# EXPERIMENTAL ANALYSIS OF GASOLINE AND CNG IN A SI ENGINE FOR PERFORMANCE AND EMISSIONS

A Major Dissertation Submitted in partial fulfillment of the
Requirements for the award of the degree of

**Master of Engineering**
In
**Thermal Engineering**
By


**RAJNISH BAIRWA**
**(University Roll No. 8580)**


Session 2009-11

Under the Supervision of

**PROF. S. MAJI** **Dr. AMIT PAL**


**Delhi College of Engineering**
**Department of Mechanical Engineering**
**Faculty of Technology**
**University of Delhi**
**Delhi-110042**

# STUDENTS’ DECLERATION

I, hereby declare that the dissertation entitled **“EXPERIMENTAL ANALYSIS OF GASOLINE AND CNG IN A SI ENGINE FOR PERFORMANCE AND EMISSIONS”,** being presented here in the partial fulfillment for the award of the Degree of Master of Engineering (Thermal Engineering), is an authentic record of my own work carried out by me under the guidance and supervision of Prof. S. Maji, Professor and Dr. Amit Pal, Assistant Professor, Department of Mechanical Engineering, Delhi College of Engineering, Delhi.

I, further declare that the dissertation has not been submitted to any other Institute/University for the award of any degree or diploma or any other purpose whatsoever.

June, 2011

**Rajnish Bairwa**

University Roll no. 8580

Master of Engineering

(Thermal Engineering)

# CERTIFICATE

Date**:** __________

This is to certify that the dissertation entitled **“EXPERIMENTAL ANALYSIS OF GASOLINE AND CNG IN A SI ENGINE FOR PERFORMANCE AND EMISSIONS”,** submitted by **Mr. Rajnish Bairwa**, 11/THR/09, **(University Roll. No.8580)** in partial fulfillment of the requirements for the award of the Degree of Master of Engineering in Thermal Engineering, is an authentic record of student’s own work carried out by him under our guidance and supervision.

This is also certified that this dissertation has not been submitted to any other Institute/University for the award of any degree or diploma.

**Prof. S. Maji**

**Professor**

**Dr. AMIT PAL**

**Assistant Professor**

**Department of Mechanical Engineering**

**Faculty of Technology**

**University of Delhi**

**Delhi-110042, INDIA**

**2011**

# ACKNOWLEDGEMENT

It is distinct pleasure to express my deep sense of gratitude and indebtedness to my learned supervisor **Prof. S. Maji, Professor and Dr. Amit Pal, Assistant Professor** in the Department of Mechanical Engineering, at Delhi College of Engineering, for his invaluable guidance, encouragement and patient review. His continuous inspiration only has made me complete this major dissertation.

I would like to thank Sh. Manmohan, Sh. Lalit Kumar & Sh. Vijay Hingorani of I.C. Engine laboratory for extending their kind support and sharing their valuable time for the completion of the project.

I am thankful to my all teachers, classmates and friends for their unconditional support and motivation during this project. It is a great opportunity for me to extend my heartiest felt gratitude to everybody who helped me throughout the course of this dissertation in anyway.

**Rajnish Bairwa**

ME (Thermal)

Univ. Roll no:-8580

# ABSTRACT

It is well known, that fossil fuel reserves all over the world are diminishing at an alarming rate and a shortage of crude oil expected at the early decades of this century. Probably in this century, it believed that crude oil and petroleum products become very scare and costly to find and produce. Gasoline and diesel will become scarce and most costly. Alternative fuel technology, availability and use must and will become more common in the coming decades. Any researchers did the several researches to substitute fossil fuel oil to another alternative fuels and one of it is used natural gas for the low emissions and sustainable fuel energy. Natural gas found in various locations in oil and gas bearing sand strata located at various depths below the earth surface. The gas is usually under considerable pressure and flows out naturally from the oil well. In addition to this, the deteriorating quality of air we breathe is becoming another great public concern and tighter regulation of both local and global emissions from engines anticipated. Natural gas is the most favourable for fossil fuel substitute. This paper is will to review the application of compressed natural gas (CNG) as an alternative fuel and the effect in engines performance and emissions. The review result shows that the CNG is the low emissions and the performance is not too decreasing than liquid fuel.

We have done an experiment by using compressed natural gas (CNG) as the main fuel instead of gasoline in a 4-cylinder, 4-stroke spark ignition Wagon-R car engine at different loading conditions. The engine was converted to computer integrated bi-fuelling system from a gasoline engine, and operated separately either with gasoline or CNG. A personal computer (PC) based data acquisition and control system was used for controlling all the operation. A detailed comparative analysis of the engine performance and exhaust emissions using gasoline and CNG has been made. It is observed that the CNG shows low power, low brake

specific fuel consumptions, higher efficiency and lower emissions of CO, $CO_2$, HC but more NOx compared to gasoline.

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# NOMENCLATURE

Symbols

| | | |
|---|---|---|
| $A$ | $m^2$ | area exposed to heat transfer |
| $A_h$ | $m^2$ | hemispherical cylinder head area |
| $A_p$ | $m^2$ | Flat piston crown area |
| $A_f$ | $m^2$ | mean flame front surface area |
| $c_p$ | kJ/kg K | specific heat at constant pressure |
| $c_v$ | kJ/kg K | specific heat at constant volume |
| $h$ | kJ/kg, | specific enthalpy, |
| | $W/m^2K$ | heat transfer coefficient |
| $M$ | kg/kmol | molecular weight |
| $Q$ | kJ | heat transfer |
| $P, p$ | kPa | Pressure |
| $p_r$ | kPa | working fluid pressure |
| $p_m$ | kPa | motoring cylinder pressure |
| $R$ | kJ/kg K | gas constant |
| $r$ | - | compression ratio |
| $s$ | kJ/kg K | specific entropy |
| $T$ | K | Temperature |
| $u$ | kJ/kg | internal energy |
| $V$ | $m^3$ | Volume |
| $V_c$ | $m^3$ | clearance volume |
| $V_d$ | $m^3$ | displaced volume |
| $V_r$ | $m^3$ | working fluid volume |
| $V$ | $m^3/kg$ | specific volume |
| $w$ | m/s | average cylinder gas velocity |
| $Y$ | - | mole fraction |

## Greek Symbols

| | | |
|---|---|---|
| $\theta$ | ˚CA | crank angle |
| $\emptyset$ | - | equivalence ratio |
| $\rho$ | kg/ $m^3$ | density of gas |
| $\omega$ | rad/sec | angular velocity |
| $\tau_b$ | sec | time constant |

## Abbreviations

| | |
|---|---|
| CNG | compressed natural gas |
| PC | personal computer |
| ICE | internal combustion engine |
| NG | natural gas |
| Tsfc | trillion standard cubic feet |
| WOT | wide open throttle |
| NGV | natural gas vehicle |
| CNG/DI | direct injection compressed natural gas engine |
| ICU | ignition control unit |
| EGR | exhaust gas recirculation |
| SI | spark ignition |
| TWC | three way catalytic |
| A/F | air fuel ratio |
| BMEP | brake mean effective pressure |
| BSEC | brake specific enrgy consumption |
| BSFC | brake specific fuel consumption |
| BTDC | before top dead center |

| | |
|---|---|
| BTE | brake thermal efficiency |
| CA | crank angle |
| MAP | manifold absolute pressure |
| MBT | maximum brake torque |
| TDC | top dead center |
| PPM | particles per million |
| SA | spark advance |
| RPM | revolution per minute |
| LPG | liquefied petroleum gas |
| LNG | liquefied natural gas |
| BP | brake power |
| CO | carbon mono oxide |
| HC | hydro carbons |
| $CO_2$ | carbon dioxide |

# 1. INTRODUCTION

## 1.1 Overview

It is well known fact that fossil fuel reserves are becoming exhausted at an alarming rate. Moreover, the combustion of such fuels results in the emission of noxious pollutants which threaten the very survival of life in this planet. The role of existing internal combustion engines needs to be reviewed now in the context of these two major crises in present. In view of the versatility of internal combustion engines, they will continue to dominate the existing transportation sector. There is a considerable limitation for the battery and fuel-cell powered vehicles with regard to range and acceleration. Under such circumstances it becomes a necessity that environment friendly technologies should be developed and alternatively-fuelled internal combustion engines be designed to ensure safe survival of the existing engine technology. Apart from the limited life period, the other problem with the unrestricted combustion of fossil fuels is the level of $CO_2$ emission into the Earth's atmosphere. There are various alternative fuels e.g. CNG, LPG, Hydrogen, Methanol, Ethanol, Biogas, Producer gas, and Vegetable oils etc. that are being seriously investigated in several parts of the world [1].

Over the past decade, alternative fuels have been studied for the possibility of lower emission, economy, better (more secure) fuel availability and lower dependence on crude oil generated fuels. Before any alternative fuels could be used as an alternative to petrol or diesel, it has to full fill some criteria. Stratton has listed some suitability factors that would support alternative fuel to become a choice over petroleum. It is necessary to finalize the decision of alternative fuel type usage based on the suitability of each alternative fuels. Natural gas, however, has many advantages compare to other alternative fuels. The Dennis

Dart, one of the United Kingdom bus manufacturers, has already evaluated eight promising alternative fuels [2].

Natural gas as a fuel for spark-ignition engines offers the potential for extremely low emissions. The evaporative emissions are essentially eliminated and the exhaust emissions can be extremely low. Unfortunately, first generation compressed natural gas (CNG) conversion kits (gas mixers without feedback control) do not always achieve low exhaust emissions (Matthews 1996). To realize the low emissions potential of natural gas, electronic engine fuel metering systems, and even catalysts formulated specifically for natural gas, are required. The primary emissions problem associated with natural gas is that the volatile organic compounds (VOCs) in the exhaust are primarily unburnt methane, a relatively inert hydrocarbon (HC). This makes it relatively innocuous as far as tropospheric ozone production is concerned, but also makes it difficult to oxidize in the exhaust system. Some current and future VOC emissions regulations specify non methane organic gas (NMOG) levels, and the total hydrocarbon (THC) levels do not dictate whether the vehicle is in regulatory compliance. Because CNG is introduced into the engine as a gas, cold starting the engine does not require overfueling **(**as in the case of liquid-fuelled engines), and the emissions produced while the catalyst(s) are warming up are lower than they would be if overfueling was required. Natural gas combustion in engines produces emissions that respond qualitatively the same as gasoline to the various engine operating parameters. Each component of interest is discussed briefly here [3].

The country's energy demand is expected to grow at an annual rate of 6.8 per cent over the next couple of decades. Most of the energy requirements are currently satisfied by fossil fuels like coal, petroleum based products and natural gas. Domestic production of crude oil can only fulfil 25-30 percent of national consumption rest we are importing from other countries. In these circumstances bio fuels are going to play an important role in meeting India's growing energy needs. Bio fuels offer an attractive alternative to fossil fuels, but a consistent scientific framework is needed to gasoline and diesel will become scarce and most costly. Alternative fuel; technology, availability and use will become more common in the coming decades. Researchers are engaged in finding the substitute of fossil fuel replaced with alternative fuels. The great problems of the world in the internal combustion engines usage until today are focuses on environment protection and most optimum consumption of available fuels. Presently in IC engines mainly gasoline and diesel engines are used to generate the power for industries and transportations [5].

The alternative fuels can be used in place of gasoline and diesel to make friendly environment, high power and efficient in fuel consumption, but presently this needs a lot of research work for the usage, storage and supply systems of alternative fuels. Natural gas is one of the proven alternative fuels which are found in various locations in oil and gas bearing sand strata located at various depths below the earth surface. The natural gas is usually under considerable pressure and flows out naturally from the oil well. Natural gas is the most favourite for fossil fuel substitution. It has been recognized as one of the promising alternative fuel due to its substantial benefits compared to gasoline and diesel. The advantages include lower fuel cost, higher octane number and cleaner exhaust gas emissions. Therefore, the numbers of vehicle powered by compressed natural gas engine are growing rapidly [4].

The power to weight ratio of the ICE is much more than that of the battery powered or fuel cell operated vehicles [7]. These factors have led scientists and researchers to develop environment-friendly technologies, and to introduce more clean fuels like natural gas (NG) to power ICE for ensuring the safe survival of the existing engine technology. The world’s total reserve of NG as of January 1, 2004 was 6,076 trillion standard cubic feet (Tscf) and on the basis of current consumption rates, it is adequate for almost 65 years [8]. There are many merits of compressed natural gas (CNG) as an automotive fuel over conventional fuels [9-10]. Due to some of the favourable physio-chemical properties [11] of CNG, the gasoline run spark ignition (SI) engines can be retrofitted to CNG operation quite easily with the addition of a second fuelling system [6].

Alternative fuel technology, availability and use must and will become more common in the coming decades. Any researchers did the several research to substitute fossil fuel oil to another alternative fuels and one of it is used natural gas. Natural gas is found in various locations in oil and gas bearing sand strata located at various depths below the earth surface [13]. The natural gas is usually under considerable pressure and flows out naturally from the oil well. In addition to this, the deteriorating quality of air we breathe is becoming another great public concern and tighter regulation of both local and global emissions from engines is anticipated [14]. Therefore, the number of vehicle powered by CNG engine was growing rapidly [15, 16]. According to [15,17 and 18] the problems needed the new design, research and technology to found the new design of the new engine or its component so it can use of the alternative fuels another gasoline and diesel, protect and friendly with the environment, high power and efficient in fuel consumption [12].

The necessity of fuel has gained the ground for adaptation of suitable energy policy for the transportation sector in order to balance the demand and supply of oil and to contain the overall release of the greenhouse gases with the eventual undesirable environmental impacts. Energy policy and planning with the related orientation have become a very important public agendum of most developed and developing countries nowadays, as a result of which, the governments are encouraging the use of alternative fuels of petroleum oil in the automotive engines. Solar powered car are still not market adaptive as it requires more dedicated design features. Hydrogen fuel has low volumetric efficiencies and frequent pre ignition combustion event because the power densities of premixed or port-fuel-injected hydrogen engines is significantly lower than gasoline [20]. Many academic researchers on the hydrogen economy have queried the rationale on why hydrogen might not be the best alternative transport fuel, including safety, cost and overall efficiency [21,22]. On the contrary, biodiesel and bio ethanol require no engine modification for smooth operation, but they create various problems in the long term operation and in the higher percentage usage, especially when bio fuels are mostly derived from vegetable oils and crops-seeds. These alternatives are strongly criticized for its environmental impact and phenomenal threat to food security [19, 23-25].

Lots of works have been done on engine operating with these fuels; few numbers of publications have compared some of these fuels together [28-33]. Methane, the main content of natural gas (up to 96%), is the most common alternative fuel and is one of the cleanest burning fuels [30]. It can be used in the form of compressed natural gas (CNG) or liquefied natural gas (LNG) to fuel vehicles. Dedicated natural gas vehicles are designed to run on natural gas only. Dual-fuel or bi-fuel vehicles are capable of operating on either gasoline or natural gas. That allows alternative fuel usage which is more economical without sacrificing vehicle operating range and mobility with wide-spread availability of gasoline or diesel [30]. Ethanol and methanol are alcohol- based fuels made by fermenting and distilling starch crops, such as corn. Both ethanol and methanol produce less emission than gasoline [31]. In Brazil, ethanol is well known as a clean, economic and available fuel for vehicles. But engines work on alcoholic fuel will experience a decrement in brake torque and power compared to gasoline.

Propane or liquefied petroleum gas (LPG) is a clean-burning fuel that can be used to power internal combustion engines (ICEs). LPG fuelled vehicles produce fewer toxic and smog-forming air pollutants [26].

The current world crisis such the war in Iraq and the tense of Iran nuclear program with certain country make the fossil fuel price increase. In the other hand, fossil fuel contribute a large pollution is a large problem. Both derivatives from the hydrocarbon fuel itself like carbon dioxides and impurities like heavy metals, sulphur, and uranium contribute to the pollution. The exploitation of full potential of alternative fuels, as means of reducing exhaust emissions irrespective of whether they are renewable or not requires dedicated engines rather than retrofitted ones, or bi-fuels ones or dual-fuels ones. Obviously, a dedicated engine requires extra cost compare to retrofitted or other type of natural gas vehicles and also require adequate fuel distribution network. It makes the dedicated engine uncompetitive and impractical at the present days. However, as the liquid fossil fuels will be finished, the research of applying natural gas fuel on engine vehicle will be an important activity. Natural gas is being used mainly in road transport; both compressed and liquefied, used also in other modes of transport, although rarely so far 35]. It is used in water transport (LNG tankers, ferries, CNG pleasure boats), and rail transport (LNG shunting locomotives. As the natural gas is being environmentally friendly, natural gas can be used in enclosed areas for forklifts in storerooms, or anywhere where clean air is a priority [36]. Natural gas, commonly referred to as gas, is a gaseous fossil fuel consisting primarily of methane ($CH_4$), the shortest and lightest hydrocarbon molecule. It is lighter than air, and so tend to dissipate. Explosive concerns with CNG used in vehicles are almost nonexistent, due to the escaping nature of the gas, and the need to maintain concentrations between 5% and 15% to trigger explosions. Compressed natural gas, or CNG, is a natural gas under pressure which remains clear, odourless, non poisonous, and non-corrosive. Natural gas can kill, however if it is present in large concentrations and thus reduces the amount of oxygen available in the air, such that amount of oxygen remaining in insufficient to sustain life. Although vehicles can use natural gas as either a liquid or a gas, most vehicles use the gaseous form compressed to pressures above 200bar [34].

The vast majority of fuels currently in use are fossil fuels, essentially natural gas, oil-based fuels or coal. The use of natural gas is primarily restricted to fixed installations and the domestic heating market because of storage difficulties for mobile use. Similarly, coal is predominantly used by fixed installations for convenience. The major fuels for transport are petrol and diesel. Since there has been a driver to replace fossil fuels, many alternative fuels have been proposed for fixed installations as well as transport. Whilst some alternative fuels that have been proposed are essentially small scale or specialised use, many have the potential for general use as substitutes for existing fuels. In this context, “alternative fuel” is taken to mean also a fuel which is currently not used in commercial quantities in specific applications, but could be so used. As an example, natural gas is used on the very large scale for heating and power generation in fixed installations, but is rarely used for automotive purposes. This paper discusses alternative uses for existing fuels, as well as fuels not currently commercially used or available. The alternative fuels that are readily available or easily prepared and identified for potential use are  Ethanol, Methanol, Compressed or liquefied natural gas for transport, Liquefied petroleum gases (propane and butane) for transport, Hydrogen, Waste solvents, Chem-fuel (blended combustible waste from chemical works), Rubber crumb, Bitumen-in-water emulsion, Waste oils, Biomass, Gasified solids, Sewage sludge.

The above list of fuels is not exhaustive, and is those most likely to be acceptable for use in the near future. Clearly some fuels will be acceptable for general use, whilst others will require specialised technology to be useful. Some of these alternative fuels may be considered direct substitutes for conventional hydrocarbon fuels and can be used in existing technology, possibly with minor modifications. Alternative fuels will vary in their use, from use by large corporate bodies, to use by members of the public. Clearly for use by the public, they will have to be relatively simple to use and clean to handle, and be perceived to be safe to make any market penetration. It is unlikely that the public will be attracted to an alternative fuel that is perceived to be difficult to use or hazardous, even if the cost is much lower. For example, gas has superseded solid fuel as the main domestic heating fuel, mainly on the grounds of ease of use, despite there being several domestic gas explosions in the UK each year compared with none for solid fuel heating appliances, and the lower cost of solid fuel [37].Some of the potential fuels used in S.I. engine are discussed below.

### 1.1.1 GASOLINE

Gasoline is a complex mixture of over 500 hydrocarbons that may have between 5 to 12 carbons. Smaller amounts of alkane cyclic and aromatic compounds are present. Virtually no alkenes or alkynes are present in gasoline. Gasoline is most often produced by the fractional distillation of crude oil. The crude oil is separated into fractions according to different boiling points of hydrocarbons of varying chain lengths. This fractional distillation process yields approximately 25% of straight-run gasoline from each barrel of crude oil. It is a translucent, yellow-tinted liquid mixture, derived from petroleum, which is primarily used as a fuel in internal combustion engine. It consists mostly of an aliphatic hydrocarbon obtained by the fractional distillation of petroleum, enhanced with isooctane or the aromatic hydrocarbons toluene and benzene to increase its octane rating. Small quantities of various additives are common, for the purposes of tuning engine performance or reducing harmful exhaust emissions. Some mixtures also contain significant quantities of ethanol as a partial alternative fuel. It is not a genuinely gaseous fuel, unlike, for example, LPG which is stored under pressure as a liquid, but is returned to a gaseous state before combustion. Early refineries used a simple distillation process to separate crude oil into its components according to their boiling points. The petrol produced by this method was only that naturally occurring in the crude oil.  As demand for motor spirit grew, engineers and chemists found that more severe heating of the higher boiling points hydrocarbons broke them down, or 'cracked' them, into smaller, lower boiling hydrocarbons more suitable for petrol production. From 1913, thermal cracking was used to increase petrol production. Substances known as 'catalysts' were later found to do a better job of cracking hydrocarbons than heat alone, by speeding up the reaction and producing a greater yield of higher octane petrol. Petrol is a derivative of petroleum. It is essentially a complex mixture of hydrocarbons that boils below 180 ºC.

Paraffin, such as hexane ($C_6H_{14}$), and octane ($C_8H_{18}$)

• Olefins, such as hexane ($C_6H_{12}$)

•Aromatics such as benzene (CH) and toluene

Petrol can vary considerably in composition, depending upon the source of the original crude oil, and the processes used in production. When there is enough oxygen, hydrocarbons can be burnt to form $CO_2$ and water vapour, releasing heat. Exhaust emissions from petrol-driven cars include, in addition to $CO_2$ and water vapor, hydrocarbons, nitrogen oxides and CO. These latter emissions may be effectively reduced by fitting a three-way catalytic converter that converts these three types of exhaust components into less reactive substances. Volatile organic compounds are also emitted into the atmosphere through evaporation from fuel tanks, carburettors and refuelling stations. These emissions can be reduced by using carbon canisters containing activated charcoal which absorbs these vapours. Evaporation can also be controlled during manufacturing and distribution with double tank roofs, improved tank seals and vapour recovery units. An important element in the efficiency of petrol combustion is the octane number. This indicates the ability of the fuel to resist detonation, which is referred to as engine pinging or knocking. Such detonation is caused by the spontaneous igniting of the fuel and air in the engine cylinders before the spark is fired. Higher octane fuels are less susceptible to detonation and thus prevent engine knock and in turn maintain engine power.

Lead has traditionally been added to petrol as an effective and economic method of boosting octane quality. However, concerns have recently arisen about the possible health effects of lead in vehicle exhaust emissions. Concerns also about atmospheric 'smog' pollution have led to the desire to remove up to 90% of the smog precursors present in engine exhaust gases by the use of catalytic converters. This in turn requires that the petrol be lead free if the catalyst is to function properly. In Australia this resulted in a decision to change to cars which operate on unleaded petrol with a lower octane than previously used, so that changes to refinery configurations, to make up for the octane loss upon the removal of the lead, would not be too extensive. This change is not without its disadvantages, since a lower octane fuel results in a less efficient engine, and an overall increase in carbon dioxide emissions. Some additional $CO_2$ emissions also arise from the changed refining processes. Thus, although the move to unleaded petrol may be successful on a local level from a smog point of view, it is likely to have an increased impact upon global air quality in terms of $CO_2$.

### 1.1.2 CNG

Natural gas was first used as fuel in China. The gas obtained from shallow wells near seepages and was distributed locally through piping made of hollowed-out bamboos. Since then, there are no records on usage of natural gas until the early 17$^{th}$ century in Northern Italy, where it was used as a fuel to provide lighting and heating. As the time moves on the usage of natural gas spread to North America, Canada, New Zealand and Europe. The usage was limited to domestic and industry heating.

When the world turned into the 20$^{th}$ century, the usage of natural gas expanded to most part of Western Europe and USA. Exploration of natural gas source was more active after the post-war years. It became a commercial item in the form of liquefied natural gas for exports and imports. The gas fields or the natural gas resource are mainly found in Asia and Middle

East countries. These include Malaysia, Brunei, Algeria, Libya, Saudi Arabia, Kuwait and Iran. By 1980s, these countries became the main exporters of natural gas.

Natural gas is produced from gas wells or tied in with crude oil production. Natural gas (NG) is made up primarily of methane ($CH_4$) but frequently contains trace amounts of ethane, propane, nitrogen, helium, carbon dioxide, hydrogen sulphide, and water vapour. Methane is the principal component of natural gas. Normally more than 90% of natural gas is methane. Natural gas can be compressed, so it can store and used as compressed natural gas (CNG). CNG requires a much larger volume to store the same mass of natural gas and the use of very high pressure. Natural gas is safer than gasoline in many respects and ignition temperature for natural gas is higher than gasoline and diesel fuel. Additionally, natural gas is lighter than air and will dissipate upward rapidly if a rupture occurs. Gasoline and diesel will pool on the ground, increasing the danger of fire. Compressed natural gas is non-toxic and will not contaminate groundwater if spilled. CNG has higher octane number than petrol. CNG Octane number would range from 120 to 130 octane compare to 93 Octane for gasoline. The engine can be operated at a relatively higher compression ratio, without any abnormal combustion problems, e.g. detonation. Higher self ignition temperature (SIT) of CNG (580°C) compared to gasoline (470°C) results in a lower risk of inflammation or explosion in the event of leakage. Advanced compressed natural gas engines guarantee considerable advantages over conventional gasoline and diesel engines. However, CNG has some advantages compared to gasoline and diesel from an environmental perspective. It is a cleaner fuel than either gasoline or diesel as far as emissions are concerned. CNG is considered to be an environmentally clean alternative to those fuels.

It is more relevant as an alternative fuel for the automotive and transport sector, as it is already well established as a primary fuel for domestic and commercial heating and large scale electricity generation. However, as the bulk density of the gaseous form is very low, it would be necessary to store it either as the compressed gas (CNG) or in the liquefied form (LNG) to make it practical to use it for transport. Biogas produced from the anaerobic digestion of sewage can be purified to about 95% methane and used directly in engines for electricity generation or in the compressed form as compressed biogas (CBG).

Compressed Natural Gas (CNG) is one of the most promising alternatives to traditional fuel energy resources for internal combustion engines of various types. Over two million natural gas vehicles (NGV) are in operation worldwide. The Auto-ignition temperature, Octane rating and Calorific value of methane is much better for use in internal combustion engines compared to gasoline. Natural gas being a gaseous fuel at normal atmospheric conditions has the inherent advantage of high level of miscibility and diffusion with gaseous air, which is essential for good combustion. On the other hand lot of development of the engine fuel system have been dedicated to proper mixing of conventional liquid fuel with gaseous air in modern internal combustion engines. As a result use of CNG in more conventional engines like those using carburettor and older versions of electronic fuel injection system results drastic improvement in exhaust emissions. The emission improvements are less dramatic for engines with sophisticated closed loop fuel supply systems and post engine emission control devices.

**Table 1 Properties of Gasoline and CNG**

| **Properties** | **Gasoline** | **CNG** |
|---|---|---|
| Minimum Ignition Energy(mJ) | 0.24 | 0.29 |
| Flame speed (cm/s) | 41.5 | 42 |
| Quench Gap (cm) | 0.2 | 0.2 |
| Diffusion coefficient | 0.05 | 0.16 |
| Higher Heating Value (MJ/kg) | 47.3 | 55.5 |
| Lower Heating Value (MJ/kg) | 44 | 50 |
| Octane number (Research) | 90-98 | 120 |
| Stoic. A/F ratio mass | 14.6 | 17.23 |
| Flammability in air vol. % | 1.4-7.6 | 5.3-15 |
| Adiabatic Flame Temperature(K) (at stoichmetric ratio) | 2266 | 2227 |
| Auto ignition temperature (K) | 743 | 853 |

## 1.2 Motivation for present work

The sharp rise of conventional fossil fuel price is creating a huge effect on world economy. The issue of environmental pollution created by conventional fossil fuels is becoming more important, as we are getting more concern about the environment of our planet. These concerns as well as emission standards enforced by legislation, have led the research for the use of alternative fuels in different prime movers, including the extensively used internal combustion engines. Fuels, which have been studied for replacing petrol, include - natural gas, compressed natural gas (CNG) liquefied petroleum gas (LPG), hydrogen, bio-gas, HCNG. Considering the energy crises and pollution problems today, investigations have concentrated on decreasing fuel consumption by using alternative fuels and on lowering the concentration of toxic components in combustion products. Also the time of finding suitable fuel and their cost effectiveness are the natural constraints. So there is a need of identification of alternative fuels that can suitably substitute the conventional fuels which can give high performance and can also reduce the emissions.

### 1.3 Organisation of the report

- Chapter 1 includes the properties of CNG and Gasoline as an alternative fuels for S.I engine.
- Chapter 2 includes literature survey.
- Chapter 3 includes study of experimental set up.
- Chapter 4 includes the performance of engine for gasoline and CNG fuel and results and discussion of the experimental work.
- Chapter 5 includes conclusion obtained by the work and recommendation for the future work.
- Chapter 6 includes the references.

# 2. LITERATURE REVIEW

## 2.1 Performance and emission characteristics of spark ignition engine with alternative fuels

The literature survey includes various alternative fuels such as CNG, Hydrogen.

According to **Ismail [38]** it is well known, that fossil fuel reserves all over the world are diminishing at an alarming rate and a shortage of crude oil expected at the early decades of this century. Probably in this century, it believed that crude oil and petroleum products become very scare and costly to find and produce. Gasoline and diesel will become scarce and most costly. Alternative fuel technology, availability and use must and will become more common in the coming decades. Any researchers did the several researches to substitute fossil fuel oil to another alternative fuels and one of it is used natural gas for the low emissions and sustainable fuel energy. The gas is usually under considerable pressure and flows out naturally from the oil well. In addition to this, the deteriorating quality of air we breathe is becoming another great public concern and tighter regulation of both local and global emissions from engines anticipated. Natural gas is the most favourable for fossil fuel substitute. This paper is will to review the application of compressed natural gas (CNG) as an alternative fuel and the effect in engines performance and emissions. The review result shows that the CNG is the low emissions and the performance is not too decreasing than liquid fuel.

**Bakar et al. [2]** finds that the alternative fuels used in gasoline and diesel engines are becoming the subjects of interest today, driven by various new laws pertaining to clean air and/or energy independence. The major alternative fuels under consideration are propane, methanol, ethanol and natural gas. Natural gas was commented by many organizations and government officials as the fuel for the future vehicle. Natural gas clearly has some substantial benefits compared to gasoline and diesel. These include lower fuel cost, higher octane content; lower maintenance cost and produces cleaner exhaust emissions. There are at least two trends in the Compressed Natural Gas (CNG) Engine research. Car manufacturers such as Honda, Ford, Chrysler and John Doo focus their research in converting and modifying the gasoline or diesel engine to be fuelled by the CNG. The trend is just doing the modification. The fuel storage, fuel metering, power train and emission control system, the injector timing, spark advance and the implementation of EGR were included in the car manufacturer's trend. University researchers and the research organizations, however tries to look for into the fundamental research. Area of interests includes flame speed, the combustion process and the burning process. A major problem of the CNG Engine was low in volumetric efficiency, low flame speed, low compression ratio usage, inappropriate air/fuel ratio usage and high ignition temperature and high ignition pressure.

**Aslam and Masjuki [6]** investigated experimentally that the potentials of using compressed natural gas (CNG) as the main fuel instead of gasoline in a 1.5 litre, 4-cylinder, retrofitted spark ignition car engine at different loading conditions have been investigated experimentally. The engine was converted to computer integrated bi-fuelling system from a gasoline engine, and operated separately either with gasoline or CNG using an electronically controlled solenoid actuated valve system. A personal computer (PC) based data acquisition and control system was used for controlling all the operation. A detailed comparative analysis of the engine performance and exhaust emissions using gasoline and CNG has been made. It is observed that the CNG shows low power, low brake specific fuel consumptions, higher efficiency and lower emissions of CO, $CO_2$, HC but more NOx compared to gasoline.

**Jahirul [19]** concluded by making a comparative analysis on engine for performance and exhaust emission on a gasoline and compressed natural gas (CNG) fuelled retrofitted spark ignition car engine. A new 1.6 L, 4-cylinder petrol engine was converted to the computer incorporated bi-fuel system which operated with either gasoline or CNG using an electronically controlled solenoid actuated valve mechanism. The engine brake power, brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature and exhaust emissions (un burnt hydrocarbon, carbon mono-oxide, oxygen and carbon dioxides) were measured over a range of speed variations at 50% and 80% throttle positions through a computer based data acquisition and control system. Comparative analysis of the experimental results showed 19.25% and 10.86% reduction in brake power and 15.96% and 14.68% reduction in brake specific fuel consumption (BSFC) at 50% and 80% throttle positions respectively while the engine was fuelled with CNG compared to that with the gasoline. Whereas, the retrofitted engine produced 1.6% higher brake thermal efficiency and 24.21% higher exhaust gas temperature at 80% throttle had produced an average of 40.84%higher NOx emission over the speed range of 1500e5500 rpm at 80% throttle. Other emission contents (unburnt HC, CO, $O_2$ and $CO_2$) were significantly lower than those of the gasoline emissions.

**Semin [39]** According to him, CNG is a gaseous form of natural gas, it have been recognized as one of the promising alternative fuel due to its substantial benefits compared to gasoline and diesel. Natural gas is produced from gas wells or tied in with crude oil production. Natural gas is promising alternative fuel to meet strict engine emission regulations in many countries. CNG has long been used in stationary engines, but the application of CNG as a transport engines fuel has been considerably advanced over the last decade by the development of lightweight high-pressure storage cylinders. The technology of engine conversion is well established and suitable conversion equipment is readily available. For petrol engines or spark ignition engines there are two options, a bi-fuel conversion and use a dedicated to CNG engine. The diesel engines converted or designed to run on natural gas, there are two main options discussed. There are dual-fuel engines and normal ignition can be initiated. Natural gas engines can operate at lean burn and stoichiometric conditions with different combustion and emission characteristics. In this paper, the low exhaust gas emissions of CNG engines research and development are highlighted. Stoichiometric natural gas engines are briefly reviewed. To keep the output power, torque and emissions of natural gas engines comparable to their gasoline or diesel counterparts. High activity for future green CNG engines research and development to meet future stringent emissions standards is recorded in the paper.

**Cho [40]** By doing thorough theoretical study he expressed that , the operating envelope, fuel economy, emissions, cycle-to-cycle variations in indicated mean effective pressure and strategies to achieve stable combustion of lean burn natural gas engines are highlighted. Stoichiometric natural gas engines are briefly reviewed. To keep the output power and torque of natural gas engines comparable to those of their gasoline or Diesel counterparts, high boost pressure should be used. High activity catalyst for methane oxidation and lean de NOx system or three way catalyst with precise air–fuel ratio control strategies should be developed to meet future stringent emission standards.

**Md. Ehsan [41]** investigated experimentally and finds that Petrol engines can run on natural gas, with little modification. The combustion characteristics of natural gas are different from that of petrol, which eventually affects the engine performance. The performance of a typical automotive engine was studied running on natural gas, firstly at a constant speed for various loads and then at a constant load for a range of speeds and results was compared with performance using petrol. Variation of the spark advance, consisting of centrifugal and vacuum advance mechanisms, was investigated. Results showed some reduction in power and slight fall of efficiency and higher exhaust temperature, for natural gas. The air-fuel ratio for optimum performance was higher for gas than for petrol. This variation in spark requirement is mainly due to the slower speed of flame propagation for natural gas. For both the cases, the best power spark advance for natural gas was found to have higher values than petrol. This issue needs to be addressed during retrofitting petrol engines for running on natural gas.

**Economides [42]** He examined carefully and presented here sources of natural gas, their limitations and potential. As global energy demand rises, natural gas now plays an important strategic role in energy supply. Natural gas is the cleanest and most hydrogen-rich of all the hydrocarbon energy sources and it has high energy conversion efficiencies for power generation. Of more significance is that gas resources discovered but as yet unexploited remain plentiful. The sector is poised for considerable growth over the next two decades and some believe that it may even overtake oil as the prime fuel between 2020 and 2030. There is a fundamental turn towards natural gas which today accounts for about 23% of the world energy demand. Large capital investments in infrastructure to enable increased gas consumption are being made on both demand and supply sides. Several gas-producing countries have embarked upon very ambitious plans for markedly increased gas output. Many new LNG facilities are being built supply chains diversifying and becoming ever more flexible. There is a growing recognition that unconventional sources of gas, such as shale gas, coal bed methane (CBM) and deep tight gas will contribute a significant component of future gas supplies as technologies evolve. Other gas conversion technologies such as GTL and CNG are attracting more serious attention, but energy efficiency, cost and cost inflation remain barriers for these promising alternatives. Natural gas is also competing strongly with other fossil fuels from an efficiency and emissions perspective as the fuel of choice for power generation. However, gas price volatility and security of supply concerns means that some power generators still favour coal and nuclear components in their power generation portfolio. As the cost of carbon emissions have a bigger impact around the world, gas has the potential to increase its share of the power generation market significantly over the coming decade. A rapid growth opportunity exists for natural gas in its potential contribution to transportation either directly or by electrifying the sector. Real and imagined environmental concerns and restricted access for OECD nations to long-term oil reserves are expected to accelerate the emergence of hydrogen fuel cells. Currently available technologies dictate that the most commercially viable source of hydrogen in large quantities is natural gas, particularly methane through the reforming processes that yield synthesis gas (i.e. carbon monoxide and hydrogen). Current technologies, investments and consumption trends suggest that natural gas will be at the centre of a worldwide transformation resulting in a greatly expanded market share of gas in the energy mix for power generation, space heating, petrochemical feed stocks and transportation fuels.

**Bhandari et al.** [**43**] By doing experiments on engine he prepared a comprehensive review of various operating parameters have been prepared for better understanding of operating conditions (spark and compression ignition engines) for natural gas fuelled internal combustion engine. It was estimated that a CNG with range and power equivalent to the gasoline model would be less efficient (25%). The study finally concluded that CNG duel fuel retrofitted vehicle could provide very large CO reduction (80-95%) compared to current gasoline vehicles. The NMHC and NOx emission impacts depended upon conversion techniques. Emission benefits in CNG engine would be greater in dedicated vehicle. The maximum level of CO emission was 0.325 percent. The results showed that an improvement in the performance emission characteristics of CNG fuelled SI engines using specially designed Electro Mechanical fuel systems would be obtained.

**How et al.** [**44**] investigated after doing experiments that the performance of the engine with respect to brake torque, brake power, brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), fuel conversion efficiency and exhaust emissions for gasoline and

CNG fuels under various steady state operations. Reduction of 8-16% brake torque and brake power with CNG operation over a speed range of 1500 to 5000 rpm was obtained. It was found that the maximum brake torque obtained were 115 Nm at 3500 rpm for gasoline and 100 Nm at 3000 rpm for CNG. The BMEP of CNG is 8-16% less than gasoline. In addition, the displacement of air by CNG in the cylinder reduces the volumetric efficiency and consequently causes the BMEP loss. Volumetric efficiency is an important factor in internal combustion engine because lower volumetric efficiency reduces the heating value of cylinder charge, thus decreasing the potential of output power. On average, CNG operation yields 22% improvement in BSFC and 13% higher fuel conversion efficiency (FCE) compared to gasoline. It was also found that CNG operation with sequential port injection achieved lower BSFC and better fuel conversion efficiency compared to mixer type of CNG operation in carburetor system of the same engine where 17-18% less BSFC and 2.90% higher FCE. CNG produces steadily lower unburned hydrocarbon emission throughout the speed range as compared to gasoline. The emission of HC is significantly reduced by 40-87% with CNG operation due to a more complete combustion of CNG as compared to gasoline. In addition, CNG operation shows significantly lower of CO and $CO_2$ emission. It was found that CNG produced less 20-98% and 8-20% of CO and $CO_2$ respectively.

**Srinivasan** [**45**] According to him natural gas contains more than 98% methane. Natural gas can be compressed, so it can be stored and used as Compressed Natural Gas (CNG). NG requires a much larger volume to store while at high pressure, about 200 bar the same mass of natural gas can be stored in a smaller volume in the form of Compressed Natural Gas (CNG). CNG is safer than gasoline in many respects and ignition temperature for natural gas is higher than gasoline and diesel fuel. Additionally, natural gas is lighter than air and will dissipated upward rapidly if a rupture occurs. Gasoline and diesel will pool on the ground, increasing the danger of fire. Compressed natural gas is non-toxic and do not contaminate groundwater if spilled. Advanced CNG engines guarantee considerable advantages over conventional gasoline and diesel engines.

**Pourkhesalian et al. [26]** finds after making analysis that the strict regulation of environmental laws, the price of oil and its restricted resources, has made engine manufacturers use other energy resources instead of oil and its products. Despite the fact that now days alternative fuels are not currently widely used in vehicular applications, using these kinds of fuels will be definitely inevitable in the future. In this paper, a computer code is developed in Mat lab environment and then its results are validated with experimental data. This simulated engine model could be used as a powerful tool to investigate the performance and emission of a given SI engine fuelled by alternative fuels including hydrogen, propane, methane, ethanol and methanol. Also, the superior of alternative fuels is shown by comparing the performance and emissions of alternative fuelled engines to those in conventional fuelled engines. Eventually, it is concluded that volumetric efficiency of the engine working on hydrogen is the lowest (28% less that  gasoline fuelled engine), gasoline produce more power than the all being tested alternative fuels and BSFC of methanol is 91% higher than that of gasoline while BSFC of hydrogen is 63% less than gasoline.

**Baldassarri [46]** investigated that the emissions from a spark-ignition (SI) heavy-duty (HD) urban bus engine with a three-way catalyst (TWC), fuelled with compressed natural gas (CNG), were chemically analyzed and tested for genotoxicity. The results were compared with those obtained in a previous study on an equivalent diesel engine, fuelled with diesel oil (D) and a blend of the same with 20% vegetable oil (B20). Experimental procedures were identical, so that emission levels of the CNG engine were exactly comparable to the ones of the diesel engine. The experimental design was focused on carcinogenic compounds and genotoxic activity of exhausts. The results obtained show that the SI CNG engine emissions, with respect to the diesel engine fuelled with D, were nearly 50 times lower for carcinogenic polycyclic aromatic hydrocarbons (PAHs), 20 times lower for formaldehyde, and more than 30 times lower for particulate matter (PM). A 20–30 fold reduction of genotoxic activity was estimated from tests performed. A very high reduction of nitrogen oxides (NOX) was also measured.

**Hodgson [3]** gives the information that the use of compressed natural gas (CNG) as a transportation fuel has been identified as one strategy that can help ameliorate some problems, which include a growing dependence on imported oil and the persistent contributions that mobile sources make to urban air pollution, associated with the use of conventional petroleum fuels. The attributes and limitations of CNG as a fuel for spark-ignition engines have been presented. The attributes are associated with its high octane rating, low cost relative to other alternative fuels, its availability, the absence of running and diurnal evaporative emissions, and its demonstrated potential for producing extremely low exhaust emissions-particularly if the volatile organic compounds emitted are expressed in terms of reactivity adjusted non-methane organic gases. The limitations associated with the use of CNG include its limited refuelling infrastructure, the cost of refuelling facilities, the cost of on-board fuel storage tanks, and its relatively low energy density. In order for the higher (relative to the gasoline-fuelled baseline vehicle) initial cost of a CNG fuelled vehicle to be recouped by the lower fuel price, CNG is most attractive in high fuel use applications. The use of CNG in small vehicles is especially challenging in that the incremental cost associated with the CNG system typically represents a higher fraction of the total vehicle cost than would be the case with larger, more expensive vehicles. In addition, because small vehicles are typically very fuel efficient, fuel costs may not represent an important factor for the vehicle owner.

**Semin [12]** concluded that CNG has long been used in stationary engines, but the application of CNG as a transport engines fuel has been considerably advanced over the last decade by the development of lightweight high-pressure storage cylinders. The technology of engine conversion was well established and suitable conversion equipment is readily available. For petrol engines or spark ignition engines there are two options, a bi-fuel conversion and use a dedicated to CNG engine. The diesel engines converted or designed to run on natural gas, there were two main options discussed. There are dual-fuel engines and normal ignition can be initiated. Natural gas engines can be operated at lean burn and stoichiometric conditions with different combustion and emission characteristics. In this study, the low exhaust gas emissions of CNG engines research and development were highlighted. Stoichiometric natural gas engines were briefly reviewed. To keep the output power, torque and emissions of natural gas engines comparable to their gasoline or diesel counterparts. High activity for future green CNG engines research and development to meet future stringent emissions standards was recorded in the study.

**Lumato [47]** after doing experiments finds that the amount of harmful exhaust emissions from diesel and petrol engines has been calculated and the reduction on the emissions after conversion to CNG established. It was found that the use of petrol and diesel produces approximately 9861, 1205, 6629 and 219 tonnes/year of CO, $CH_4$, NOx, and PMs, respectively; and that if all Dar Es Salaam city buses were converted into CNG the reduction in these emissions would be 49% of CO, 55% of NOx and 92% of PMs. Also, adoption of CNG would save the foreign currency used to import petrol and diesel as natural gas is produced locally and that there is a large natural gas resources in Tanzania. It was therefore concluded that the CNGV technology is advantageous and suitable for use in Tanzania, starting with the commercial city of Dar Es Salaam. Finally, it was recommended that the Government of Tanzania, through the Ministry of Energy and Minerals, forms a board to coordinate implementation of this project, in collaborations with other stake holders such as natural gas producers and transport authorities.

**Kaleemuddin [48]** has done an experiment on dual fuel single cylinder natural gas engine and finds that the experimental investigations carried and up gradation of 395 cc air cooled engine to dual fuel (CNG/Gasoline) application. The original 395 cc direct injection naturally aspirated, air cooled diesel engine was first converted to run on Gasoline by addition of electronic ignition system and reduction in compression ratio to suit both gasoline and CNG application. CFX software has been employed to calculate and improve the cooling capacity of engine with the use of CNG. Materials of major engine components were reviewed to suit CNG application. The engine was subsequently tuned with dual multi-mapped ignition timing for bi-fuel stoichiometric operation on engine dynamometer and then fitted on a 3-Wheeler vehicle. The vehicle was optimized on a chassis dynamometer to meet the proposed Bharat Stage-III norms. The engine has passed current BS-II emission norms with 48% margin in CO emission and 76% margin in NMHC (Non-Methane Hydrocarbons) and Extensive trials were conducted on engine and vehicle to optimize with CNG kit and minimum loaded three way cat-con to finally to met proposed BS-III norms.

**Molla et al. [49]** concluded from his experimental investigations that among alternative fuels for internal combustion engine, natural gas can be considered as the single largest alternative fuel. Natural gas can substitute totally or partially the liquid fossil fuels (gasoline and diesel). This research work was intended to study the performance characteristics of a two cylinder diesel engine converted to spark ignition (SI) engine to run on 100 percent CNG. In this study the test emissions were measured with the advancement in ignition timing which is very uncommon with other available test reports and this gives new relation of emissions level with ignition timing change. From the experimental results, it is seen that a converted natural gas fulled SI engine can deliver approximately equal output to its diesel counterpart. The combustion of natural gas in CNG fuelled SI engine is found to be more efficient at the equivalence ratio of 0.9. The exhaust gas temperature of natural gas fuelled SI engine is found to be 120 ºC to 180 ºC above that of diesel and petrol engine of similar type. The exhaust gas emissions (CO and HC) of natural gas fuelled SI engine are found to be much lower than their respective admissible limits. Natural gas fuelled engine is friendly to environments for its lower level of air pollution and lower level of green house gas emission.

**Mansha [50**] finds in the present study, the detailed reaction mechanisms were developed and was implemented to predict the formation of pollutant species in compressed natural gas (CNG) fired internal combustion (IC) engine. The proposed mechanisms were developed by coupling the EXGAS (an automatic mechanism generation tool for alkane oxidation) mechanisms with the Leed's NOx mechanism. The simulation results of each proposed mechanism were validated by the experimental measurements for profiles of temperature, pressure and pollutant species (CO, NOx). The rate of production analysis of each mechanism identified the important reactions in each mechanism which contributed to the formation of pollutant species. In spite of some discrepancies, the experimental measurements indicate that Mechanism-IV (consisting of 208 reactions and 78 species) showed closer agreement for each of the predicted profiles of temperature, pressure and pollutant species (CO, NOx).

**Purwaha et al. [51]** According to him vehicular emission is the main contributor to urban air pollution. In line with public concern over the health effects of traffic pollution, regulatory bodies and the public at large have contributed significantly towards the progressive improvement of vehicular emission standards which hopefully alleviate the worsening of our urban air quality. California Air Resource Board (CARB) and the European Commission have introduced a set of stringent emission targets and is anticipated that these standards will become the basis for the similar emission legislation to be introduced all over the world. Natural gas has been considered as the most promising alternative fuel for its cleanliness and abundance. With the growing concern for environment in General and air quality in metropolis in particular, Government of India had entrusted GAIL(India)Ltd, a leading public undertaking natural gas transmission & distribution company, the job of implementation of CNG as alternative fuel for vehicles. GAIL conducted a pilot program in early 1993 in 3 cities namely Delhi, Mumbai and Baroda to understand the technology and to provide the framework for a commercial program. After successful implementation of the pilot program, joint venture companies were formed in Delhi and Mumbai for developing the CNG market. This paper presents the experience, challenges and problems encountered in the development of CNG in India.

**Ristovski [52]** The purpose of this work was to evaluate the physical and chemical properties of emission products from a six cylinder sedan car under a variety of operating conditions, before and after it has been converted to compressed natural gas (CNG) fuel. The specific focus of the measurements was on emission levels and characteristics of ultra fine particles and the emission levels together with the emissions of gaseous pollutants for a range of operating conditions before and up to 3 months after the vehicle was converted are presented and discussed in the paper. The investigations showed that converting a petrol operating vehicle to CNG has the potential of reducing some of the emissions and thus risks, while it does not appear to have an impact on others. In particular there was no statistically significant change in the emission of particles for the vehicle operating on petrol, before the conversion, compared to the emissions for the vehicle operating on CNG, after the conversion. There was a significant lowering of emissions of total polycyclic aromatic hydrocarbons and formaldehyde when the vehicle was operated on CNG, and a reduction of global warming potential was also observed when the vehicle was run on CNG, but the later gain is only at high vehicle speeds loads, and would thus have to be considered in view of traffic and transport models for the region.

## 2.2 Important findings from literature review

1. From the studies reported it could be concluded that in general CNG engines result in lower emissions of toxic compounds, however, for example, one study found that formaldehyde emissions are comparable to emissions from gasoline engines.
2. All the studies conducted showed that CNG emissions have a low ozone forming potential.
3. The range of emissions, levels of individual pollutants from vehicles operating on CNG quoted in the literature were: CO from 0.1 to 12.2 g/km, NOx from 0.05 to 7.5 g/km (the last value is for buses) and $CO_2$ from 290 to 390 g/km.
4. The diesel engine volumetric efficiency and the total fuel consumption per cycle is higher than the port injection dedicated compressed natural gas (CNG) spark ignition engine.
5. The CNG has higher octane number than petrol and therefore permits higher CR that helps in resisting knocking and throttle at intake.
6. In low-load condition for a DF engine, the exhaust is always smokeless; even in case of full-load condition, smoke is still less than that from diesel engine.
7. NOx level is high but the CO level remains low.
8. The maximum automotive engine power produced when running on natural gas will be lower compared to when running on petrol. This should not have very visible effect during normal cruise of a vehicle. However it may increase the time taken by the vehicle to accelerate when
9. Brake mean effective pressures of natural gas engines are limited by knocking and thermal loading. EGR can improve knock limit by reducing combustion temperature.
10. Its use extends petroleum supplies, and there are large quantities of the fuel available in the world.

## 2.3 Objective of present work

1. Experimentally determining the performance characteristics of CNG and gasoline.
2. Experimentally determining the emission characteristics of CNG and gasoline.

# 3. EXPERIMENTAL SETUP

## 3.1 Description of experimental set up

The setup consists of four cylinder, four strokes, Petrol (MPFI) engine connected to eddy current type dynamometer for loading. It is provided with necessary instruments for measurements of combustion pressure and crank-angle. These signals are interfaced to computer through engine indicator for P-θ & PV diagrams. The set up has stand-alone panel box consisting of air box, fuel tank, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and engine indicator. Rotameters are provided for cooling water and calorimeter water flow measurement. Photograph of engine setup, schematic diagram of engine and photograph of gas analyzer is shown in Figure 3.1, 3.2, 3.3 and 3.4 respectively.

The setup enables study of engine performance for brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency, specific fuel consumption, A/F ratio and heat balance. Windows based Engine Performance Analysis software package “Engine soft” is provided for on line performance evaluation. Gas analyzer is used for emission measurements.

The main aim of this experiment is to investigate the effects on performance of gasoline and CNG in four cylinder Wagon R engine.

**Figure 3.1 Experimental setup**

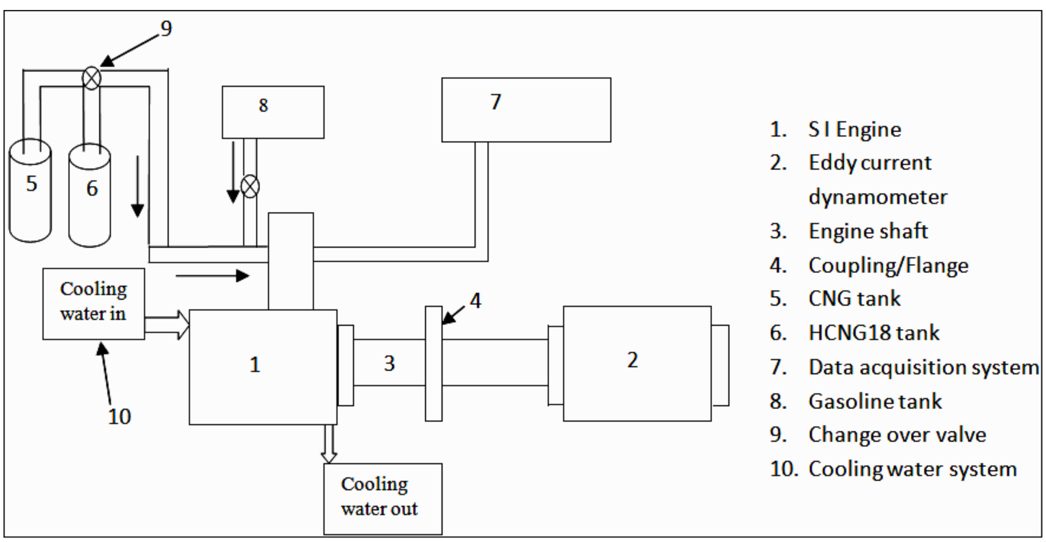



**Figure 3.2 Schematic diagram of engine setup**

**Figure 3.3 Gas Analyser**

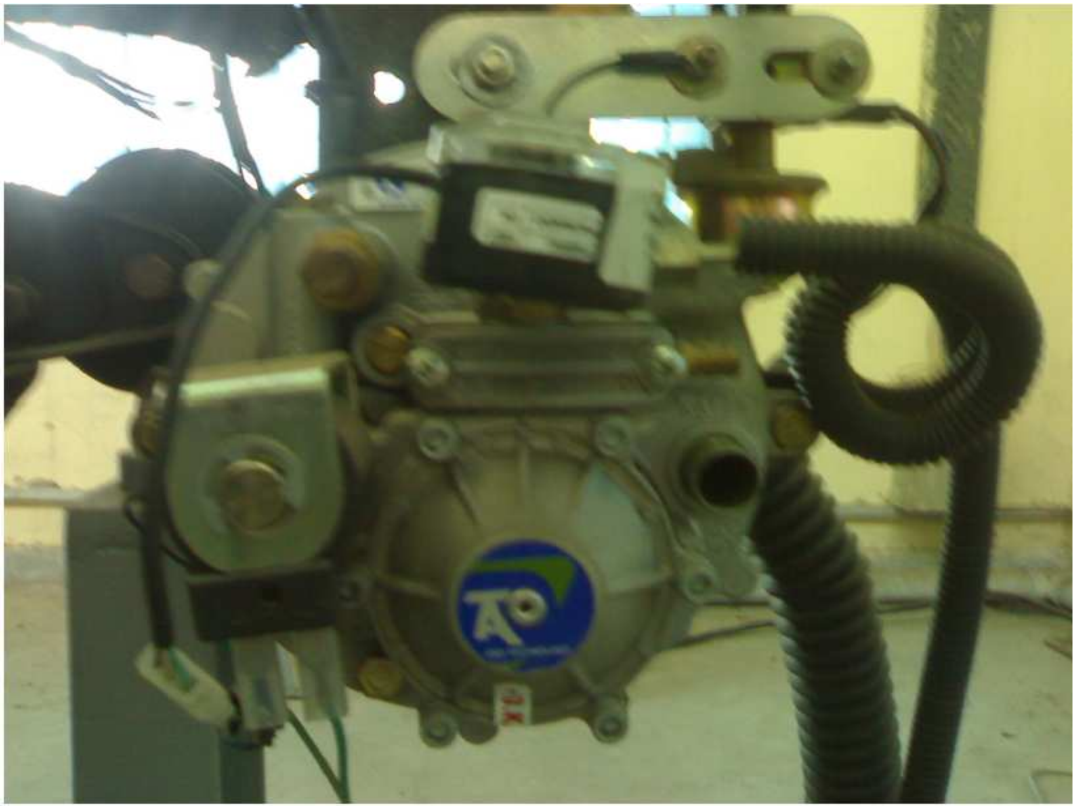


**Fig. 3.4 CNG Conversion Kit**

## 3.2 Engine specifications

| | |
|---|---|
| **Engine** | Make-Maruti, Model Wagon-R MPFI, Type 4 Cylinder, 4 Stroke, Petrol (MPFI), Water cooled, Power 44.5 KW at 6000 rpm, Torque 59 NM at 2500 rpm, Stroke 72 mm, bore 69 mm, 1100 CC, CR 9.4:1. |
| **Dynamometer** | Type eddy current, Water cooled, with loading unit, Make – Saj test plant Pvt. Ltd, Model AG80. |
| **Propeller shaft** | With universal joints, Make Hindustan Hardy Spicer. |
| **Air Box** | M S fabricated with orifice meter and manometer (Orifice Dia. 40 mm). |
| **Fuel tank** | Capacity 15 litre with glass fuel metering column. |

| | |
|---|---|
| **Calorimeter** | Type Pipe in pipe, 25-250 LPH. |
| **Rotameter** | Make-Eureka Model PG 5, Range 25-250 lph, Connection ¾ `` BSP vertical screwed, packing Neoprene. |
| **Rotameter** | Make-Eureka Model PG 9, Range 100-1000 lph, Connection 1`` BSP vertical screwed, packing Neoprene. |
| **Piezo sensor** | Make-PCB Piezotronics, Model HSM111A22, Range 5000 psi, Diaphragm stainless steel type & Hermetic Sealed. |
| **Crank angle sensor** | Make-Kubler-Germany Model 8.3700.1321.0360, Dia: 37 mm shaft size: size 6mm x length 12.5mm, Supply Voltage 5-30 V DC, Output Push Pull (AA,BB,OO), PPR:360, Outlet cable type axial with flange 37mm to 58mm. |
| **Load Indicator** | Make-Selectron, Model PIC 152-B2, 85 to 270 V AC, Retransmission output 4-20 mA. |
| **Battery** | Make-Exide, Model MHD 350 06687, 12 V DC. |
| **Engine Indicator** | Input Piezo sensor, Crank angle sensor, No. of channels 2, Communication RS232. |
| **Digital millivoltmeter** | Range 0-200mV, Panel mounted. |
| **Temperature sensor** | Make-Radix Type K, Ungrounded, Sheath Dia. 6mmX110mmL, SS316, Connection ¼`` BSP (M), Adjustable compression fitting. |
| **Fuel measuring unit** | Make-Apex, Glass Model FF0.090. |
| **Temperature Transmitter** | Make-Wika, model T19.10.3K0-4NK-Z, Input thermocouple. (type K), Output 4-20 mA; Supply 24 V DC, Calibration 0-1200 deg C. |
| **Load Indicator** | Digital, Range 0-50 Kg, Supply 230 V AC. |

| | |
|---|---|
| **Load Sensor** | Make-Sensotronics Sanmar Ltd, Model 60001, Type S beam, Universal Capacity 0-50 kg. |
| **Fuel flow transmitter** | DP transmitter, Range 0-500 mm WC. |
| **Air flow transmitter** | Pressure transmitter, Range (-) 250 mm WC. |
| **CNG Conversion Kit** | Make-Tomasetto Achilles. |
| **Gas Analyser** | Make- AVL, (AVL for DIGAS) for emission measurement. |

# 4. RESULTS AND DISCUSSION

This chapter includes experimental results and performance studies on S.I engine using gasoline and CNG.

**Table 4.1 Test engine specifications**

| Parameters | Value |
|---|---|
| Bore | 69 mm |
| Stroke | 72 mm |
| Connecting rod length | 112.5 mm |
| Compression ratio | 9.4:1 |
| Cylinder | Four |

## 4.1 Collection of experimental data

For doing comparative analysis of performance and emissions, experiments were carried with S.I engine running on gasoline, CNG. The experiments were conducted on a 4-cylinder, four stroke Wagon-R engine. The experimental data obtained are shown in Table. It shows that the operating conditions in which speed, load are changed widely for gasoline and CNG. The experimental data of P-$\theta$ curve on the following operating conditions are obtained by ‘engine soft’ software.

## 4.2 Performance Evaluation

The data measured during the tests included engine speed, brake power, torque, and fuel consumption, SFC. During the test engine load was varied while maintaining a constant engine speed. The tests were performed with five different speed range 2500, 3000, 3500, 4000, and 4500 rpm. Fuels that have been used are gasoline and CNG. Formulations used for calculation of various parameters are described below.

Torque (kg m) = Load × Arm length

Brake power (kW) = (2 × π × Speed × Torque × 9.81) / (60 × 1000)

$$\text{Brake Thermal Efficiency (\%)} = \frac{\text{Brake power} \times 3600 \times 100}{\text{fuel fow } \left(\frac{\text{kg}}{\text{hr}}\right) \times \text{calorific value } \left(\frac{\text{kJ}}{\text{kg}}\right)}$$

$$\text{Specific fuel consumption } \left(\frac{\text{Kg}}{\text{kwhr}}\right) = \frac{\text{Fuel flow } \left(\frac{\text{kg}}{\text{hr}}\right)}{\text{Brake power (kW)}}$$

$$\text{Specific energy consumption(MJ/kWhr)} = \frac{\text{SFC} \times \text{Calorific value}}{1000}$$

$$\text{Mechanical Efficiency (\%)} = \frac{\text{Brake power (kW)} \times 100}{\text{Indicated power (kW)}}$$

## 4.3 Results and discussion

All the tests and data analysis were performed for gasoline and CNG on SI engine in the I.C. Engine Laboratory. The test results were used as a basis for the comparison of the engine performance and emissions of the two different fuels and it will be also useful for the Indian new CNG/DI engine in future. The performance characteristics of the engine operated by gasoline and CNG obtained are given below.

## 4.4 Performance Studies

### 4.4.1 Comparison of P-θ diagrams

Figures 4.1 to 4.5 shows the cylinder pressure variation for gasoline and CNG at WOT for speeds 2500, 3000, 3500, 4000 and 4500 rpm. As shown in the Figures of the P-θ diagram peak pressure is relatively high for gasoline as compared to CNG. Factors that contribute to the rise in peak cylinder temperature are inlet pressure, compression ratio, equivalence ratio ignition timing, and speed. Considering the first factor the inlet pressure of CNG is less than gasoline, which results in the lower pressure, as with higher inlet pressure the cylinder pressure rise. Since the compression ratio was kept constant throughout the engine operation, therefore it does not contribute much in cylinder pressure variation.

Equivalence ratios are having a strong influence on rise of cylinder pressure and temperature. Peak cylinder pressure and temperature increase with increasing equivalence ratio towards the richer side. As more fuel is available combustion rate increase and complete combustion of fuel takes place. This results in high cylinder pressure and high burned gas temperature. This effect can be vividly seen in Figures 4.1 to 4.5. One important factor that influences the results is ignition timing. With advancing ignition (spark advance) the peak cylinder pressure will raise because the compression charge is ignited and the rising piston in the compression phase compress the burned charge resulting in high peak pressure and temperature. For the gaseous fuel ignition timing is required to be in advance. But the engine where test has been performed is designed for the conventional fuel (gasoline). When operating the engine by CNG the peak cylinder pressure will be low as compared to the result obtained by gasoline. Therefore in Figures 4.1 to 4.5 at different speeds we get the above results.

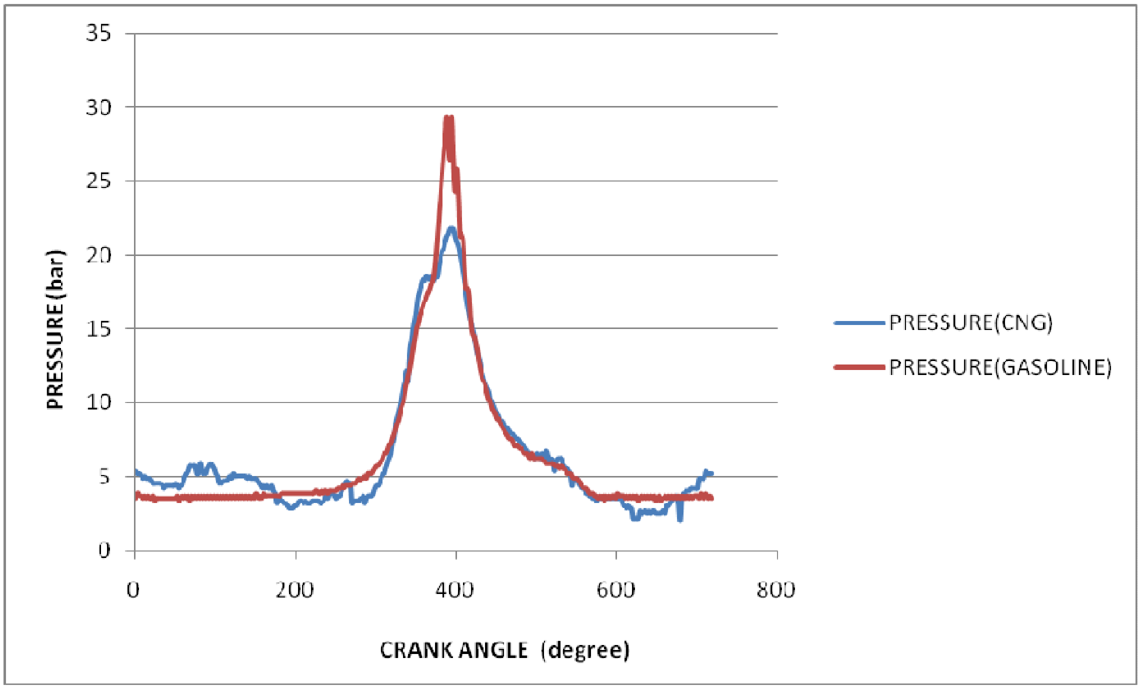



**Fig.4.1 Cylinder pressure v/s crank angle at speed 2500 rpm**

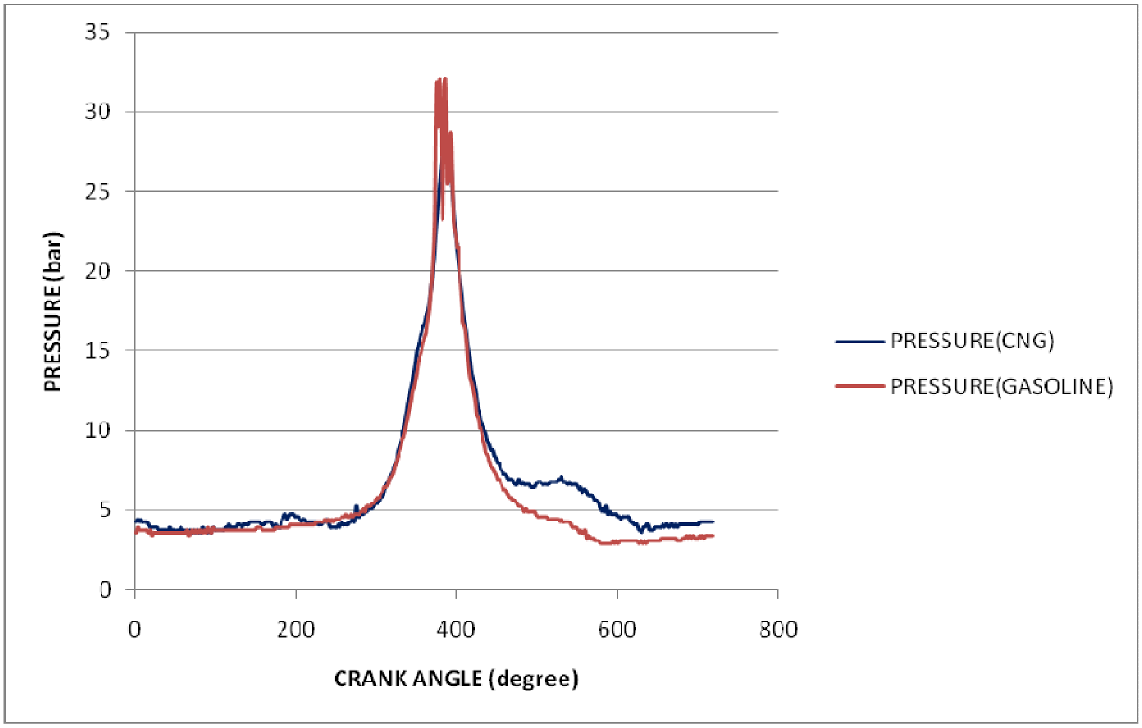



**Fig.4.2 Cylinder pressure v/s crank angle at speed 3000 rpm**

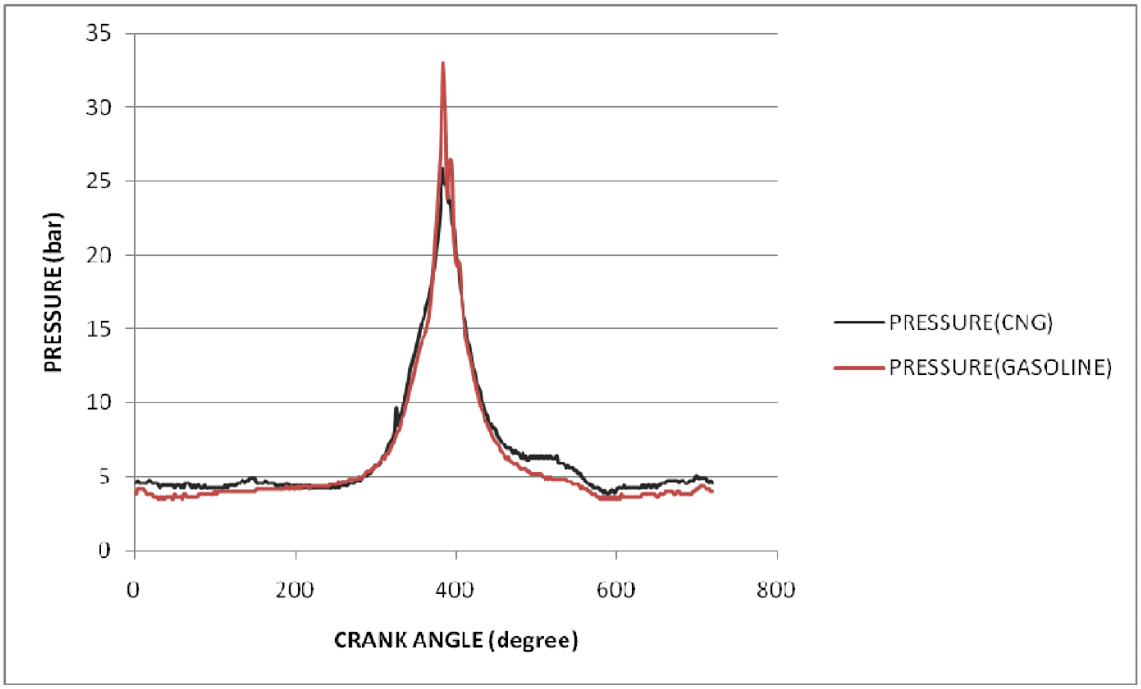



**Fig.4.3 Cylinder pressure v/s crank angle at speed 3500 rpm**

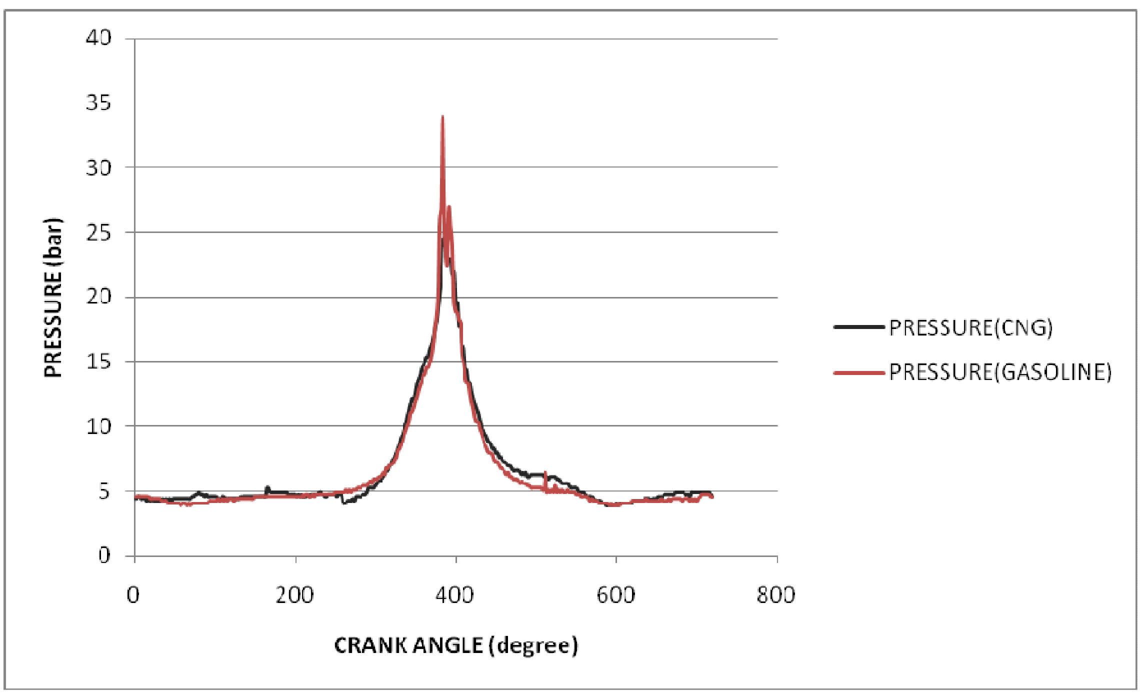



**Fig.4.4 Cylinder pressure v/s crank angle at speed 4000 rpm**

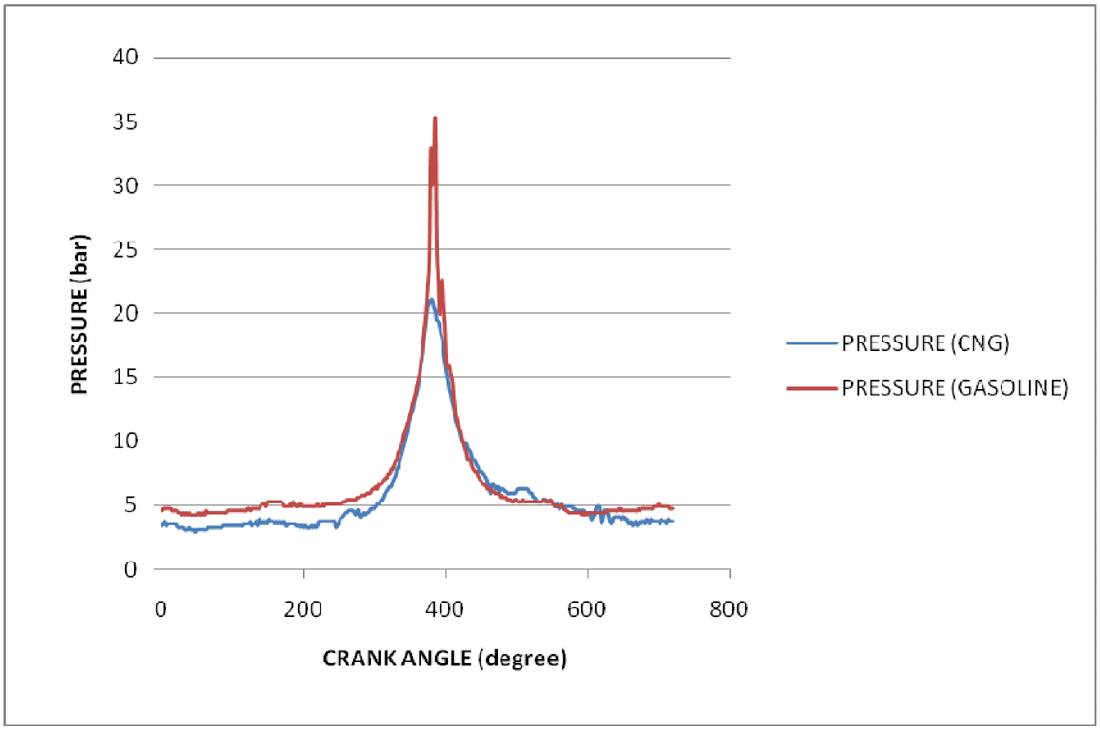



**Fig.4.5 Cylinder pressure v/s crank angle at speed 4500 rpm**

### 4.4.2 Engine performance

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

#### (1) Brake specific fuel consumption

The BSFC curve of Fig. 4.6 is for full throttle, variable speed operation. At any speed, it represents the BSFC which will result when the engine is carrying its maximum load at that speed. It is seen (Fig.4.6) that BSFC drops as the speed is increased in the low speed range, nearly levels off at medium speeds, and increases in the high speed range. This is because of this, at low speeds, the heat loss to the combustion chamber walls is proportionately greater resulting in higher fuel consumption for the power produced. At high speeds, the friction power increases at a rapid rate, resulting in a slower increase in brake power than in fuel consumption with a consequent increase in BSFC. It is seen that BSFC for CNG was always less than gasoline throughout the speed range. This was mainly due to the higher heating value of the CNG (47.669 MJ/ kg) as compared to that of the gasoline (44 MJ/kg) and the slow burning of CNG as compared to that of the gasoline. The lowest BSFC occurs at 3500 rpm for both the fuels, and it was 1000 gm/kWh and 450 gm/kWh for gasoline and CNG respectively, and on average, BSFC of CNG was near about 18% lower than that of gasoline.

Figs. 4.6 to 4.11 show the variation of BSFC with constant speed of 2500, 3000, 3500, 4000 and 4500 rpm respectively with the variable engine load of 4 kg to 17 kg of engine full load. The reason for the rapid increase in BSFC with the reduction of load is that the friction power remains essentially constant, while the indicated power is being reduced. So, the brake power drops more rapidly than fuel consumption, and thereby the BSFC rises. The lowest BSFC was attained at 17 kg of engine full load for both gasoline and CNG, and there were 420, 590, 660, 800 and 820 gm/kWh for gasoline and 340, 410, 490, 500 and 550 gm/kWh for CNG. It is found that BSFC for both the fuels was increased slightly with increasing speed. As the load is fixed, the rate of increase of friction power with speed was more than that of indicated power in this condition, which results in more BSFC. The difference of BSFC for gasoline and CNG at different speeds varied a little bit and shows an average difference of 17.3%.

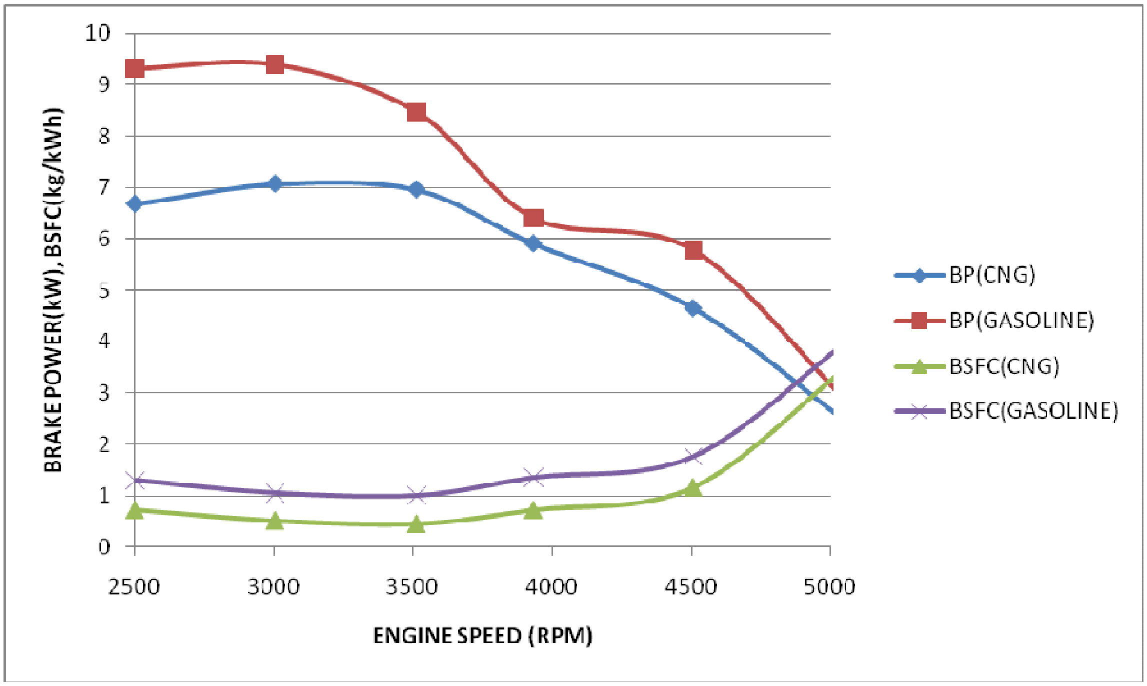



**Fig.4.6 BP, BSFC v/s engine speed at WOT**

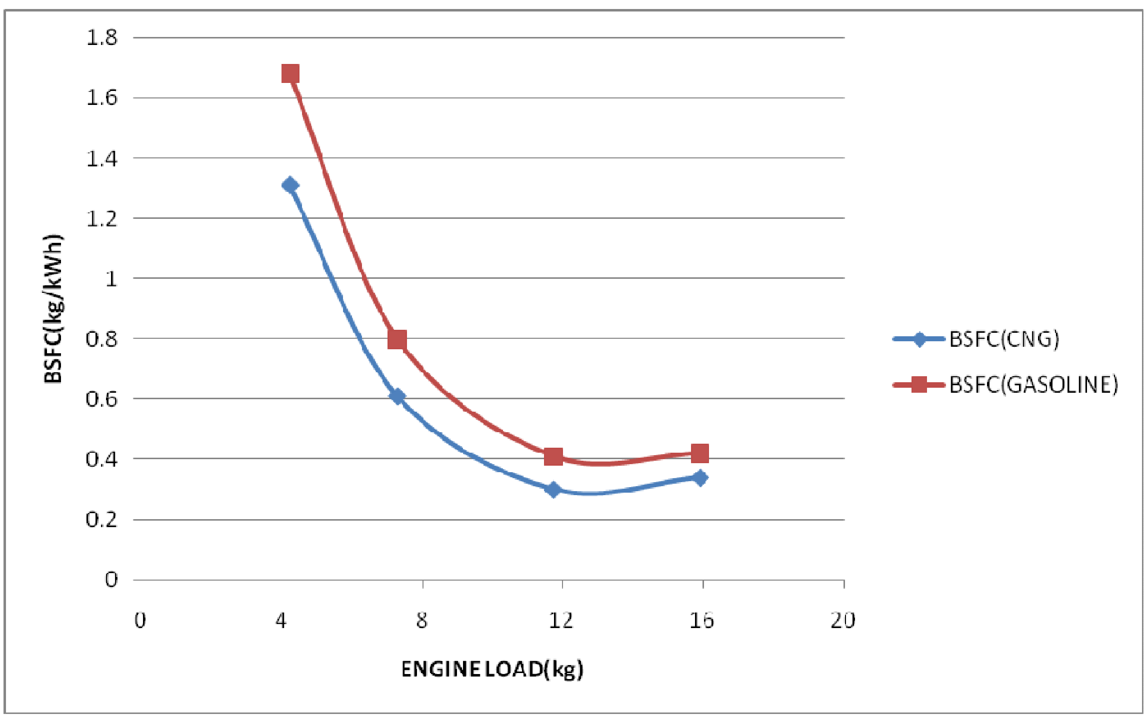



**Fig.4.7 BSFC v/s Engine Load at 2500 rpm**

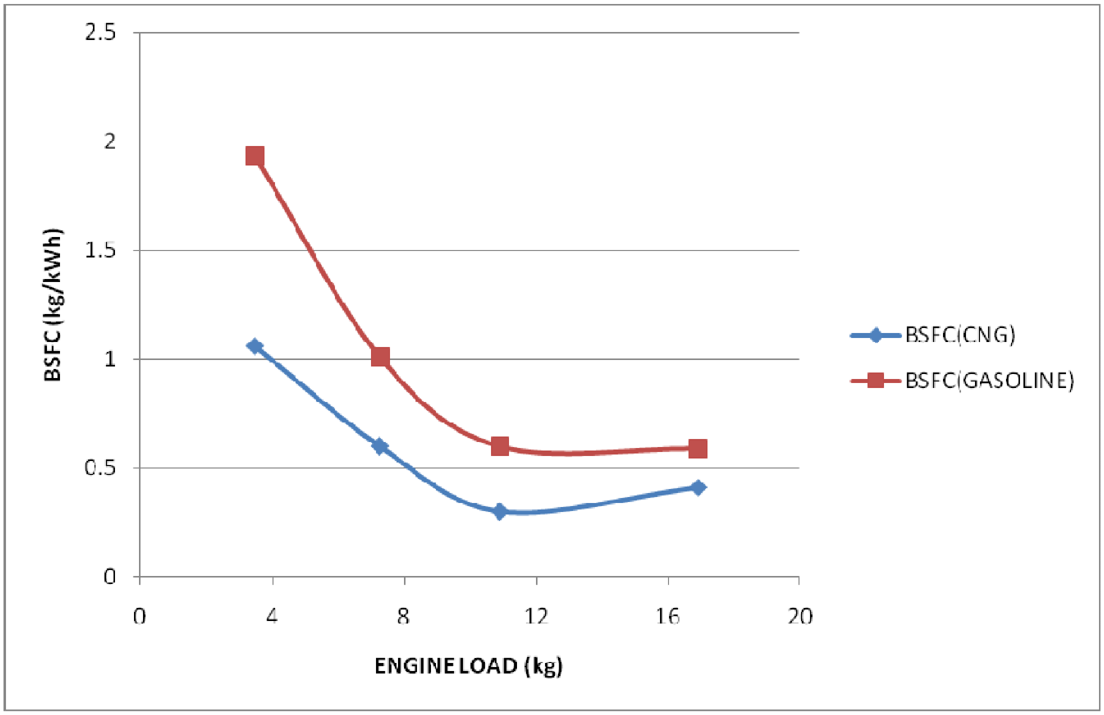



**Fig.4.8 BSFC v/s Engine Load at 3000 rpm**

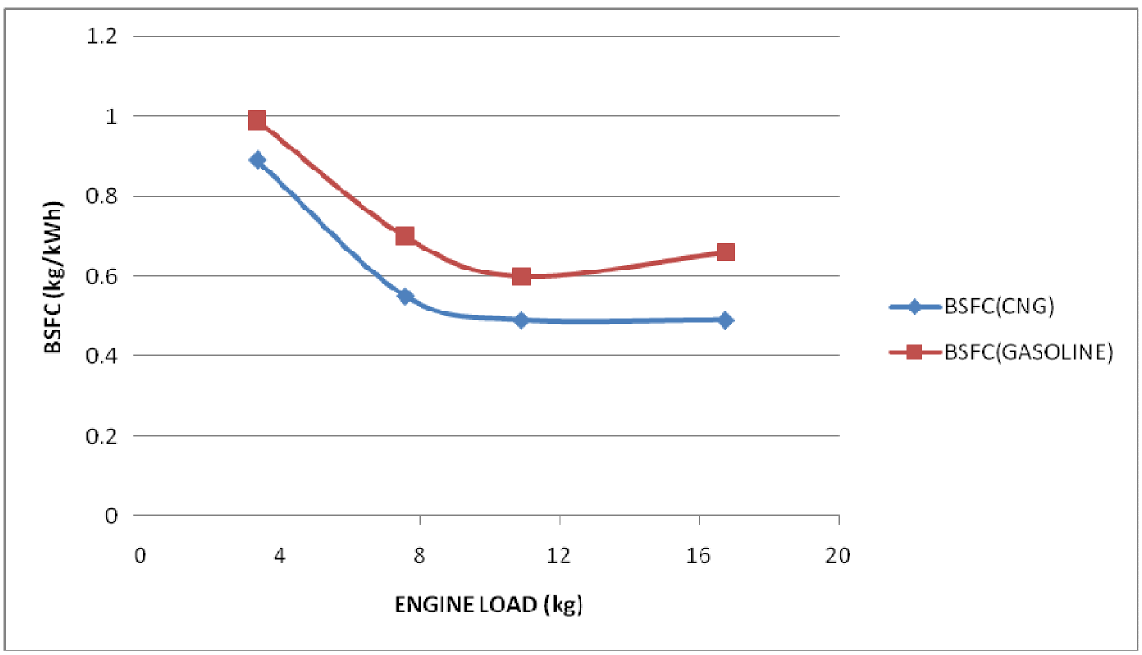



**Fig.4.9 BSFC v/s Engine load at 3500 rpm**

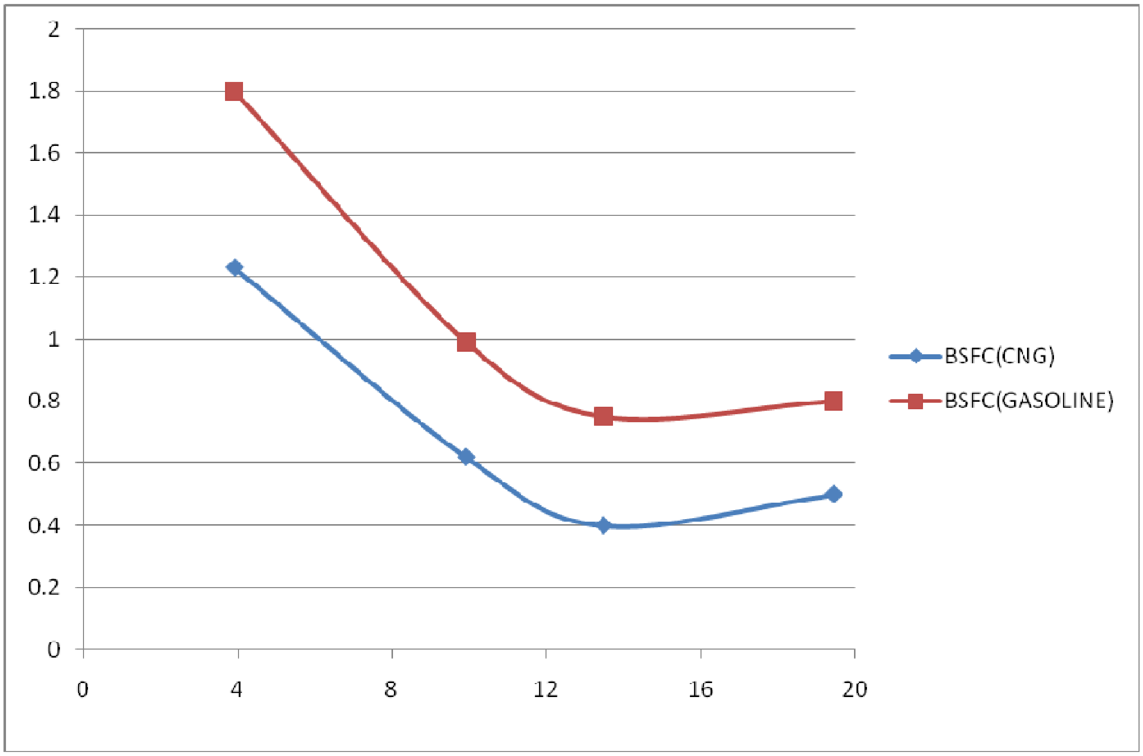



**Fig.4.10 BSFC v/s Engine Load at 4000 rpm**

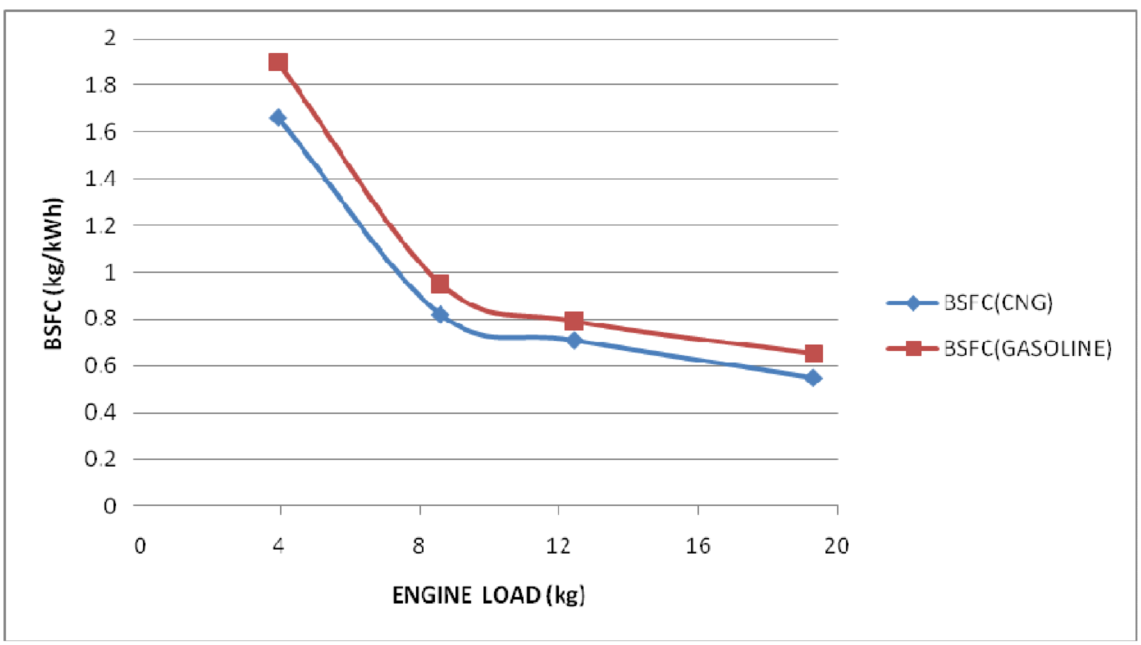



**Fig.4.11 BSFC v/s Engine Load at 4500 rpm**

**2) Brake Power**

Referring to Fig. 4.6, it can be seen that the brake power developed by the engine running with CNG was always lower than gasoline fuel throughout the speed range. Displacement of air by natural gas and by the slower flame velocity of CNG were the main reasons of the lower brake power as compared to that of the gasoline, as a result of which both the air volumetric efficiency and the charge energy density per injection into the engine cylinder reduced the CNG content. CNG produced nearly an average of 16% less brake power compared to gasoline fuel. This happened due to the lower volumetric benefits and less energy density of CNG in comparison with gasoline per power stroke of the engine. In case of liquid fuels, it is considered that the fuel does not reduce the amount of air captured in the cylinder. Hence, a gasoline-fuel-designed engine converted to CNG will be capable of significantly lessening peak power. The curve's trend is nearly same for both the fuels due to the fact that every operating condition was the same; while the only change was fuel itself.

### 4.4.3 Comparison of Engine Emissions

**(1) CO emissions**

Exhaust emissions of a CNG operated SI engine vary strongly with air-fuel ratio. Poor mixing of air and fuel, local rich regions and incomplete combustion produces CO when $\lambda$ value is lower than stoichiometric value. CO emissions versus engine speed at WOT and CO emissions versus engine load for speed values 2500, 3000, 3500, 4000 and 4500 rpm are shown in the Figures 4.12 4.17 respectively for gasoline and CNG. CO emission is lower with CNG as compared to gasoline because it easily forms more homogenous mixture with air and can run leaner than gasoline engines. With CNG carbon content percentage is much lower compare to gasoline. From fig. 4.12, it is observed that CNG produced much less CO

(80%). Thus, the CNG is more combustible than the gasoline fuel. Higher combustion temperature was another reason of the low CO emission of the CNG fueled engine. Gasoline is basically iso-octane ($C_8H_{18}$) and CNG is basically ($CH_4$). From the chemical equilibrium, it is evident that for higher hydrogen to carbon ratio (H/C) of a fuel, the amount of CO will be lower. Hence the above emissions of CO for gasoline and CNG are fairly expected as CNG has the favorable hydrogen/carbon ratio of almost 4:1 (gasoline 2.3:1).

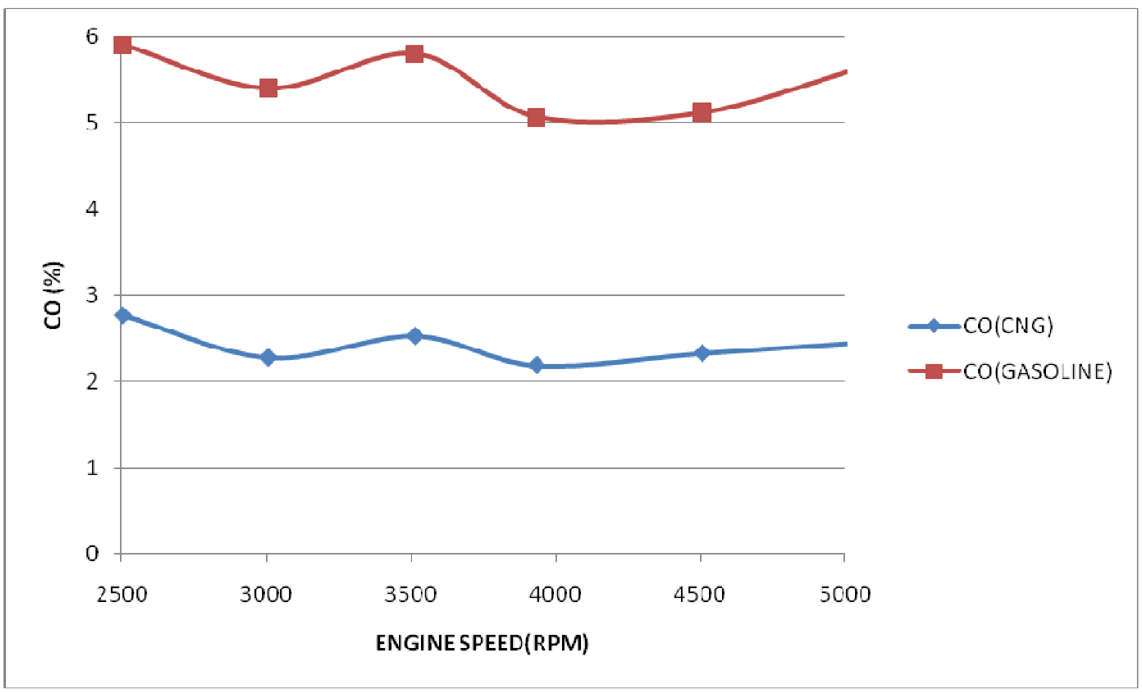



**Fig.4.12 CO emissions v/s engine speed at WOT**

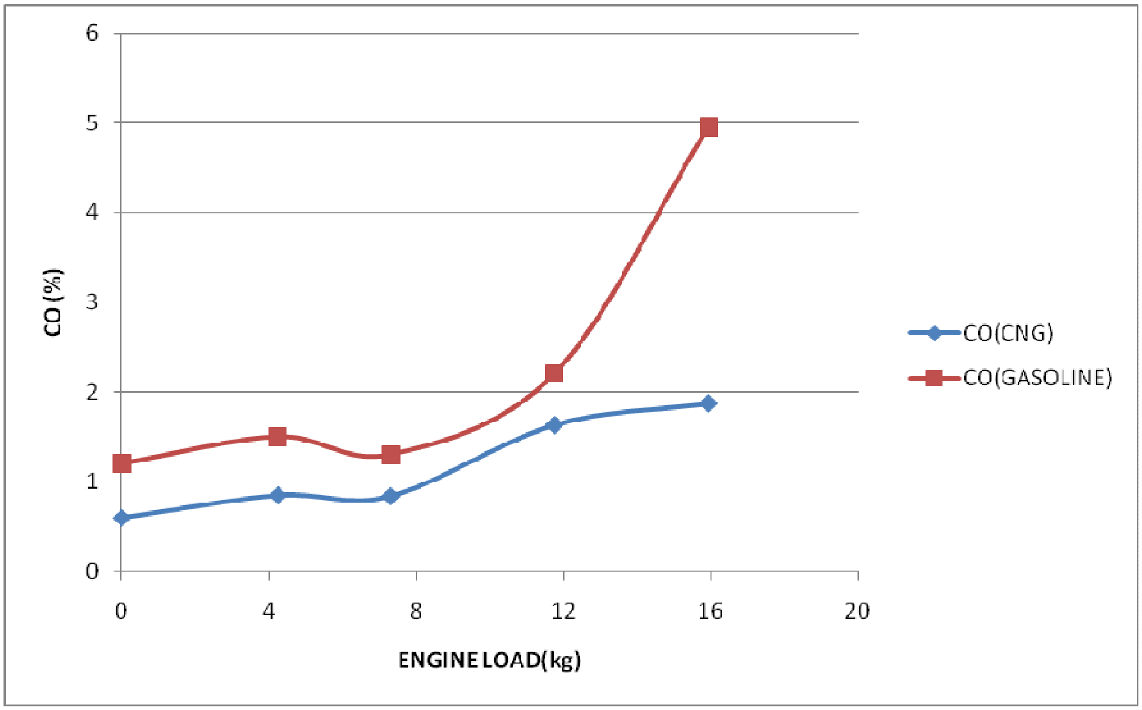



**Fig.4.13 CO emissions v/s Engine Load at 2500 rpm**

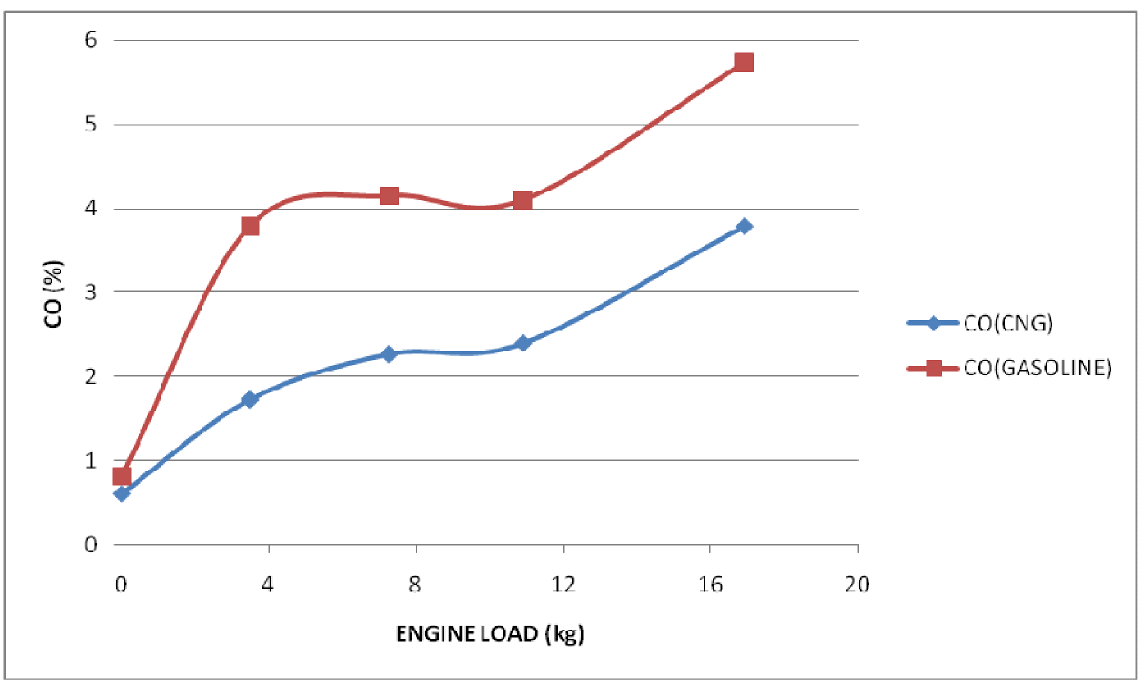



**Fig.4.14 CO emissions v/s Engine Load at 3000 rpm**

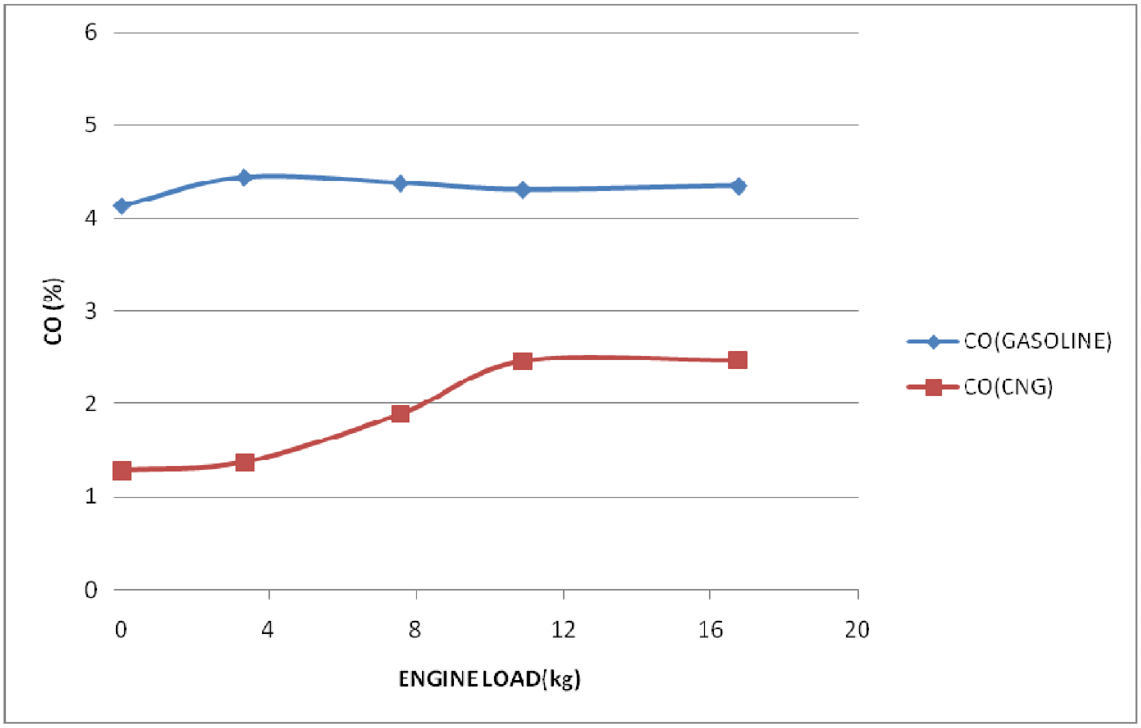



**Fig.4.15 CO emissions v/s Engine Load at 3500 rpm**

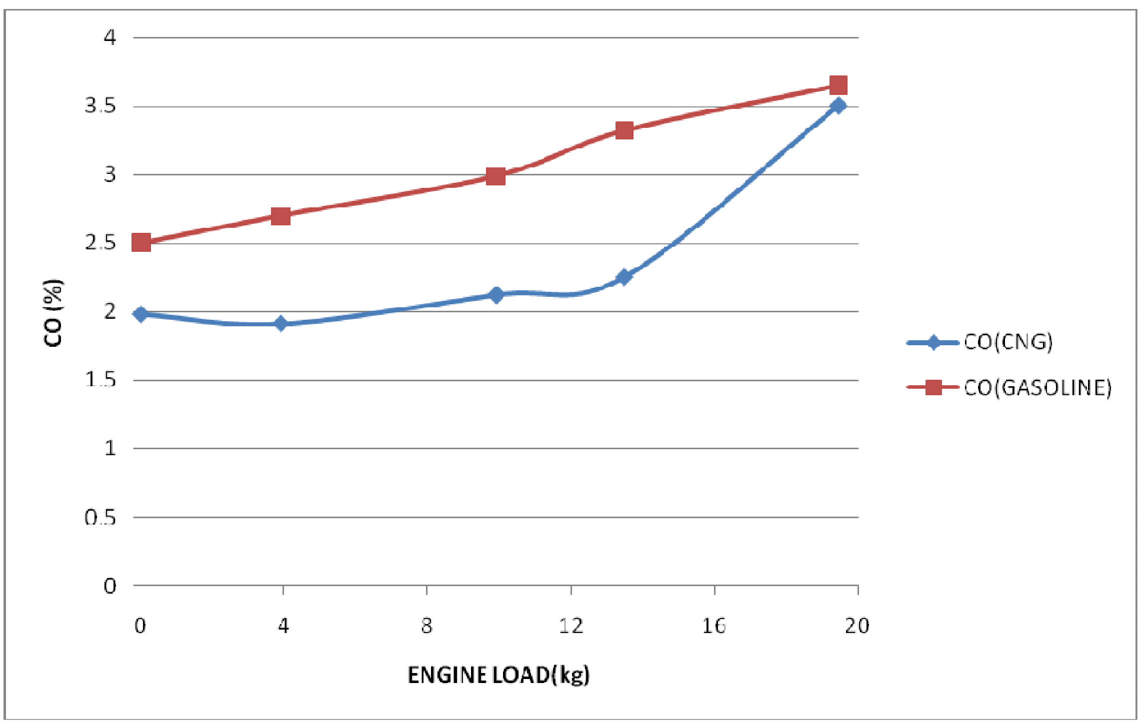



**Fig.4.16 CO emissions v/s Engine Load at 4000 rpm**

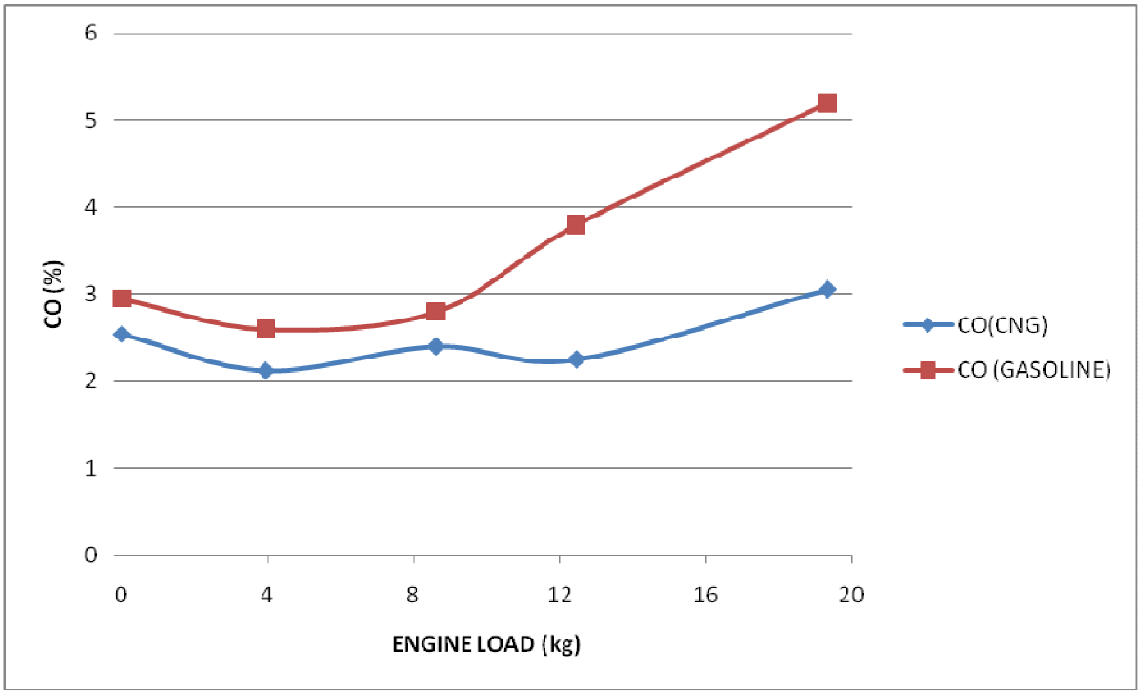



**Fig.4.17 CO emissions v/s Engine Load at 4500 rpm**

**(2) HC emissions**

The rate of HC release is influenced by the molecular weight of the respective fuel. The molecular weight of gasoline (114) is much higher than NG (16.04). Being light weight fuel, NG can form much better homogeneous air fuel mixture. On the other hand, liquid fuel requires time for complete atomization and vaporization to produce a homogeneous mixture.HC emissions versus engine speed at WOT and HC emissions versus engine load for speed range 2500, 3000, 3500, 4000 and 4500rpm are shown in the Figure 4.18 to 4.23 respectively for gasoline and CNG. The trend shown in the figure 4.19 to 4.23 is that at the maximum load the HC concentration is lower. At higher power, expansion and exhaust stroke temperature is higher and the in-cylinder oxidation rate, if oxygen available will be higher. However, as the exhaust gas flow rate increases, the residence time in critical sections of the exhaust system decreases and a reduction in exhaust port HC oxidation occur. The net trend is for HC concentration to decrease modestly as load is increased. In comparison to gasoline fuel, CNG produced less emissions of HC.

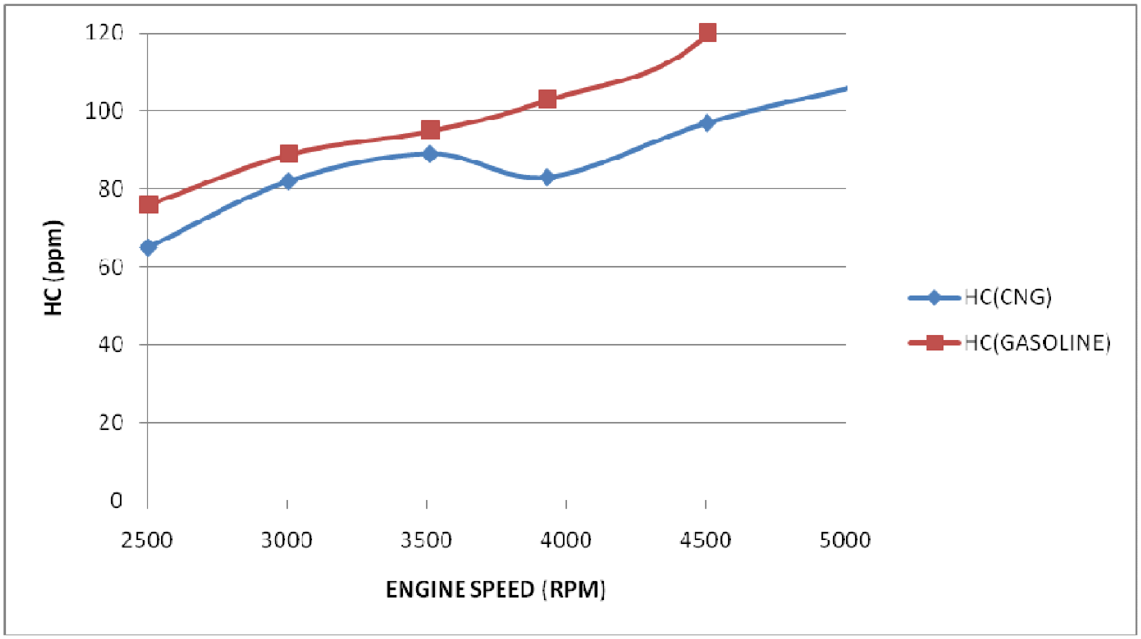



**Fig.4.18 HC emissions v/s Engine speed at WOT**

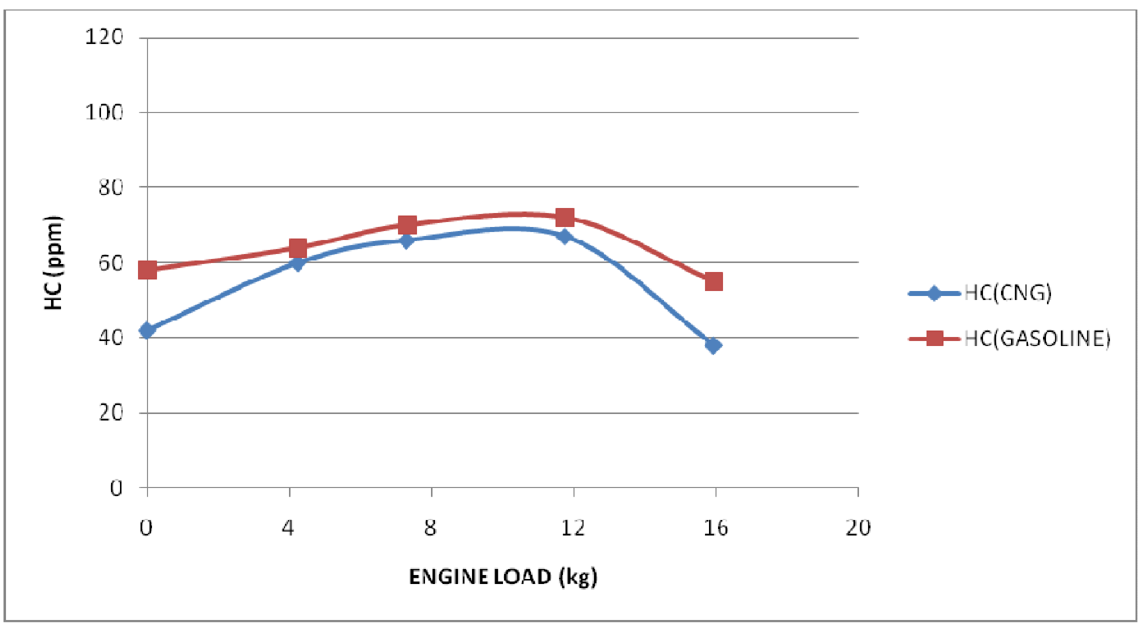
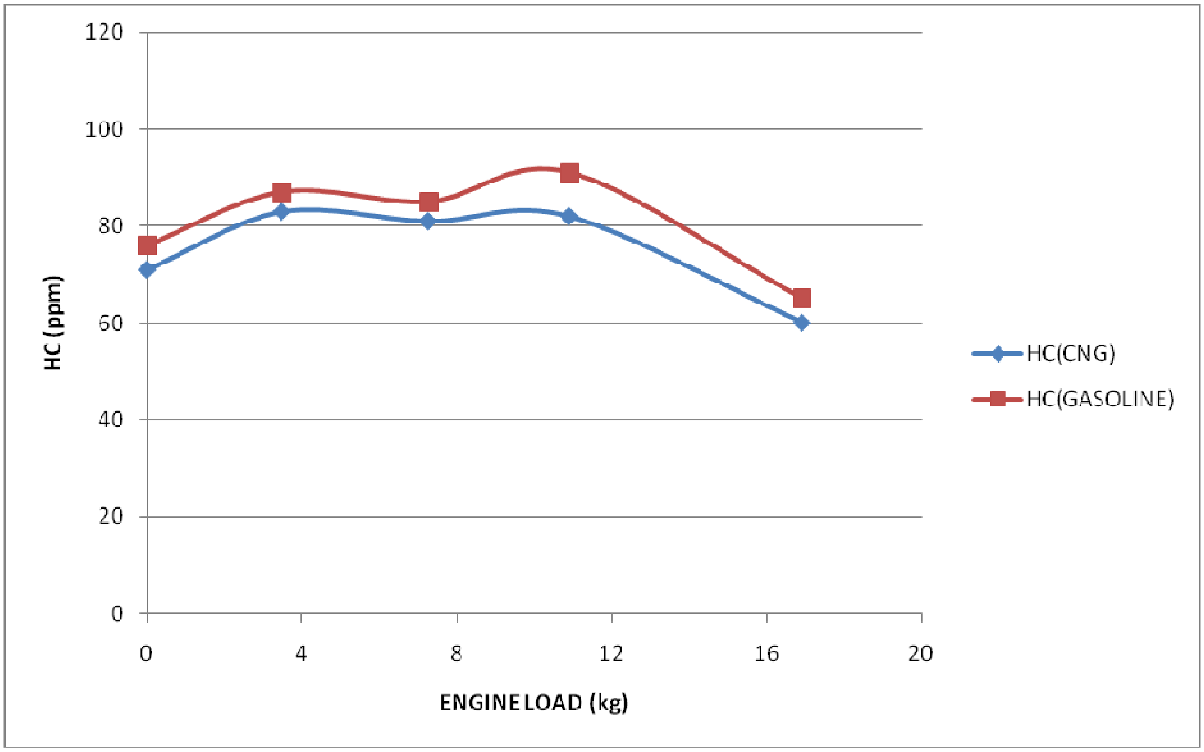



**Fig.4.19 HC emissions v/s Engine Load at 2500 rpm**




.

**Fig. 4.20 HC emissions v/s Engine Load at 3000 rpm**

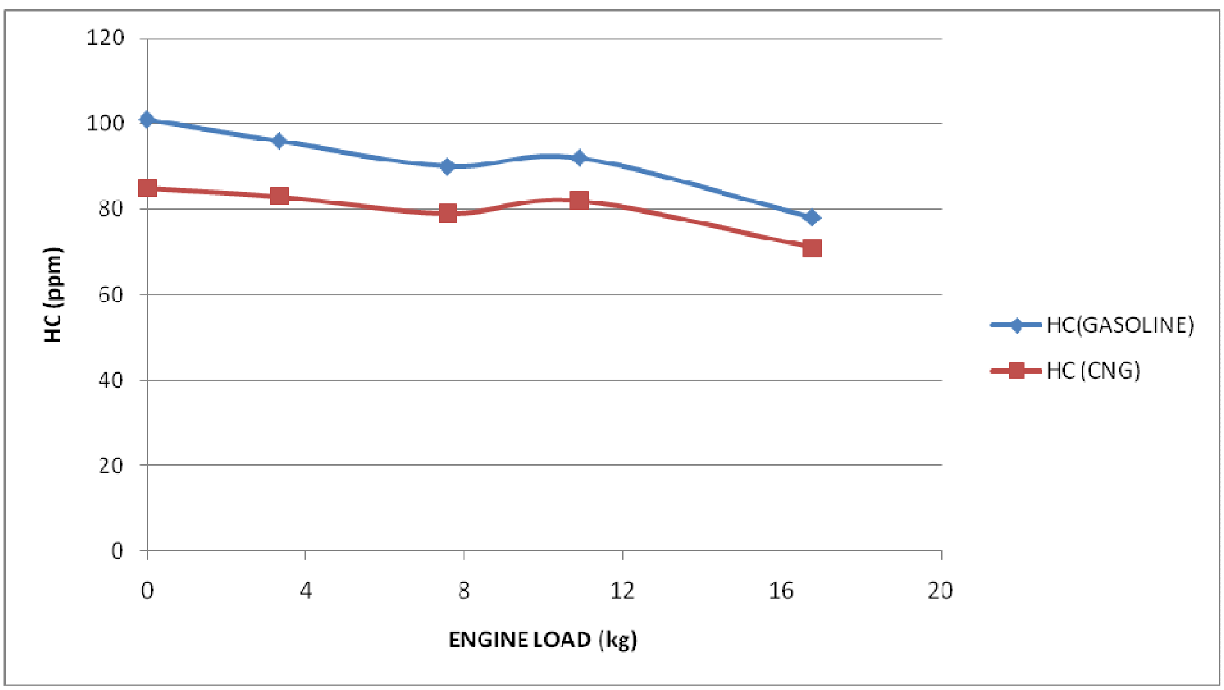



**Fig.4.21 HC emissions v/s Engine Load at 3500 rpm**

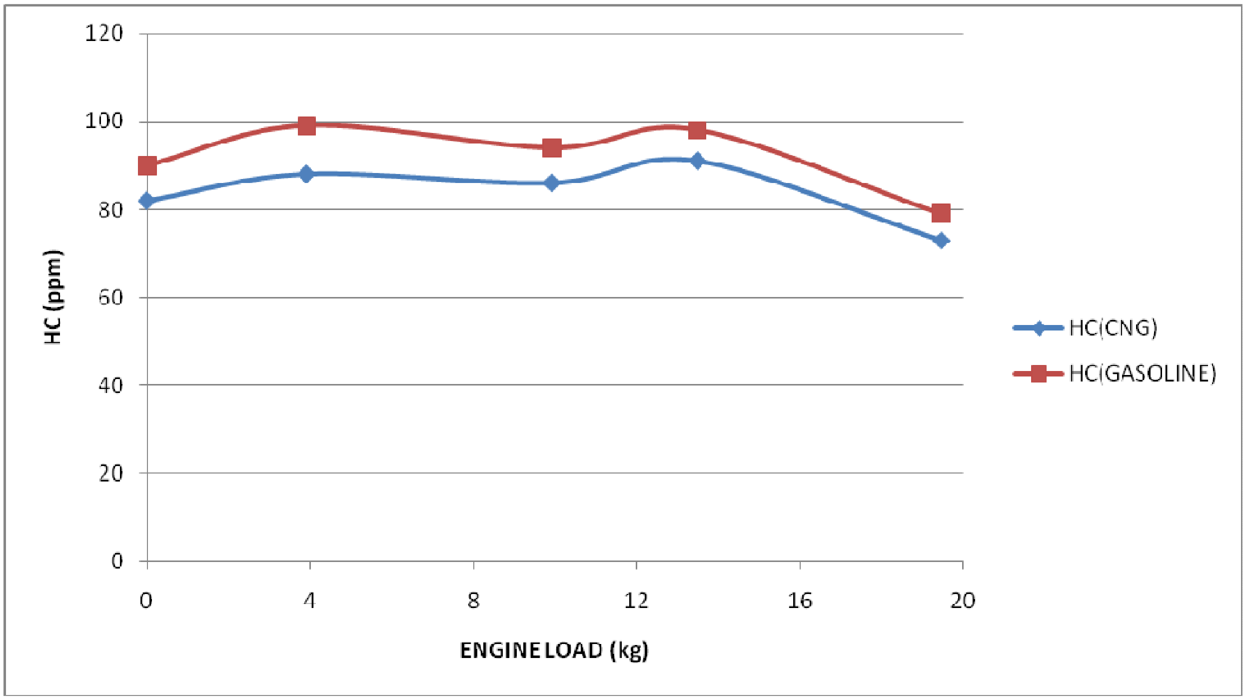



**Fig.4.22 HC emissions v/s Engine Load at 4000 rpm**

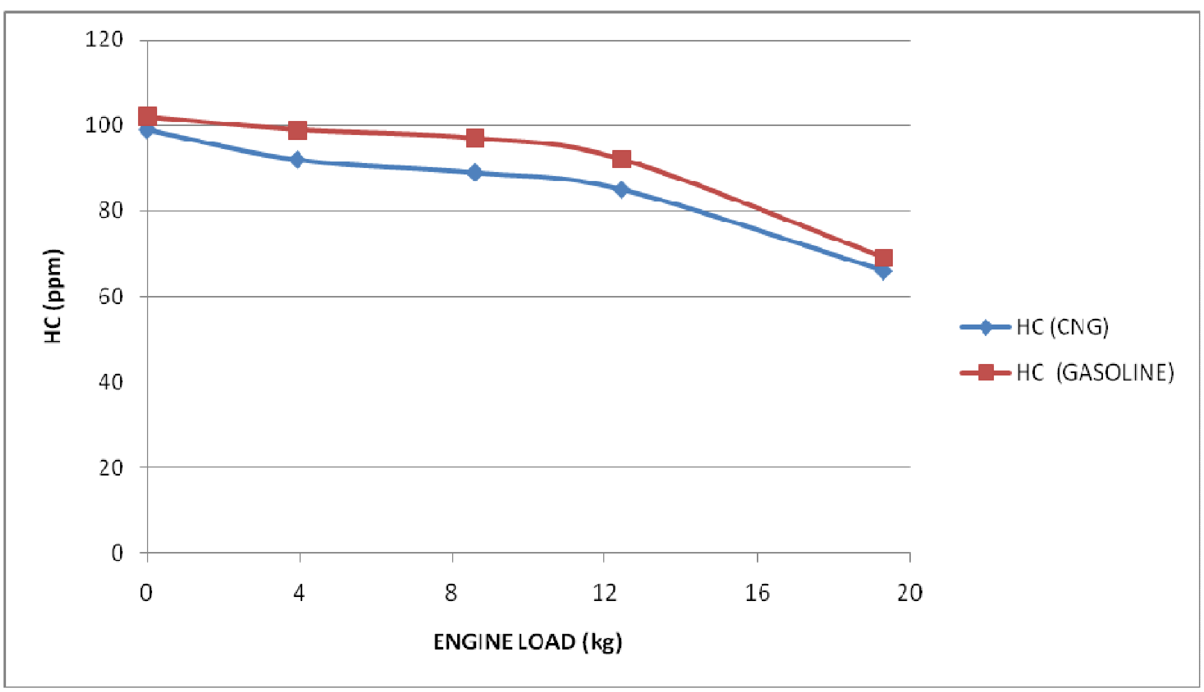



**Fig.4.23 HC emissions v/s Engine Load at 4500 rpm**

**(3) $CO_2$ emissions**

The composition of gas showed that the CNG consisted mostly of Methane ($CH_4$) whereas the gasoline ($C_8H_{18}$) compound packed less hydrogen per carbon (2.5). Thus, the percentage of carbon in the methane, i.e., the CNG was lower than that of the gasoline. This led to the lower emission of $CO_2$ for the CNG than the gasoline fuel. The $CO_2$ emission increased with the increase of engine speed for both the CNG and the gasoline fuels. This was due to the increase of fuel conversion efficiency.

$CO_2$ emissions versus engine speed at WOT and $CO_2$ emissions versus engine load for constant speeds 2500, 3000, 3500, 4000 and 4500 rpm are shown in the Figure 4.24 to 4.29 respectively for gasoline and CNG From above figures it is observed that CNG produced less $CO_2$ emission compared to gasoline.

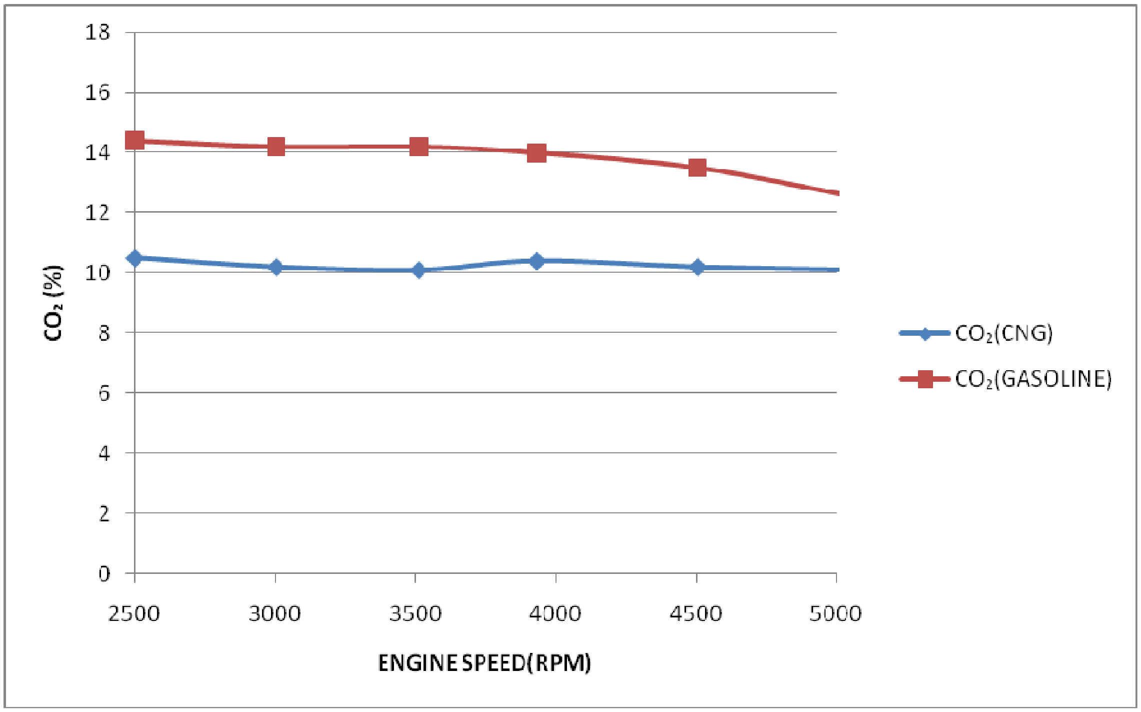



**Fig.4.24 $CO_2$ emissions v/s engine speed at WOT**

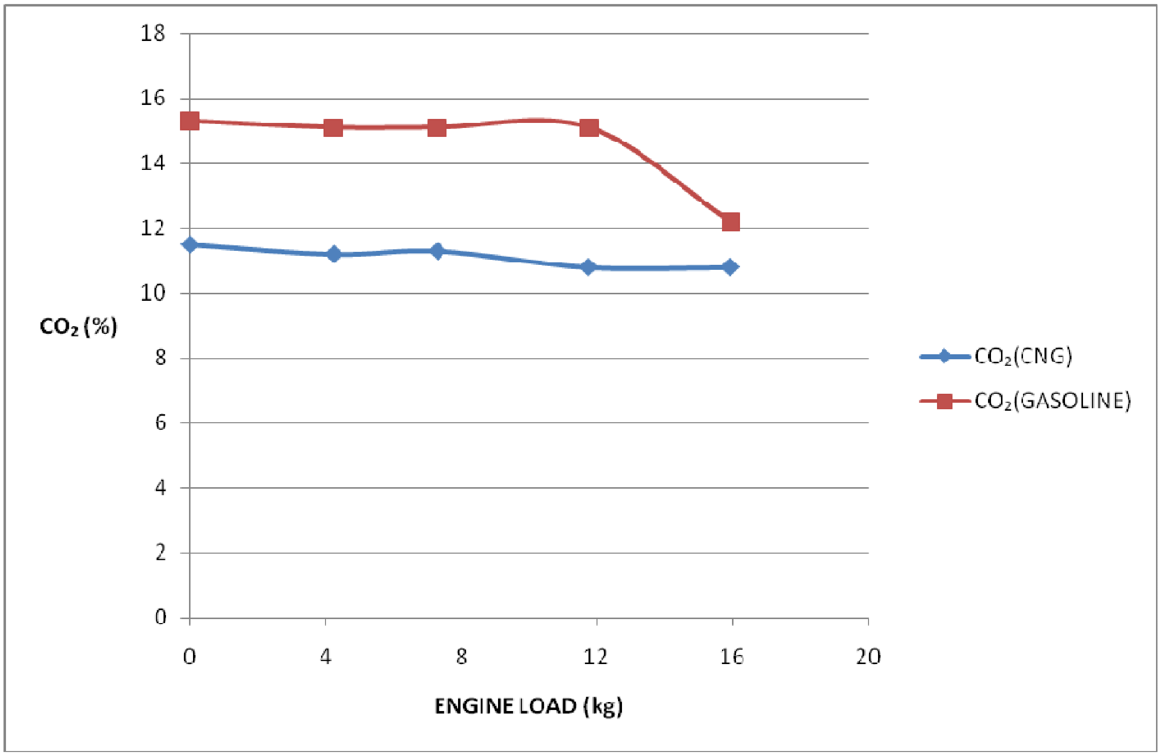



**Fig.4.25 $CO_2$ emissions v/s Engine load at 2500 rpm**

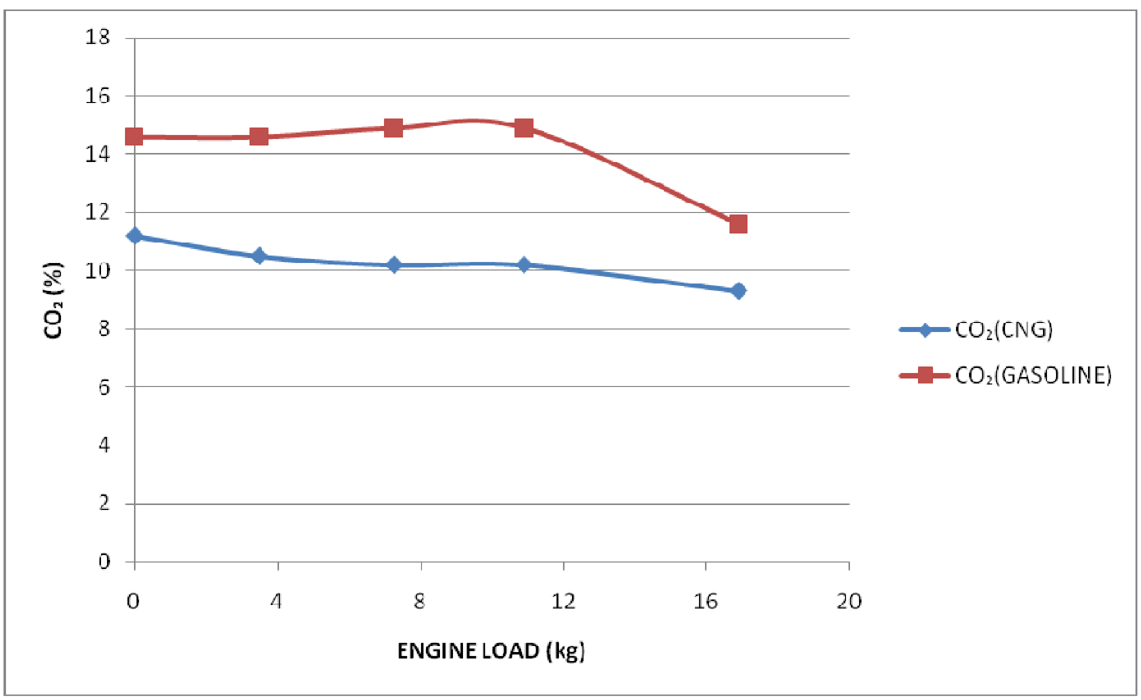



**Fig.4.26 $CO_2$ emissions v/s Engine load at 3000 rpm**

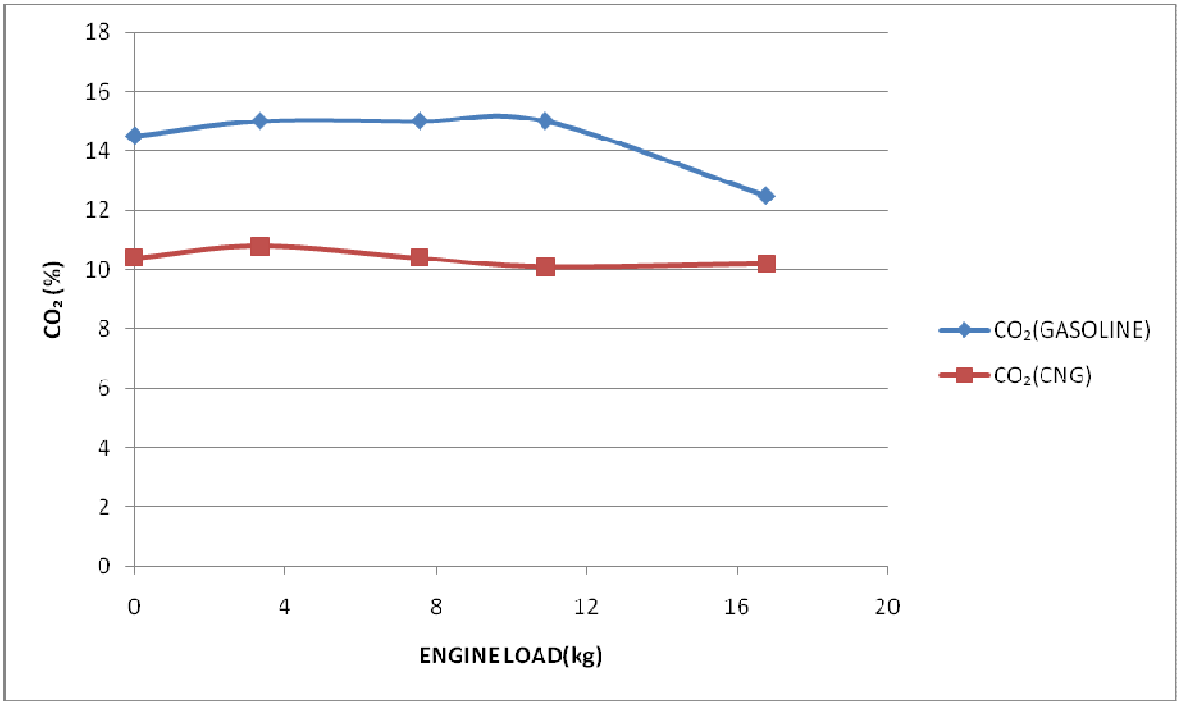



**Fig.4.27 $CO_2$ emissions v/s Engine load at 3500 rpm**

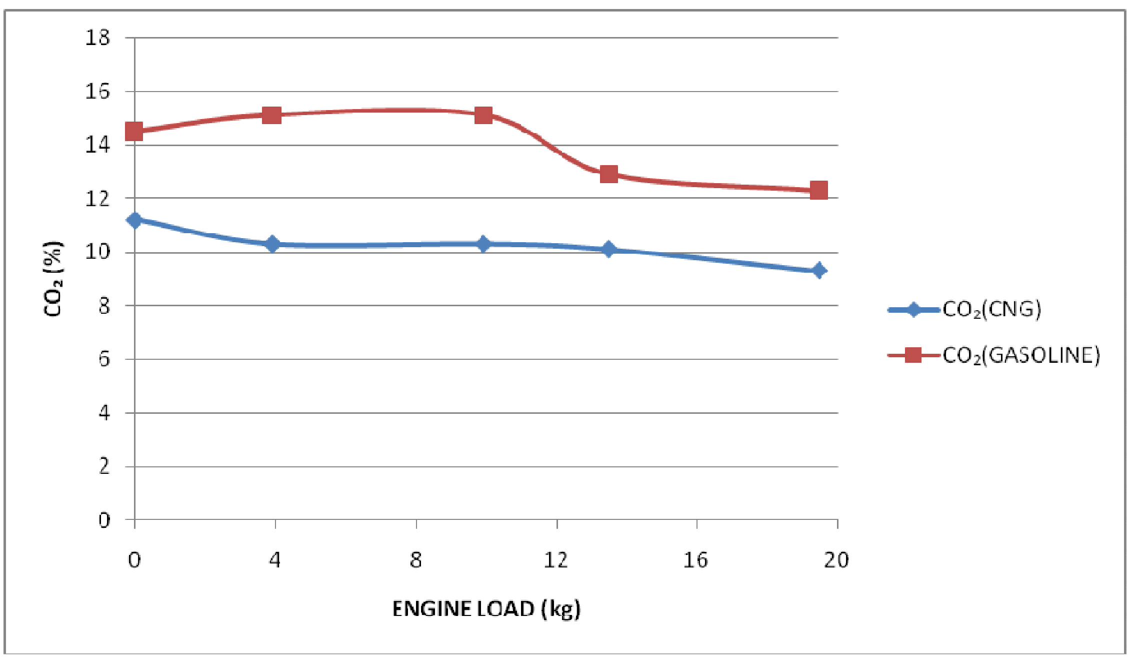



**Fig.4.28 $CO_2$ emissions v/s Engine load at 4000 rpm**

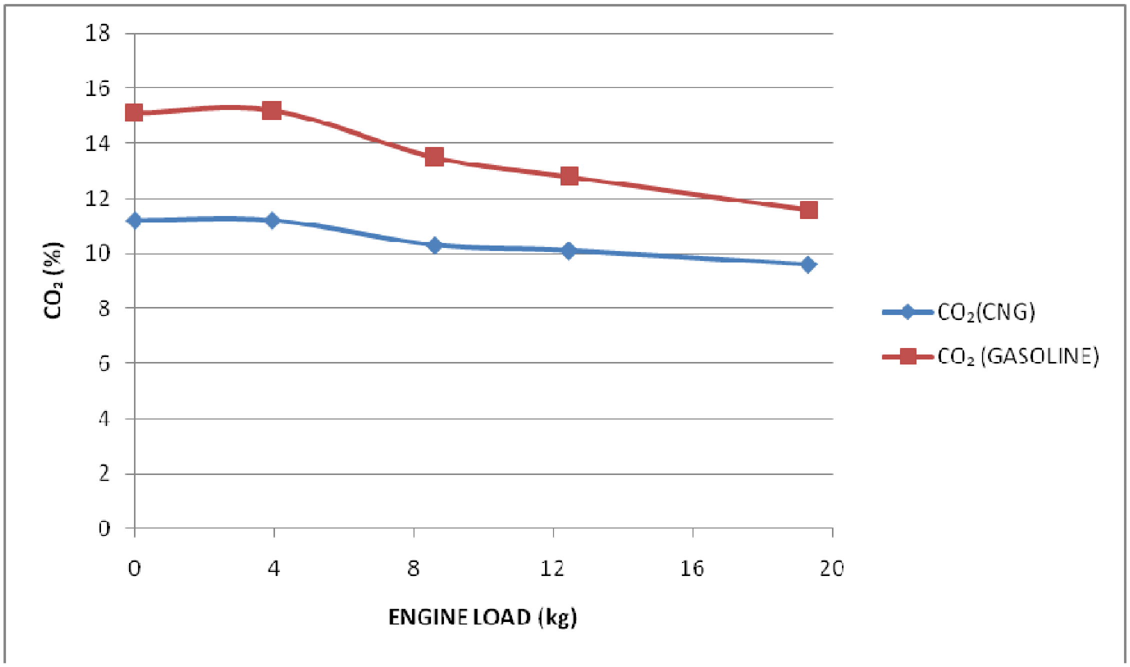



**Fig.4.29 $CO_2$ emissions v/s Engine load at 4500 rpm**

# 5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

## 5.1 Conclusion

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

- The peak cylinder pressure and the area of P-$\theta$ curve for CNG is lower as compared to gasoline.
- The BSFC is higher for wide range of speed and at different loads for gasoline as compared to CNG.
- CO, HC and $CO_2$ emissions of CNG are much lower as compared to gasoline.
- The CNG produces lower brake power than the gasoline throughout the speed range.
- CNG does have its shortcomings like less power, heavier fuel storage tank, etc., but its advantages are far too favourable to avoid it as an alternative clean fuel.
- The CNG has an advantage of higher brake thermal efficiency on an average of 1.1% and 1.6% than gasoline.
- The engine exhaust gas temperature produced by the CNG burning is always higher as compared to the gasoline.

## 5.2 Recommendations for future work

- Experiments should be carried out for wide range of advance spark timing and HCNG blends in S.I engine.
- For Indian scenario, the implementation of CNG engine in a passengers cars will be depend on three factors: the government, the users and the car manufactures.
- By having a clear policy in encouraging the implementation of CNG cars, not only the user and the car manufacturers will have the advantages but the future generation will also have the benefit by having a clean and healthy world.

# 6.REFERENCES


[1] Das L.M., Gulati R, Gupta PK. A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuel, Int. J. Hydrogen Energy 25(8) August(2000) 783-793.

[2] Rosli Abu Bakar, Mardani Ali Sera and Wong Hong Mun. Towards The Implementation Of CNG Engine: A Literature Review Approach To Problems And Solutions BSME-ASME International Conference on Thermal Engineering 31 December 2001 – 2 January 2002, Dhaka.

[3] Hodgson Jeffrey W. and Taylor John D. Emissions and Performance Evaluation of a Dedicated Compressed Natural Gas Saturn. July 1997 NRELISR-540-22626 UC Category: 1504.

[4] Kumar Rajesh, Performance and emission analysis of a multi cylinder C.I. fueled with diesel CNG dual fuel(2009).

[5] Chelani A.B. and Devotta S. (2005), Impact of Change in Fuel Quality on PM10 in Delhi. Bulletin of Environmental Contamination and Toxicology 75(3): 600–607.

[6] Aslam M. U., Masjuki H.H., Kalam M. A., Amalina M. A. A Comparative Evaluation of the Performance and Emissions of a Retrofitted Spark Ignition Car Engine, J. of Energy & Environment 4 (2005) 97 – 110.

[7] L. M. Das, R. Gulati and P. K. Gupta, A comparative evaluation of the performance characteristics of a spark ignition engine using hydrogen and compressed natural gas as alternative fuels, International journal of hydrogen energy, Vol. 25(2000), 2003, pp 783-793.

[8] http://www.eia.doe.gov/oiaf/ieo/nat_gas.html, 2004

[9] N. O. Nylund, J. Laurikko and M. Ikonen, Pathways for natural gas into advanced vehicles, IANGV (International Association for Natural Gas Vehicle) Edited draft report, Version 30.8, 2002.

[10] M.U. Aslam, H. H. Masjuki, M. A. Maleque, M. A. Kalam, T. M. I. Mahlia, Z. Zainon, M. A. Amalina and H. Abdesselam, Introduction of natural gas fueled automotive in Malaysia, in Proc., TECHPOS'03, UM, Malaysia, 2003, pp 156-161.

[11] J. B. Heywood, Internal combustion engine fundamentals, McGraw-Hill book company, Appendix D, 1988.

[12] Semin, Ismail A.R., Bakar R.A. Green Engines Development Using Compressed Natural Gas as an Alternative Fuel: A Review, American J. of Environmental Sciences 5 (3): 371-381, 2009.

[13] Catania, A.E., D. Misul, E. Spessa and A. Vassallo, Analysis of combustion parameters and their relation to operating variables and exhaust emissions in an upgraded multivalve bi-fuel CNG SI engine. SAE Technical Paper 2004-01-0983.

[14] De C., D.B. Remo, V. Ramón, M.R. Vander, F. De Magalhaes and E. Francisco, 2003. Performance and emission analysis of the turbocharged spark ignition engine converted to natural gas. SAE Technical Paper 2003-01-3726.

[15] Poulton, M.L., 1994. Alternative Fuels for Road Vehicles. Comp. Mechanic Publications, UK.

[16] Pischinger, S., M. Umierski and B. Hüchtebrock,. New CNG concepts for passenger cars:Hightorque engines with superior fuel consumption. SAE Technical Paper 2003-01-2264.

[17] Andrzej, K., Combustion System of High Speed Piston I.C. Engines.

[18] Ganesan, V., 1999. Internal Combustion Engines. 2nd Edn., Tata McGraw-Hill, New Delhi.

[19] Jahirul M.I., Masjuki H.H., Saidur R., Kalam M.A, Jayed M.H., Wazed M.A. Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine. Applied Thermal Engineering 30 (2010) 2219-2226.

[20] C.M. White, R.R. Steeper, A.E. Lutz, The hydrogen-fueled internal combustion Engine: a technical review. International Journal of Hydrogen Energy 31 (10). (2006) 12921305.

[21] S.G. Chalk, J.F. Miller, Key challenges and recent progress in batteries, fuel cells, and hydrogen storage for clean energy systems. J. of Power Sources 159 (1) (2006) 7380.

[22] R. Shinnar, The hydrogen economy, fuel cells, and electric cars. Technology in Society 25 (4) (2003) 455476.

[23] M.H. Jayed, H.H. Masjuki, R. Saidur, M.A. Kalam, M.I. Jahirul, Environmental aspects and challenges of oilseed produced biodiesel in Southeast Asia. Renewable and Sustainable Energy Reviews 13 (9) (2009) 24522462.

[24] J.C. Escobar, E.S. Lora, O.J. Venturini, E.E. Yáñez, E.F. Castillo, O. Almazan, Biofuels: environment, technology and food security. Renewable and Sustainable Energy Reviews 13 (2009) 12751287.

[25] S. Srinivasan, The food v. fuel debate: a nuanced view of incentive structures. Renewable Energy 34 (4) (2009) 950954.

[26] Pourkhesalian Ali M., Shamekhi Amir, Salimi Farhad. Alternative fuel and gasoline in an SI engine: A comparative study of performance and emissions characteristics. Fuel 89 (2010) 1056–1063.

[27] Verhelst S, Maesschalck P, Rombaut N, Sierens R. Efficiency comparison between hydrogen and gasoline, on a bi-fuel hydrogen/gasoline engine. Int J. Hydrogen Energy 2009; 34:2504–10.

[28] Bayraktar Hakan, Durgun Orhan. Investigating the effects of LPG on spark ignition engine combustion and performance. Energy Conver Manage 2005;46:2317–33.

[29] Mustafi N.N., Miraglia Y.C., Raine R.R., Bansal P.K., Elder S.T. Spark-ignition engine performance with 'Power-gas' fuel (mixture of $CO/H_2$): a comparison with gasoline and natural gas. Fuel 2006;85:1605–12.

[30] Shamekhi A, Khtibzade N, Shamekhi AH. Performance and emissions characteristics of a bi-fuel SI engine fueled by CNG and gasoline. ASME paper, ICES2006-1387; 2006.

[31] Cavalcante Cordeiro de Melo T, Bastos Machado G, Machado RT, Pereira Belchior Jr CR, Pereira PP. Thermodynamic modelling of compression, combustion and expansion processes of gasoline, ethanol and natural gas with experimental validation on a flexible fuel engine. SAE World Congress, 2007-24-0035; 2007.

[32] Verhelst S, Sierens R, Verstraeten S. Development of a simulation code for hydrogen fuelled SI engines. ASME paper, ICES2006-1317; 2006.

[33] Schoenung Susan M. Hydrogen vehicle fueling alternatives: an analysis developed for the international energy agency. SAE World Congress, 2001-01-2528;

[34] Semin, Awang Idris, Bakar R.A. An Overview of Compressed Natural Gas as an Alternative Fuel and Malaysian Scenario European Journal of Scientific Research ISSN 1450-216X Vol.34 No.1 (2009), pp.6-15.

[35] Rahnama, Alireza. The Great Progress in CNG, A Giant Leap in Iran, 2nd ANGVA Conference, November 27-29, (2007). Bangkok, Thailand.

[36] Energy Information Administration (1998). Natural Gas Issues & Trends, www.eia.doe.gov.

[37] Astbury G.R. A review of the properties and hazards of some alternative fuels. Process safety and environment protection 86 (2008) 397–414.

[38] Bakar Rosli Abu, Semin, Ismail Abdul Rahim. Application Review of Compressed Natural Gas as a Sustainable Alternative Fuel in the Internal Combustion Engines.

Proceedings of the 1st International Conference of the IET Brunei Darussalam Network, 26-27 May 2008.

[39] Semin, Ibrahim, Bakar Rosli Abu, Ismail Abdul Rahim.A Review of Green Engines Research and Development Based on Compressed Natural Gas.

[40] Cho Haeng Muk, He Bang-Quan. Spark ignition natural gas engines—A review Energy Conversion and Management 48 (2007) 608–618

[41] Ehsan Md. Effect of Spark Advance on a Gas Run Automotive Spark Ignition Engine. J.of Chemical Engineering, IEB. Vol. ChE. 24, No.1, December (2006).

[42] Economides Michael J., Wood David A. The state of natural gas. J. of Natural Gas Science and Engineering 1 (2009) 1–13

[43] Bhandari K, Bansal A, Shukla A and Khare M. Performance and emissions of natural gas fueled internal combustion engine, J of Scientific & Industrial Research 64(5) May(2005) 333-338.

[44] How HG, Taib I.M., Shahrir A, Yusoff A, Azhari S, Elvis A. Experimental Investigation of Performance and Emission of a Sequential Port Injection Natural Gas Engine, European J. Scientific Research 30(2) (2009) 204-214.

[45] Srinivasan KK. The Advanced Injection Low Pilot Ignited Natural Gas Engine: A Combustion Analysis, J. Eng. Gas Turbines Power 128(1) (2006) 213-218.

[46] T Luigi Turrio-Baldassarria, Battistellia C. Laura, Contia Luigi, Crebellia Riccardo. Evaluation of emission toxicity of urban bus engines: Compressed natural gas and comparison with liquid fuels. Science of the Total Environment 355 (2006) 64– 77.

[47] Lumato, Modestus Martin. Natural gas as fuel for commuter buses in Dar es Salaam. Deptt. of petroleum engineering and applied Geophysics. June (2005).

[48] Kaleemuddin Syed, Rao G.Amba Prasad. Development of Dual Fuel Single Cylinder Natural Gas Engine an Analysis and Experimental Investigation for Performance and Emission. American J. of Applied Sciences 6 (5): 929-936, 2009 ISSN 1546-9239.

[49] Molla M.S.A., Hossain M.A, Sapuan S.M., Ahmed M.M.H.M. Performance and Emission characteristics of a CNG fuelled SI Engine. International Energy Journal: vol. 2, no. 1, June 2001

[50] Mansha M., Saleemi A. R., H. Javed S, Ghauri Badar M. Prediction and measurement of pollutant emissions in CNG fired internal combustion engine. Journal of Natural Gas Chemistry 19(2010)539–547.

[51] A.K.Purwaha CNG Developments – An Indian Experience 23rd World Gas Conference, Amsterdam 2006.

[52] Ristovski Z., Morawska L, yokoa G.A.A, G.Johnson, D.Gilbert. Emissions from a vehicle fitted to operate on either petrol or compressed natural gas. Science of the Total Environment 323 (2004) 179–194.

# **APPENDIX A**: Experimental Data

### Table A-1 Performance parameters for CNG and gasoline at WOT

| SPEED (rpm) | BP(CNG) (kW) | BP(GASOLINE) (kW) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|---|---|
| 5079 | 2.34 | 2.72 | 3.6 | 4.1 |
| 4506 | 4.66 | 5.79 | 1.16 | 1.76 |
| 3933 | 5.91 | 6.41 | 0.72 | 1.35 |
| 3513 | 6.96 | 8.48 | 0.45 | 1 |
| 3006 | 7.07 | 9.4 | 0.51 | 1.05 |
| 2503 | 6.68 | 9.32 | 0.72 | 1.3 |

### Table A-2 Performance parameters for CNG and gasoline at 2500 rpm

| LOAD (kg) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|
| 15.93 | 0.34 | 0.42 |
| 11.75 | 0.3 | 0.41 |
| 7.3 | 0.61 | 0.8 |
| 4.24 | 1.31 | 1.68 |

### Table A-3 Performance parameters for CNG and gasoline at 3000 rpm

| LOAD (kg) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|
| 16.91 | 0.41 | 0.59 |
| 10.9 | 0.3 | 0.6 |
| 7.26 | 0.6 | 1.01 |
| 3.48 | 1.06 | 1.93 |

**Table A-4 Performance parameters for CNG and gasoline at 3500 rpm**

| LOAD (kg) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|
| 16.76 | 0.49 | 0.66 |
| 10.9 | 0.49 | 0.6 |
| 7.57 | 0.55 | 0.7 |
| 3.33 | 0.89 | 0.99 |

**Table A-5 Performance parameters for CNG and gasoline at 4000 rpm**

| LOAD (kg) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|
| 19.47 | 0.5 | 0.8 |
| 13.49 | 0.4 | 0.75 |
| 9.92 | 0.62 | 0.99 |
| 3.91 | 1.23 | 1.8 |

**Table A-6 Performance parameters for CNG and gasoline at 4500 rpm**

| LOAD (kg) | BSFC(CNG) (kg/kWh) | BSFC(GASOLINE) (kg/kWh) |
|---|---|---|
| 19.32 | 0.55 | 0.65 |
| 12.45 | 0.71 | 0.79 |
| 8.6 | 0.82 | 0.95 |
| 3.94 | 1.66 | 1.9 |

### Table A-7 CO emissions for CNG and gasoline at WOT

| SPEED (rpm) | CO(CNG) (% vol.) | CO(GASOLINE) (% vol.) |
|---|---|---|
| 5079 | 2.46 | 5.66 |
| 4506 | 2.33 | 5.12 |
| 3933 | 2.19 | 5.07 |
| 3513 | 2.53 | 5.8 |
| 3006 | 2.28 | 5.4 |
| 2503 | 2.77 | 5.9 |

### Table A-8 CO emissions for CNG and gasoline at 2500 rpm

| LOAD (kg) | CO(CNG) (% vol.) | CO(GASOLINE) (% vol.) |
|---|---|---|
| 15.93 | 1.87 | 4.96 |
| 11.75 | 1.63 | 2.2 |
| 7.3 | 0.84 | 1.3 |
| 4.24 | 0.85 | 1.5 |
| 0 | 0.6 | 1.2 |

### Table A-9 CO emissions for CNG and gasoline at 3000 rpm

| LOAD (kg) | CO(CNG) (% vol.) | CO(GASOLINE) (% vol.) |
|---|---|---|
| 16.91 | 3.79 | 5.73 |
| 10.9 | 2.4 | 4.1 |
| 7.26 | 2.27 | 4.15 |
| 3.48 | 1.73 | 3.79 |
| 0 | 0.61 | 0.82 |

**Table A-10 CO emissions for CNG and gasoline at 3500 rpm**

| LOAD (kg) | CO(GASOLINE) (% vol.) | CO(CNG) (% vol.) |
|---|---|---|
| 16.76 | 4.35 | 2.47 |
| 10.9 | 4.31 | 2.46 |
| 7.57 | 4.38 | 1.89 |
| 3.33 | 4.44 | 1.37 |
| 0 | 4.14 | 1.28 |

**Table A-11 CO emissions for CNG and gasoline at 4000 rpm**

| LOAD (kg) | CO(CNG) (% vol.) | CO(GASOLINE) (% vol.) |
|---|---|---|
| 19.47 | 3.5 | 3.65 |
| 13.49 | 2.25 | 3.32 |
| 9.92 | 2.12 | 2.99 |
| 3.91 | 1.91 | 2.7 |
| 0 | 1.98 | 2.5 |

**Table A-12 CO emissions for CNG and gasoline at 4500 rpm**

| LOAD (kg) | CO(CNG) (% vol.) | CO (GASOLINE) (% vol.) |
|---|---|---|
| 19.32 | 3.06 | 5.2 |
| 12.45 | 2.25 | 3.8 |
| 8.6 | 2.4 | 2.8 |
| 3.94 | 2.12 | 2.6 |
| 0 | 2.54 | 2.95 |

**Table A-13 HC emissions for CNG and gasoline at WOT**

| SPEED (rpm) | HC(CNG) (ppm) | HC(GASOLINE) (ppm) |
|---|---|---|
| 5079 | 107 | 180 |
| 4506 | 97 | 120 |
| 3933 | 83 | 103 |
| 3513 | 89 | 95 |
| 3006 | 82 | 89 |
| 2503 | 65 | 76 |

**Table A-14 HC emissions for CNG and gasoline at 2500 rpm**

| LOAD (kg) | HC(CNG) (ppm) | HC(GASOLINE) (ppm) |
|---|---|---|
| 15.93 | 38 | 55 |
| 11.75 | 67 | 72 |
| 7.3 | 66 | 70 |
| 4.24 | 60 | 64 |
| 0 | 42 | 58 |

**Table A-15 HC emissions for CNG and gasoline at 3000 rpm**

| LOAD (kg) | HC(CNG) (ppm) | HC(GASOLINE) (ppm) |
|---|---|---|
| 16.91 | 60 | 65 |
| 10.9 | 82 | 91 |
| 7.26 | 81 | 85 |
| 3.48 | 83 | 87 |
| 0 | 71 | 76 |

**Table A-16 HC emissions for CNG and gasoline at 3500 rpm**

| LOAD (kg) | HC(GASOLINE) (ppm) | HC (CNG) (ppm) |
|---|---|---|
| 16.76 | 78 | 71 |
| 10.9 | 92 | 82 |
| 7.57 | 90 | 79 |
| 3.33 | 96 | 83 |
| 0 | 101 | 85 |

**Table A-17 HC emissions for CNG and gasoline at 4000 rpm**

| LOAD (kg) | HC(CNG) (ppm) | HC(GASOLINE) (ppm) |
|---|---|---|
| 19.47 | 73 | 79 |
| 13.49 | 91 | 98 |
| 9.92 | 86 | 94 |
| 3.91 | 88 | 99 |
| 0 | 82 | 90 |

**Table A-18 HC emissions for CNG and gasoline at 4500 rpm**

| LOAD (kg) | HC (CNG) (ppm) | HC (GASOLINE) (ppm) |
|---|---|---|
| 19.32 | 66 | 69 |
| 12.45 | 85 | 92 |
| 8.6 | 89 | 97 |
| 3.94 | 92 | 99 |
| 0 | 99 | 102 |

**Table A-19 $CO_2$ emissions for CNG and gasoline at WOT**

| SPEED (rpm) | $CO_2$(CNG) (% vol.) | $CO_2$(GASOLINE) (% vol.) |
|---|---|---|
| 5079 | 10.1 | 12.5 |
| 4506 | 10.2 | 13.5 |
| 3933 | 10.4 | 14 |
| 3513 | 10.1 | 14.2 |
| 3006 | 10.2 | 14.2 |
| 2503 | 10.5 | 14.4 |

**Table A-20 $CO_2$ emissions for CNG and gasoline at 2500 rpm**

| LOAD | $CO_2$(CNG) | $CO_2$(GASOLINE) |
|---|---|---|
| 15.93 | 10.8 | 12.2 |
| 11.75 | 10.8 | 15.1 |
| 7.3 | 11.3 | 15.1 |
| 4.24 | 11.2 | 15.1 |
| 0 | 11.5 | 15.3 |

**Table A-21 $CO_2$ emissions for CNG and gasoline at 3000 rpm**

| LOAD (kg) | $CO_2$(CNG) (% vol.) | $CO_2$(GASOLINE) (% vol.) |
|---|---|---|
| 16.91 | 9.3 | 11.6 |
| 10.9 | 10.2 | 14.9 |
| 7.26 | 10.2 | 14.9 |
| 3.48 | 10.5 | 14.6 |
| 0 | 11.2 | 14.6 |

**Table A-22 $CO_2$ emissions for CNG and gasoline at 3500 rpm**

| LOAD (kg) | $CO_2$(GASOLINE) (% vol.) | $CO_2$(CNG) (% vol.) |
|---|---|---|
| 16.76 | 12.5 | 10.2 |
| 10.9 | 15 | 10.1 |
| 7.57 | 15 | 10.4 |
| 3.33 | 15 | 10.8 |
| 0 | 14.5 | 10.4 |

**Table A-23 $CO_2$ emissions for CNG and gasoline at 4000 rpm**

| LOAD (kg) | $CO_2$(CNG) (% vol.) | $CO_2$(GASOLINE) (% vol.) |
|---|---|---|
| 19.47 | 9.3 | 12.3 |
| 13.49 | 10.1 | 12.9 |
| 9.92 | 10.3 | 15.1 |
| 3.91 | 10.3 | 15.1 |
| 0 | 11.2 | 14.5 |

**Table A-24 $CO_2$ emissions for CNG and gasoline at 4500 rpm**

| LOAD (kg) | $CO_2$(CNG) (% vol.) | $CO_2$ (GASOLINE) (% vol.) |
|---|---|---|
| 19.32 | 9.6 | 11.6 |
| 12.45 | 10.1 | 12.8 |
| 8.6 | 10.3 | 13.5 |
| 3.94 | 11.2 | 15.2 |
| 0 | 11.2 | 15.1 |