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Performance and Emissions of Internal Combustion Engine Fuelled With CNG - A Review

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***Abstract* – The development of alternative fuels such as natural gases has become very essential because of the continuously decrease in the petroleum reserves and also their contribution for pollutants. In this paper, a survey of research papers on the utilization of Compressed Natural Gas in the Internal Combustion engines along with its effects on the performance and emissions is done. It is revealed that the performance characteristics except thermal efficiency and exhaust temperature, various other performance parameters like brake mean effective pressure, power, torque and brake specific fuel consumption are decreased for CNG fuelled engine while the emission characteristics of unburnt hydrocarbon, Carbon monoxide and Carbon-di-oxide except nitrogen oxides are better for CNG compared to petrol and diesel engines. The improvement in performance is observed with the addition of hydrogen.**

***Keywords* – Engine fuel, CNG.**

I. Introduction

Nowadays the world is facing serious problem of the air pollution with the increase in population and its increasing demand of the energy. To meet the required demand the alternative fuels used in gasoline and diesel engines are becoming the subjects of interest today. Most of the concerns are driven by two factors first is various new laws pertaining to clean air and second is energy independence from petroleum based fuel. Natural gas, referred to as green fuel, has emerged as a solution to depleting crude oil resources as well as deteriorating urban air quality problem. There are three forms of natural gas: liquefied natural gas (LNG) liquefied petroleum gas (LPG) and compressed natural gas (CNG).Both LNG and CNG are based on methane. The difference is LNG made by refrigerating natural gas to condense it into a liquid while CNG still in the gaseous form. LNG is much denser than natural gas or CNG. That means LNG is good for large trucks that need to go a long distance before they stop for more fuel. LPG is based on propane and other similar types of hydrocarbon gases. These hydrocarbons are gases at room temperature, but turn to liquid when they are compressed [5, 10]. Before any alternative fuels could be used as an alternative to petrol or diesel, it has to fulfill some criteria. Following listed suitability factors that would support alternative fuel to become a choice over petroleum fuels, these includes [1, 4]

a) Reserve of fuel must be plentiful.
b) Sufficient number of refueling points must exist.
c) Specialized engines, fuel tank and other parts must be commercially available.
d) Process efficiency.
e) The cost associated with using alternative fuel must be comparable with the existing one.
g) The fuel storage system must be compatible to get install on the vehicle.
h) Alternative fuel must offer reduced emissions.

CNG meet almost all the requirements mentioned above. CNG a gaseous form of natural gas clearly has some substantial benefits compared to gasoline and diesel. CNG resources are available in abundant quantity and wide spread geographically, based on the current consumption rates of the fossil fuels, the reserves of natural gases are sufficient to supply energy needs for almost 200 years. The availability of the gaseous fuels and the demand to use them for power generation has led to manufacturing of the gas engines. Most of the engines are modified from the diesel engines to run on gas by introducing the gas governing, ignition, carburetion also some changes in design by changing the compression ratio, valve timing, and changes in combustion chamber. Optimized gas engines are expected to produce less carbon monoxide near zero reactivity of methane. However the main problem that all researchers and manufacturers are facing now with CNG engine is the low power output due to losses in volumetric efficiency, low flame speed and absence of fuel evaporation. This lack of engine performance is cause by two main factors the one is CNG fuel characteristics and other is the improper operating conditions of the CNG engine. Therefore, most of the researches on CNG engine are directed to accomplish these factors.

The main objective of the paper is to study the suitability and properties of CNG as an alternate fuel also to study performance & emissions of CNG fuelled engine along with the factors affecting them.

II. CNG as an Alternative Fuel

CNG is a mixture of hydrocarbons in gaseous form, consists of approximately 80-90 % of methane along with some percentage of ethane, propane, nitrogen [3]. The main source of CNG fuel are mainly underground reserves, it can also be made from agricultural waste, human waste and garbage. The composition of CNG is given in the Table no.1

Table 1: Compressed Natural Gas Composition

Component	Symbol	Volumetric %
Methane	CH_4	89.4
Ethane	C_2H_6	4.6
Propane	C_3H_8	1
Butane	C_4H_{10}	0.3
Nitrogen	N_2	4

Thermodynamic properties of CNG, Petrol & Diesel are described in the Table no.2**,** CNG has low energy density, and hence it is compressed to a pressure of 200 to 250 MPa to enhance the vehicle on-board energy storage [10]. CNG is colorless, odorless, non-toxic, lighter than air and inflammable. The advantages of CNG compared to gasoline & diesel are as follows [2, 8].

a) Unique combustion and suitable mixture formation properties.
b) Due to high octane number of CNG, engine operates smoothly with high compression ratios without knocking.
c) Higher flammability compared to gasoline that make it appropriate to run on lean burn technology will leads to lowering exhaust emissions and fuel operating cost.
d) CNG is safer, lighter, burns cleaner and dissipates quickly than most of the other fuel.
e) It ignites quickly, it ignites only when the gas to air ratio is between 5-15% by volume.
f) Because it is a clean burning fuel, engine durability is very high, it reduces the required maintenance of vehicle, can be half of gasoline-oil changes more than every 15-30,000 km, spark plug points can be up to 120,000 km.
g) Also it does not mix up with the lubricants to dilute it or reduce its viscosity so that lubricant consumption is lower in gas engines than gasoline or diesel engines.

The rates of CNG are cheaper per liter equivalent than gasoline. Engine-out emissions of HC and CO can be reduced below the corresponding levels for gasoline and diesel engines, In addition to this, there are fewer toxic and carcinogenic pollutants, little or no particulate matter and no evaporative emissions. The main drawback of CNG is its lower flame speed compared to petrol. This lower flame speed causes the total combustion duration prolonged compared with petrol fuel. It lacks latent heat of vaporization and has poor combustion stability.

Table.2 Thermodynamic properties of CNG, Petrol & Diesel [1, 4, 11]

Properties	CNG	Petrol	Diesel
Formula	CH4	C4-C12	C8-C25
Stoichiometric ratio	17.2	14.2	14.7
Octane/Cetane number	120	90-100	40-45
Auto Ignition Temp °C	540	257	316
Higher heating value (MJ/Kg)	50.3	45	45.76
Lower heating value (MJ/Kg)	45.9	42.2	42
Latent heat of vaporization (KJ/Kg)	-	349	233
Density @ 25 °C (kg/m3)	2.52	749	840
Molecular weight (kg/kmol)	16	106.2	200
Minimum Ignition Energy(MJ)	0.26	0.33	-
flame propagation speed(m/sec)	0.43	0.5	-
Adiabatic Flame Temp (K)	2266	2227	2250
Compression Ratio	9 to 12	9 to 12	16 to 24

Both the SI and CI engines can be converted to run on CNG by using the Bi-fuel and duel fuel conversion kit respectively. Considering the advantages and suitability, CNG seems a very attractive and suitable option as alternate fuel.

III. Performance Characteristics

The various performance parameters such as break power, torque, exhaust temperature, brake specific fuel consumption under study are summarized as follows

3.1 Brake specific fuel consumption

Fuel consumed for one kilowatt power generation in one hour is defined as brake specific fuelconsumption.The experimental analysis [4] held on four cylinders, bi-fuel petrol engine showed that the specific fuel consumption, when the engine was running using the CNG, was always lower than that for the gasoline throughout the speed range. This was mainly due to the higher heating value of the CNG (47MJ/kg) as compared to that of the petrol (44 MJ/kg) and the slow burning of CNG as compared to that of the petrol. At low throttle operation, the specific fuel consumption increases at high rpm because of the rapid increase of friction power as compared to that as displayed by the indicated power. The average specific fuel consumption differences between the gasoline and the CNG operations were around 15.96% and 14.68% at 50% and 80% throttle conditions respectively.

SFC rapidly dropped in the low speed range and nearly leveled off at medium speeds and finally spurted in the high speed range. At low speeds, the heat lost to the combustion chamber walls was proportionately greater, resulting in higher fuel consumption for the power produced. At high speeds, the friction power was rapidly increasing, resulting in a slower increase in the brake power than the rate in fuel consumption, with a consequent increase in the SFC. About 19% of BSFC is less for the CNG engine than petrol engine for the engine speed range of 1500 – 5500 rpm and also it is concluded that the maximum difference is about 24% at lower speed of 2000rpm [1].

The experiment investigation [7] on the CNG dual-fuel variable compression ratio engine observed that the brake specific fuel consumption was reduced with increase in the CNG substitution rate. CNG contributes to an extra heat release on combustion which results in better BSFC than diesel mode.

3.2 Brake Power and Brake Mean Effective Pressure

The low density of CNG where gaseous fuel occupies a larger volume per unit energy and the absence of fuel evaporation cause the air volumetric efficiency and the charge energy density per injection into the engine cylinder reduced the CNG content. In the case of liquid fuels, it was considered that the fuel did not reduce the amount of air sucked into the cylinder. Hence, an engine which was converted to CNG operation would significantly produce the low peak power than that of the gasoline throughout the speed range. The slower flame velocity of CNG causes the total combustion duration prolonged and requires a more advance spark timing to achieve a complete combustion within the correct portion of the engine cycle, this can cause a further reduction in the engine power output of 5–10% compared with petrol fuel and diesel fuel [4].

In an experimental study [1], it is learnt that the engine torque and brake power of CNG fuelled engine are considerably lower than that of petrol engine. The brake mean effective pressure is inversely proportional to engine air/fuel ratio for CNG and petrol fuelled engine with respect to engine speed, it is lower for the CNG as compared to petrol. The faster burning rate of UBC chamber lead to average five percent increase in brake mean effective pressure, and an increase in the lean limit of combustion.

3.3 Exhaust gas temperature

The exhaust gas temperature of the CNG is always higher than that of the gasoline throughout the speed range. Slower flame propagation speed of the CNG than petrol allowed the combustion to precede until the end of the expansion stroke which increased the exhaust gas temperature for the CNG operation also it goes on increasing with the increase of engine speed.

An experimental study proved that on the average exhaust gas temperature was around 5.91-24% and 21.6% more than the petrol for the 50% and the 80% throttle conditions respectively, due to the higher heating value and ignition temperature of the CNG than that of the gasoline. [6]**.**

The experiment [5] showed that the CNG temperature affected the output power produced and three different temperatures produced different values of cylinder pressures. Lower the temperature, higher is the pressure produced in the cylinder. At 250ºC CNG temperature, the pressure produced nearly 40.5 bars, while at 350ºC it dropped to 34.7 bars, this phenomenon happen due to increase in fuel density with the decrease of fuel temperature.

3.4 Thermal Efficiency

Brake thermal efficiency is the function of actual power gain from total supplied energy input. More heat input gives you better results thus higher the calorific value of fuel and better the performance.

A study [6, 14] on the effects of hydrogen addition on the natural gas engine operation resulted that the combination of hydrogen and CNG/air mixture had notable effects on the combustion delay, extended lean burn limit and increased burning rate. For a specific excessive air ratio, thermal efficiency decreases with the increase of hydrogen fraction in natural gas when the hydrogen fraction is less than a certain value 20%, whereas engine power output and thermal efficiency increase with further increase of hydrogen fraction when the hydrogen fraction exceeds value of 20%. The engine operating on lean burn natural gas-hydrogen combustion is favorable for getting higher thermal efficiency.

The experiment investigation [13] on CNG bi-fuel passenger car observed that the brake thermal efficiency improved with hydrogen operation compared to systems running on CNG. The BTE was as high as 31.19% for hydrogen operation compared to that of 27.59% for CNG.

3.5 Volumetric Efficiency

Volumetric efficiency of any engine is defined as the ratio of actual air sucked to total swept volume. Higher volumetric efficiency gives you higher air in resulting into complete combustion causing higher thermal efficiency. The value of air supply is dependent of calorific value; lower the calorific value higher the amount of air needed for combustion of more fuel supplied for maintaining power.

In an experimental study [1, 15] it is observed that the volumetric efficiency of CNG fuelled engine is lower than petrol engine, as the CNG engine occupies more volume of inlet air. The volumetric efficiency for CNG decreases about 13.3% and it has occur at engine speed 4000 rpm and its average value is about 12.3% throughout the engine speed range.

IV. EMISSION CHARACTERISTICS

The carbon monoxide (CO) and dioxide (CO_2) were lower than that of petrol and diesel fuelled engine for all engine speed range, due to low carbon content. The unburnt hydrocarbon (HC) emissions from CNG fuelled engines are less than that of gasoline engines. Theoretically, the HC emissions from CNG fuelled engines should be lower due to the gaseous form which gives an excellent mixing. Hydrogen has strong effects on the combustion of natural gas that can be used to reduce emissions. Addition of hydrogen into natural gas decreases the exhaust HC concentration. However, addition of hydrogen into natural gas will increase NOx concentration.

4.1 Unburnt hydrocarbon (HC) emission

Hydrocarbon is also product of incomplete combustion of fuel. The formation of hydrocarbon is due to lack of proper air supply .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 CNG (16.04), being light weight fuel, CNG 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 During expansion, drop in the pressure in cylinder draws compressed unburnt fuel from crevice volume to create reverse blowby. At the end of this reverse blowby, flame reaction quenched and some unreacted fuel particle remains in the exhaust. Rich air-fuel ratio with insufficient oxygen prompts the incomplete combustion of fuel as a misfire produces the unburnt hydrocarbons.

In the experimental investigation [6] the HC emission of CNG was lower than that of the gasoline throughout the speed range, and on an average of 22.14% and 29.71% lower than petrol. Thus the lean mixtures and exhaust gases temperature of CNG fuelled engine are responsible for reduction in HC emissions compared to petrol engine. The addition of hydrogen in to CNG reduces the exhaust HC concentration.

4.2 Carbon mono-oxide (CO) emission

Carbon monoxide is a product of incomplete combustion of fuel. Formation of carbon monoxide indicates loss of power, result of oxygen deficiency in combustion chamber. Poor mixing of air and fuel, local rich regions and incomplete combustion produces CO. The CNG is more combustible than the gasoline fuel. Higher combustion temperatures is another reason of the low CO emission of the CNG fueled engine. At high combustion temperatures, the CO get converts to CO_2 during combustion.

The CO emission of the CNG was significantly lower than that of the gasoline throughout the speed range. On the average 45.5% and 29.87% less CO emission occurred for the CNG at the 50% and the 80% throttle conditions respectively [4].

According to the experimental investigation [13] carried out on CNG dual fuel retrofitted vehicle, the carbon monoxide (CO) emissions are very lower, up to 80-95% less as compared to current petrol engine.

4.3 Carbon dioxide (CO_2) emission

The composition of gas showed that the CNG consisted mostly of methane (CH_4) whereas the gasoline ($C8H_{18}$) 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 petrol. This led to the lower emission of CO_2 for the CNG than the petrol and diesel 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.

In the experimental work [1] the CO_2 emissions are same for both engines at higher speeds range that is 3500-5000 rpm and also the produced CO_2 in CNG engine is less than petrol and maximum of about 12.5% at engine speed 2500 rpm. It is know that the air/fuel ratio of CNG fuelled engine is very much closer to stoichiometric conditions. Hence CO emissions of CNG fuelled engine is much lower than petrol engine.

The experiment [4] showed that CO_2 emission of the CNG was found to be lower than that of the gasoline throughout the speed range, and on an average, it was around 30.88% and 34.97% lower than that of the gasoline for the 50% and the 80% throttle condition respectively.

4.4 Nitrogen oxides (NOx) emission

Nitrogen oxides are generated from oxygen and nitrogen under high pressure and temperature conditions in the engine cylinder. The NO_x emissions are strongly related to the lean fuel with the high cylinder temperature or high peak combustion temperature. A fuel with high heat release rate at premix or rapid combustion phase and lower heat release rate at mixing controlled combustion phase would produce the NO_x. For this reason; the CNG emitted more NO_x than the gasoline [16]. NO_x is produced more in the post-flame gases than in the flame front. The mixture which burned early in the combustion process was being compressed to a higher temperature, thus increasing the NO_x formation rate, as the combustion proceeded and the cylinder pressure increased. NO_x emissions generally increase with increasing hydrogen content. However, if a catalytic converter, an EGR system or lean burn technique is used, NO_x emission values can be decreased to extremely low levels [9].

The various emissions reduction urban vehicle emissions (based on performance of van) under real world tested by British Gas by using CNG against petrol and diesel are summarized in the table no.3.

Table.3. Emissions Reduction by CNG

Emissions	Reduction against Petrol	Reduction against Diesel
Carbon Monoxide	22-24%	10%
Carbon Dioxide	76%	Natural gas and diesel both low
Nitrogen Oxides	83%	80%
Non Methane Hydrocarbons	88%	80%
Benzene	99%	97%
Lead	100%	not applicable
Sulphur	nearly 100%	nearly 100%

V. Conclusion

Based on the reviewed papers for the utilization of CNG as an alternate fuel, performance and emissions, it is revealed that CNG is a suitable choice as an alternate fuel. Performance parameter except thermal efficiency and exhaust temperature various other parameters like brake mean effective pressure, power, torque and brake specific fuel consumption, volumetric efficiency are decreased for CNG fuelled engine and emissions characteristics such as HC, CO and CO_2 are decreased. Thus a number of conclusions are comprehensible from the results of various experimental studies.

a) The CNG fuelled engine produces less power than that of gasoline or diesel engine. The power reduction occurred due to initial condition of the operating.
b) The engine exhaust gas temperature produced by the CNG burning is always higher as compared with that of the gasoline. The fuel temperature affects output power of CNG fuelled engine due to increase of fuel density.
c) Retrofitted car engine runs on lower BSFC when using CNG than on gasoline.
d) The CNG has an advantage of higher thermal efficiency on an average of 1.1% and 1.6% than that of gasoline and it further increases with addition of hydrogen.
e) CNG fueled retrofitted car engine produced lower emission of HC, CO and CO_2 for all operating conditions.
f) Higher NOx emission is the main emission concern for CNG as automotive fuel which increases with addition of H_2.
g) Addition of hydrogen into natural gas engine power output and thermal efficiency decrease with the increase of hydrogen fraction in natural gas up to 20% whereas engine power output and thermal efficiency increase when the hydrogen fraction exceeds 20%, also there is decreases the exhaust HC concentration.

Thus the present study indicates that the CNG is a better choice as an alternate automobile fuel than the gasoline both economically and environmentally. Thus CNG fuelled engines have a great possibility to be comparable to that of petrol and diesel.

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