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Performance Analysis by Compression Ratio optimization for improved thermal efficiency using CNG as Fuel.

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ABSTRACT

Environmental degradation is on the rise due to an increased motor vehicle population. One of the strategies adopted to curb deteriorating environmental quality is the use of alternative fuels like Ethanol, Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG). Natural gas is abundantly available in all the continents and increase in the use of natural gas will also help in delay of depletion of fossil fuel reserves.
CNG has been promoted as a promising clean fuel alternative to spark ignition engines because of its relatively higher octane level. Due to its high research octane number, CNG (120) and LPG (104), they can be used in combustion at higher compression ratio without knocking. It also offers much lower greenhouse gas emissions.
A high compression ratio is desirable because it allows an engine to extract more mechanical energy from a given mass of air-fuel mixture due to its higher thermal efficiency. Compression Ratio has a large influence on the engine performance, combustion, and emissions. High compression ratio engines burn both much more cleanly and much more efficiently than lower-compression engines.
Objective of the project is to upgrade the performance of a CNG engine & optimize its compression ratio from 9.5:1 to 12.5:1 by modifying its piston bowl geometry for better thermal efficiencies.
Reducing Bowl Depth will decrease the Bowl volume, which will directly help in increasing the Compression Ratio. The reduction in the clearance volume helps combustion, resulting in an increase in the flame temperature, which will increase the thermal efficiency.
Main features of this technology are its cost-effective operation, environment friendly, and can be easily adapted on old generation of vehicles.

Keywords— Compression Ratio,Piston Bowl, Thermal Efficiency

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I. INTRODUCTION

The Recent depletion and fluctuation in prices due to uncertain supplies for fossil fuel have compelled us to find renewable, safe and non-polluting sources of energy. Apart from development of Common Rail Direct Injection and hybrid vehicles, this need has also caused development of gaseous fuels. Compressed Natural Gas (CNG), Liquefied Petroleum Gas (LPG) or Hydrogen could be the best possible alternative depending upon its availability. This will also help in delaying the depletion of fossil fuel reserves.

Compressed Natural Gas (CNG) engine has proved itself to be worthy replacement for diesel in heavy commercial and passenger transport application. Developmentof CNG distribution infrastructure and stringent emission regulations has increased the efforts by Original Equipment Manufacturers (OEM) to concentrate on development of

CNG vehicles across all the segments. Indian cities are facing airquality degradation due to high vehicle density and since contribution of light commercial vehicles in intra city application is enormous, application of dedicated CNG vehicle has been made mandatory in some cities.

As a fossil fuel, natural gas is formed from the decaying remains of pre-historic plant and animal life. It has higher octane number (120) than petrol (91-97).The use of CNG in internal combustion engines yielded higher thermal efficiency and better fuel economy compared to gasoline. This is due to mainly the higher octane rating which permits greater engine compression ratio without the occurrence of knock.

CNG fuelled engines have been used in automotive field, in all combination as an alternate fuel. The advantages of CNG are – clean burning fuel because it produces lower reactive hydrocarbons, improved efficiency because it allows higher compression ratio due to high octane rating, and lower CO_2 emission, due to high H/C ratio.

Main features of this technology are its cost-effective operation and adaptation on old generation of vehicles. These gaseous fuels are having very simple carbon chain structure with lower carbon-to-hydrogen ratio of fuel compared to all other crude oil products. Hence they improve the greenhouse gas emissions. Combustion of Natural Gas or LPG gives lower CO_2 and more water vapor than burning gasoline.

CNG has been used majorly in three different ways. The first is bi-fuel engine when CNG is used with gasoline. It is applied when gasoline engine is converted to operate with CNG also.

II. Background

In recent years, CNG has been promoted as a promising clean fuel alternative to spark ignition engines because of its relatively higher octane level. Higher research octane number, CNG (120), allows their combustion at higher compression ratio without knocking. It also offers much lower greenhouse gas emissions than those from the burning of other hydrocarbons as a result of its higher hydrogen to carbon ratio.CNG has high octane rating, which means it can be used to run at higher CR.

Current CNG engines run at a compression ratio of 9.5:1. A high compression ratio is desirable because it allows an engine to extract more mechanical energy from a given mass of air-fuel mixture due to its higher thermal efficiency. High ratios place the available oxygen and fuel molecules into a reduced space along with the adiabatic heat of compression, causing better mixing and evaporation of the fuel droplets. Thus they allow increased power at the moment of ignition and the extraction of more useful work from that power by expanding the hot gas to a greater degree.

High compression ratio engines burn more cleanly and more efficiently as compared to lower-compression engines.

III. Compression Ratio

Compression ratio refers to how the cylinder's space changes from when the piston is down to when the piston is up. To calculate the ratio of a vehicle, we must use the formula, compression ration = volume at bottom dead center divided by volume at top dead center.

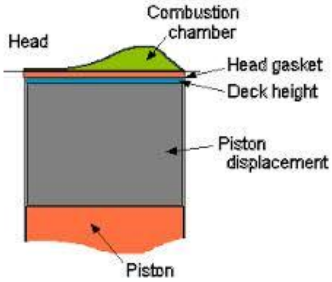

Fig. 1 Swept and Clearance volumes

Compression ratio (CR) is the ratio of the total volume of the combustion chamber when the piston is at the bottom dead center (BDC) to the total volume of the combustion chamber when piston is at the top dead center (TDC).

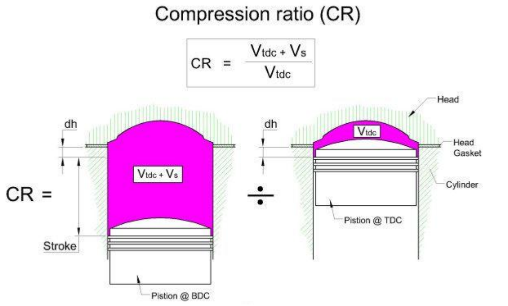

Fig. 2 Compression Ratio Calculation

Theoretically, increasing the compression ratio (CR) of an engine can improve the overall efficiency of the engine by producing more power output. The ideal cycle analysis for SI combustion chamber show that indicated fuel conversion efficiency increased continuously with compression ratio according to Equation.

$$\eta_T = (1 - \frac{1}{r_C^{\gamma-1}})$$

Where, γ is ratio of specific heats (for air γ = 1.4).

However, changing the compression ratio has effects on the actual engine for example, the combustion rate. Also over the load and speed range, the relative impact on brake power and thermal efficiency varies. Therefore, only testing on real engines can show the overall effect of the compression ratio. Knocking, however, is a limitation for increasing the compression ratio.

Higher CR increases the combustion efficiency of CNG engines. With the higher compression ratio the lean burn limit increases because of the reduction in initial combustion period. Under part load conditions, the fuel economy can be improved with higher compression ratio. However, this is often associated with problem of knocking and roughness.

Lean burning improves the fuel economy as well as reduces the emission levels. However, lean burning leads to problems such as quenching of flame, which can be overcome by increasing the compression ratio. However increasing compression ratio leads to higher operating cylinder pressures and temperature at low operating speeds at higher throttle openings. This nullifies the advantage of better fuel economy at low load operating condition.

To accurately calculate compression ratio, following information are requires:

1) The bore and stroke of the cylinder
2) The volume of the combustion chamber
3) The compression height of the piston.
4) The dome/dish volume of the piston.
5) The piston-to-deck clearance.
6) The bore diameter and thickness of the head gasket.

IV. EFFICIENCY OF AN OTTO CYCLE

The starting point is the general expression for the thermal efficiency of a cycle:

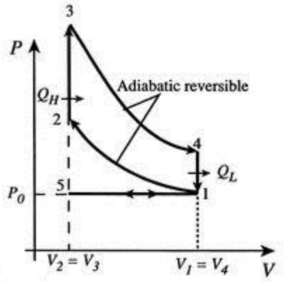

Fig. 3P-V Diagram of Otto Cycle

$$\eta = \frac{\text{work}}{\text{heat input}} = \frac{Q_H + Q_L}{Q_H} = 1 + \frac{Q_L}{Q_H}.$$

The convention, as previously, is that heat exchange is positive if heat is flowing into the system or engine, so Q_L is negative. The heat absorbed occurs during combustion when the spark occurs, roughly at constant volume. The heat absorbed can be related to the temperature change from state 2 to state 3 as:

$$Q_H = Q_{23} = \Delta U_{23} \qquad (W_{23} = 0)$$

$$= \int_{T_2}^{T_3} C_v dT = C_v(T_3 - T_2).$$

The heat rejected is given by (for a perfect gas with constant specific heats)

$$Q_L = Q_{41} = \Delta U_{41} = C_v(T_1 - T_4).$$

Substituting the expressions for the heat absorbed and rejected in the expression for thermal efficiency yields

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2}.$$

We can simplify the above expression using the fact that the processes from 1 to 2 and from 3 to 4 are isentropic:

$$T_4 V_1^{\gamma-1} = T_3 V_2^{\gamma-1}, \qquad T_1 V_1^{\gamma-1} = T_2 V_2^{\gamma-1}$$

$$(T_4 - T_1) V_1^{\gamma-1} = (T_3 - T_2) V_2^{\gamma-1}$$

$$\frac{T_4 - T_1}{T_3 - T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

The quantity V1/V2 =r is called the compression ratio. In terms of compression ratio, the efficiency of an ideal Otto cycle is:

$$\eta_{\text{Otto}} = 1 - \frac{1}{(V_1/V_2)^{\gamma-1}} = 1 - \frac{1}{r^{\gamma-1}}.$$

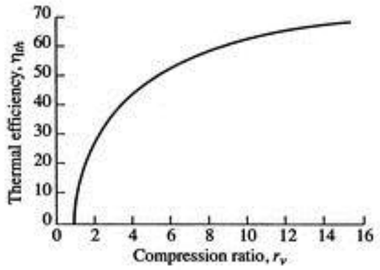

Fig. 4Thermal efficiency vs. Compression ratio for Otto cycle

The ideal Otto cycle efficiency is shown as a function of the compression ratio in Figure. As the compression ratio, r, increases, efficiency of Otto cycle increases, but so does T2. If T2 is too high, the mixture will ignite without a spark (at the wrong location in the cycle).

V. FUEL PROPERTY ANALYSIS

Important fuel properties of gaseous fuels such as octane number, calorific value etc.

TABLE I
FUEL PROPERTIES

PROPERTY	GASOLINE	CNG
Chemical formulae	C8H18	CH4
Carbon, % composition	85-88	75
Hydrogen, % composition	12-15	25
Density, kg/m3	720	0.550
Octane Number	89-94	120+
Auto-ignition temperature, °C	290	610
Latent heat of vaporization, kJ/kg	9.94	12.79
Stoichiometric air/fuel, weight	14.7	17.2
Calorific value, kJ/kg	44000	45000

The effect of these fuel properties on gas engine performance is discussed below.

1) *Octane Number:* The octane number for gaseous fuels is comparatively higher than that of gasoline. This indicates better anti-knock properties. As a result, higher compression ratio can be used for CNG as compared to gasoline. This directly contributes to the power, thermal efficiency and fuel economy.

2) *Composition:*Gasoline has higher percentage of carbon as compared to gaseous fuels. On the other hand presence of C-H bonds in gaseous fuels as compared to C-C bonds in gasoline tends to reduce emission.

3) *Density:*Density for gaseous fuels especially for CNG is very low as compared to gasoline. As a result, for the same amount of air handled, CNG displaces about 10% and LPG displaces 2% of

the air, which is comparatively higher than that for gasoline. This results in reduced volumetric efficiency for gaseous fuels.

4) *Latent Heat of Vaporization:* Gaseous fuels like CNG lack latent heat of vaporization. As a result, the reduction of mixture temperature in the chamber, which occurs in gasoline injection, is absent for gaseous fuel. This also contributes to reduction in volumetric efficiency.

5) *Stoichiometric Ratio:* The stoichiometric air fuel ratio for gaseous fuels is more than that for gasoline. As a result, for same amount of air handled by engine less amount of gaseous fuel is burned. For same quantity of air handled by the engine, quantity of fuel that can be burned is lower by 15% for CNG and 9 % for LPG.

6) Calorific Value: The calorific value for CNG is about 1% higher than that of gasoline. However the energy obtained from gaseous fuels for same amount of air handled, is about 13% less for CNG and about 2% less for LPG as compared to that of gasoline.

VI. Literature Review

A) Mr. Shinde, B. J and Adsure, S. S, of Force Motors Ltd., performed the similar experiment on a single cylinder engine while converting it from diesel to CNG. Their findings were, Optimized CNG with compression ratio (11:1) shows 9-10% improvement in power and 8-11% improvement in brake specific fuel consumption.

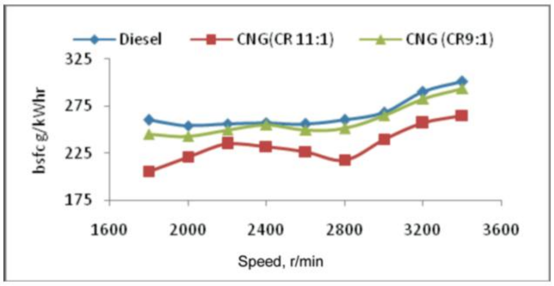

Fig. 5 Brake Specific Fuel Consumption Comparison

B) Mr. Shanmugam, Anbukarasu, AS Babu, YR and VinayHarne of TVS Motor Company performed the similar experiment on a 2 Stroke CNG engine for 3-wheeler vehicle. They concluded that the effect of compression ratio and spark timing is only limited for NOx emission in this test condition however power and torque performance is directly proportional to CR. With the higher compression ratio the lean burn limit increases because of the reduction in initial combustion period. Under part load conditions, the fuel economy can be improved with higher compression ratio. However, this is often associated with problem of knocking and roughness. Lean burning improves the fuel economy as well as reduces the emission levels. However, lean burning leads to problems such as quenching of flame, which can be overcome by increasing the compression ratio. However increasing compression ratio leads to higher operating cylinder pressures and temperature at low operating speeds at higher throttle openings.

C) S. Krishnan, D. S. Kulkarni and J. P. Mohite of TATA Motors in their research tested engine with higher compression ratio (CR 9.0 to CR 9.5) and found good results. Power with 9.5 CR is 2.5% more than with 9.0 CR cylinder head. They concluded Higher CR would help to improve engine and vehicle performance further.

D) V S Midhun, S Karthikeyan and S Krishnan of Ashok Leyland, conducted similar work on Piston and Bowl Geomtry to achieve desired compression ratios which helped them in reducing the cost of by having the same casting for both the diesel and CNG piston and the change being in the machining only.

VII. Methodology

In the CNG mode, Thermal efficiencies for four Compression Ratios (CR) (9:1 to 12.5:1) will be analyzed with hemispherical piston bowl geometry. Modifying the dimensions of the piston bowl in the combustion chamber will be done to attain different compression ratio for the investigation, viz. CR 9.5 to 10, 11, 12 and 12.5.

Decrease in Clearance volume will increase the Compression ratio and this will be achieved by decreasing Piston Bowl Volume. Refer Figure no.6;Reducing Bowl Depth will decrease the Bowl volume, which will directly help in increasing the Compression Ratio.

Fig. 6Example of Piston Bowl depth variation

For the engine testing, CNG dedicated engine will be tested by testing at 5 compression ratio pistons as 9, 10, 11, 12 and 12.5. Theengine testing schematic is shown in figure 7.

Fig. 7Test Setup

The setup consists of single cylinder, four stroke, VCR (Variable Compression Ratio) Research engine connected to eddy current dynamometer. It is provided with necessary instruments for combustion pressure, crank-angle, airflow, fuel flow, temperatures and load measurements. These signals are interfaced to computer through high speed data acquisition device. The set up has stand- alone panel box consisting of air box, twin fuel tank, manometer, fuel measuring unit, and transmitters for air and fuel flow measurements, process indicator and piezo powering unit. Rotameters are provided for cooling water and calorimeter water flow measurement.

Engine performance study includes brake power, indicated power, frictional power, BMEP, IMEP, brake thermal efficiency, indicated thermal efficiency, Mechanical efficiency, volumetric efficiency and heat balance.

VIII. CONCLUSIONS

From above literature it can be concluded that CNG is suitable alternative for SI engine. But the performance and emission characteristic of CNG fuelled engine was studied at lower compression ratio. And it was observed that engine output decreases. As it’s known, CNG has a high octane number. Thus, it may lead to operating with higher compression ratios, and consequently, the engine efficiency and fuel economy would be better than those, which were determined here.

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