2 together are called as NOx.
- CO results from incomplete oxidation of fuel carbon when insufficient oxygen is available to completely oxidize the fuel. CO rises steeply as the air-fuel (A/F) ratio is decreased below the stoichiometric A/F ratio.
- HC originates from the fuel escaping combustion primarily due to flame quenching in crevices and on cold chamber walls, fuel vapor absorption in the oil layer on the cylinder and in combustion chamber deposits, and presence of liquid fuel in the cylinder during cold start.

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