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Effects of CNG Injection Pressure on Performance, Emission and Combustion Characteristics of Multi-cylinder SI Engine

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Abstract: ***This Paper shows the effect of port fuel injection pressure of CNG in 3-cylinder SI Engine at Wide Open Throttle position using sequential port fuel injection system. All trials are performed on 4-stroke, 796 cc MPFI S.I engine at injection pressure of 2.0, 2.2, 2.4, 2.6, 2.8 bar for constant speed of 2500, 3000, 3500, 4000 & 4500 rpm. During the trial compression ratio is kept constant at 9.2 with Maximum Brake Torque (MBT) spark timing of 15°BTDC. Optimum torque is obtained for CNG at injection pressure of 2.6 bar and 3000 rpm. Gasoline trials are performed at same compression ratio for comparison with CNG at same injection pressure. Performance and emission characteristics with combustion analysis are performed at optimum injection pressure of 2.6 bar.***

Keywords: CNG, Injection Pressure, PFI, bsfc, Gasoline, HRR, brake specific fuel consumption, brake power

I. INTRODUCTION

Due to the low particulate matter and CNG Emission CNG being the best fuel for SI Engine. To improve the thermal efficiency, lean burn approach to the fuel is effective way to reduce the emission. To see how the fuel pressure during injection impacts on performance, the test is carried out. CNG is insoluble in engine oil. It does not contaminate and dilute lubricating oil. Therefore CNG does not form the deposits on spark plug which in turn increases the life of spark plug. It mixes with air completely and evenly providing smother and cleaner cold operation. Proper mixing of air fuel, does not create the problem like backfiring and knocking at higher Compression Ratio which in turn increase the life of spark plug**.** By looking its advantages, natural gas would play a big role in satisfying the energy demands. Natural gas Production saw huge growth in the last decade. Its Production increased in many parts of the world so there may be increase in coming years also. CNG is one of the most environment friendly fuels because of its rich content of chemical property such as Research Octane Number (120 to 130). High Compression Ratio can be obtained easily without abnormal combustion like detonation. Natural gas has many advantages over gasoline. The ignition temperature of natural gas is higher than diesel fuels and gasoline. [1]

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II. LITERATURE RIVIEW

H.L Jones et.al [2] studied the high pressure injection on Compression ignition and direct injection on natural gas engine. A Six cylinder, 4 stroke DI engine was experimented. At high load, high injection pressure reduces particulate emissions. The effect of injection pressure on PM is quite less as in cylinder geometry changes. At moderate speed, with increase in high pressure CO emissions are reduced. CO emissions increase due to change in cylinder geometry. HC emissions are inconsistent and insignificant for different operating conditions. Barisat Tabrisat [3] has experimented for concomitant injection for turbocharged injection. Result shows that thermal efficiency is improved by the concomitant injection compared to gasoline. This technique shows better performance for CNG than gasoline with respect to fuel consumption and emission. The injection mode has low deterioration on mass fraction of CNG. For gasoline mode, the emission like HC,CO, NOx but for CNG is 25%. M Baharm [4] has studied the effect at medium injection Pressure (1.4Mpa) for the different injection timing on hydrogen blends (0%, 3%, 5%, 8%). 120^0, 180^0, 300^0 CA BTDC were the different injection timing at WOT Condition with Equivalence ratio equal to one was selected. Result shows that the performance [BP, BMEP, Brake Torque] have highest Value at injection timing of 180^0 followed by 120^0 CA BTDC and 300 CA BTDC. Addition of small amount of hydrogen reduces the emission and enhances combustion for any selected injection timing. The injection timing of 300^0 CA BTDC was considered to have better engine performance compared to others. Semin [5] have considered sequential Port Fuel injection on CNG Engine. To improve the efficiency perfect mixing of air and fuel should be there.

By arranging the injector nozzle by number in 1.78 mm, 3.55mm, 5.33mm, 7.10mm valve lift the 4 hole injector nozzle have shown best air fuel mixing. In 1.78mm Valve Lift best air fuel mix is observed at 4 hole injector nozzle. In 3.55 mm Valve Lift, best air fuel mix is observed for 4 hole injector nozzle.

In 5.33mm valve lift, best air fuel mix is observed at 2 hole injector nozzle. In 7.10mm Valve Lift, best air fuel mix is observed at 4 hole injector nozzle. Saad aljamali [6] experimented CNG Engine with the effect of injection on direct injection.1.6L capacity engine, 4-cylinder SI Engine with CR=14 was used. At the end of 120^0 BTDC, injection timing was set at 4000 rpm. Brake Power and Brake Torque are high at 180^0 BTDC. At 120^0 BTDC, BSFC was reduced. And CO_2 emission was also reduced at low speed. R.S Hosmath [7] Studied how the injection timing is effected on dual engine functioning with honge oil methyl ether [HOME] and CNG. Maximum BTE of 28.7% at rate of 0.6 KG/hr of BTDC is obtained for DF Engine operation but it is lower than HOME operation and the low CO emission are observed at 26% with the rate of 0.6 Kg/Hr and 27 BTDC compared to HOME operation. Z Taha [8] studied the injection characteristics for high pressure of CNG fueled SI engine. The effect of CNG injection pressures done in Case 1 and the effect of pulse-width of injection duration is evaluated in second case. In first case, it was seen that injection pressure affects the mass flow rate. However, in second case, that the average mass flow rate at short injection durations is less than that of in Case 1. Based on the experiment, the mass flow rate is in the range of 0.4 g/s to 1.2 g/s for injection pressure of 20 bar to 60 bar which is theoretical flow rate which is required by the engine, At 50 bar injection pressure, the average mass flow rate for Case 2 is 0.7 g/s and for Case 1 is 1.1 g/s respectively.

III. Experimental Setup

Trials are performed on 3-cylinder, 4 Stroke 796 CC water cooled SI Engine. Eddy current dynamometer is used for engine loading and exhaust emissions are measured with AVL 5-gas analyzer. All the results are calculated using 'IC Engine Soft' Ni-DAQ Software. For cranking the engine, DC Motor is used. To measure the dynamic load, special high alloy steel Load cell is used on rotor shaft of dynamometer. The speed is measured with Crank angle sensor and the exhaust temp is measured by thermocouple which is inserted at center at 0.05 m diameter exhaust pipe. Air Box is used for the measurement of air in which diameter of orifice is 35 mm of water column and the fuel is measured by burette method in LPM [Liter Per Minute] of fuel. Hot water is circulated in an engine around CNG Vaporizer to avoid icing of CNG outlet nozzle. Engine exhaust emission such as CO, CO_2, HC, O_2 and NO_x are measured by AVL-5 gas Analyzer. Chemiluminesence method is used for the NO_x measurement. Timing light is used to measure MBT spark timing on crank angle teeth gear. The Piezoelectric transducer is used to measure in-cylinder pressure. IC Engine Soft 9.0 Combustion Software is used for combustion analysis.

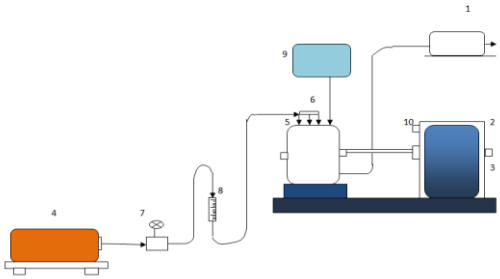

Fig 1: Experimental setup

1-Exhaust Gas Analyzer, 2-Eddy Current Dynamometer, 3-Crank Angle and Rpm Sensor, 4-CNG Cylinder, 5-CNG Rail with injector, 6-CNG ON/OFF Valve, 7-CNG Two Stage Regulator, 8-CNG flow meter, 9-Air Box with manometer, 10-Load Cell

Fig1a : Engine Setup

IV. Properties of Fuel

Sr No	Property	CNG	Gasoline	Diesel
1.	Octane /Cetane No	120-130	85-95	45-55
2.	Molar Mass (Kg/mol)	17.3	109	204
3.	Stoichiometric (A/F) Mass	17.2	14.7	146
4.	L.H.V (MJ/kg)	47.5	43.5	42.7
5.	Combustion Energy	24.6	42.7	36
6.	Flame Propagation Speed(m/s)	0.41	0.5	-
7.	Adiabatic Flame Temp C	1890	2150	2054
8.	Auto Ignition Temp	540	258	316
9.	Wobble Index (MJ/m3)	51-58	-	-

V. Experimental Procedure

All the Trails are performed at wide open throttle WOT Condition with fuel injection pressure of 2.0,2.2,2.4,2.6,2.8 bar having compression ratio 9.2:1 and MBT spark Timing at 15^0. Depending upon the engine speed and load, the equivalence ratio is varied by injection pressure. By varying the regulator the injection is monitored by integrated gasoline ECU. Readings are taken at engine speed of 2500, 2500, 3000, 3500, 4000 rpm. With decrease in load the engine speed increases at WOT position.

Equivalent weight of water column is calculated as,

$$h_a\rho_a = h_w\rho_w$$

where $\rho_a = \frac{P}{RT} = \frac{101325}{0.287 \times 300} = 1.12 kg/m^3$

Actual Volume of air Sucked

$V_a = C_d \times \sqrt{(2gh_a)} \times A_0$

where,

P=Atmospheric pressure, bar
C_d= Coefficient of discharge
g=Acceleration due to gravity
h_a=Equivalent weight of air column, m
A_0=Area of orifice, m

Standard observation

Engine Specification

Engine Type	Four Stoke
No of cylinders	Three
Bore	66.50mm
Connecting rod length	114mm
Compression ratio	9.2:1
Fuel system	Port injection
Cooling system	Water cooled
Density of CNG	1.6679 kg/m³
Calorific Value	46720 J/kg
Radius of Brake Drum	210mm
Diameter of Cylinder	62mm
Stroke Length	72mm
Orifice Diameter	35mm
Engine Rated Power	27.6kW @5000 rpm
Torque	59 N-m @2000 rpm

VI. Result and Discussion

The results presented in the paper are at Wide Open Throttle (WOT) condition having compression ratio 9.2:1 and MBT Spark Timing 15^0 BTDC, with 2.6 bar optimum injection pressure.

Performance Characteristics:

1. Volumetric Efficiency

Fig 3 shows the volumetric efficiency at different operating conditions, Volumetric efficiency gives the idea of mass of air and fuel admitted to the engine. Volumetric Efficiency firstly decreases and then increases with increase in the injection. At 2500 rpm, maximum volumetric efficiency is noted for the injection pressure of 2.8 bar which shows approx. 92% while for the 2.6 bar it is observed the minimum which equal to 70% and the Volumetric efficiency graph for 2.2 bar and 2.4 bar lies in the middle which has the efficiency range from 85% to 80% from maximum to minimum value.

2. Brake Specific Fuel Consumption

Fig 4 shows BSFC at WOT condition with compression ratio 9.2, the nature of the graph decreases with increases in the injection pressure. At 2 bar about 1.1 kg/kW-hr is maximum fuel consumption and for 2.0 bar with speed of 4000 rpm and minimum value of the fuel consumption is at 2.8 bar which is equal to 0.3 kg/kW-hr.

3. Brake Specific Energy Consumption

Fig 5 shows the Brake Specific Energy Consumption variation with different injection pressure. As the injection pressure increases from 2 bar to 2.8 bar, energy consumption is reduced up to 12 MJ/kW-hr. at 4000 rpm for 2.8 bar. Maximum BSFC is at 2 bar which is 50 mJ/kW.hr and at minimum pressure of 2.4 bar it is 13 mJ/kW-hr at speed of 2500 rpm.

4. Brake Thermal Efficiency

Fig 6 shows the Brake Thermal Efficiency as a function of speed with different injection pressure Maximum and minimum BTE is observed at 2.8 bar and 2.0 bar respectively which shows 22% for maximum at 2500 rpm and minimum 7% at 4000 rpm at 2.8 bar. Brake Thermal efficiency decreases with the CNG fuel due to higher fuel consumption. BTE is reduced by 24% between the upper and lower limits of pressure.

5. Torque

Fig 7 shows Torque as a function of speed with change in injection pressure. At 2.8 bar, it shows 37 N-m at 2500 rpm. As the speed increases it decreases. According to the experimental results these parameters are decreased in CNG fuelled engine. Torque is reduced by 20% with CNG operation for the maximum and minimum pressure. More reduction in torque is observed with increase in speed. At 2.2 bar, 6 N-m torque is observed by increasing the speed up to 4000 rpm, it decreases gradually. A minimum torque is observed for 2.0 bar where is 7 N-m so it is clear that by increasing the speed it shows downward trend.

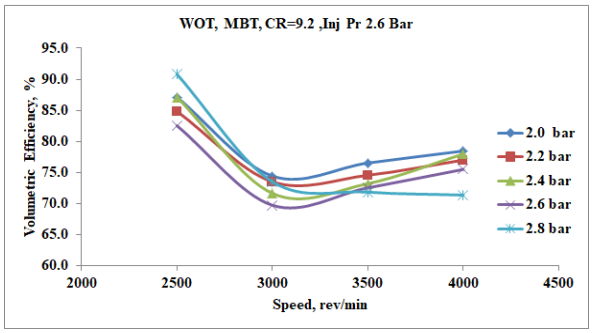

Fig 3: Volumetric Efficiency with Variation in speed

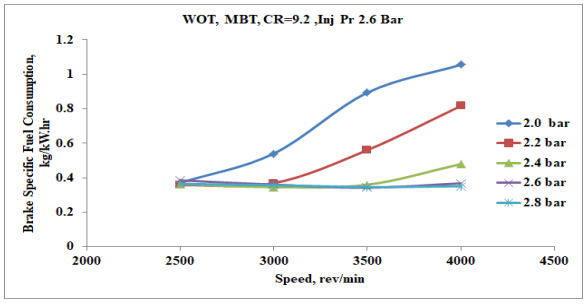

Fig 4: Brake Specific Fuel Consumption with Variation in speed

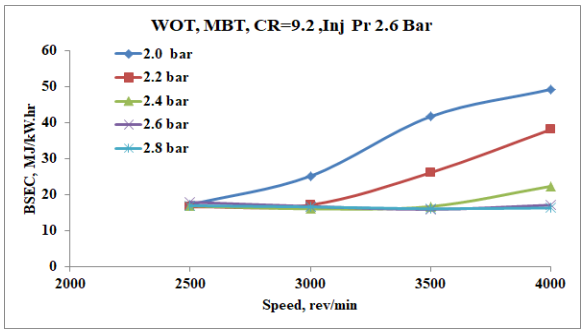

Fig 5: Brake Specific Energy Consumption with Variation in speed

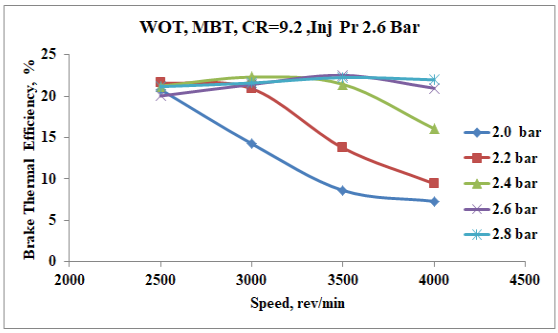

Fig 6: Brake Thermal efficiency with Variation in speed

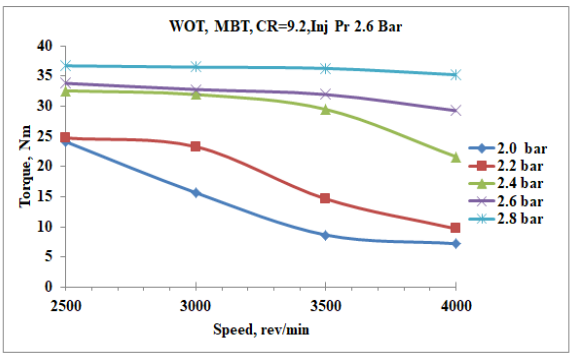

Fig 7: Torque with Variation in speed

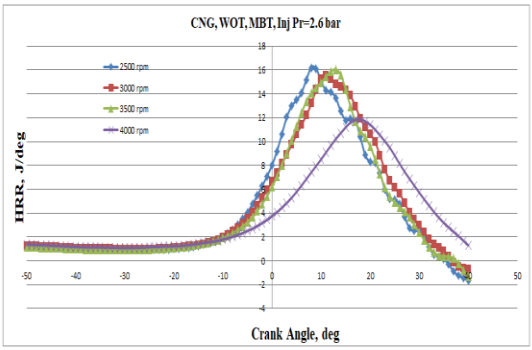

Fig 8: Heat Release Rate with change in Crank Angle

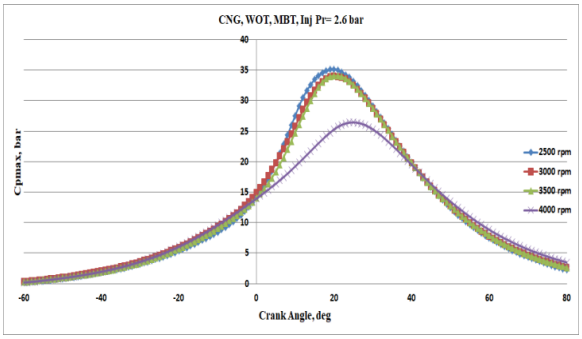

Fig 9: Cylinder Pressure with change in Crank Angle

Combustion Analysis:

6. Heat Release rate

Fig 8 shows how heat release rate varies with crank angle. For the different crank angle varying from -50^0 to 50^0, heat release rate for different speed are plotted where maximum heat release is observed at 2500 rpm and minimum at 4000 rpm.

7. Cylinder Pressure

Fig 9 shows how Cylinder pressure varies with crank angle Cylinder Pressure is maximum for Crank angle 20^0 at speed of 2500 rpm. As the speed increases Cylinder Pressure reduces and is lowest at 30^0 at speed of 4000 rpm.

Emission Characteristics

8. Carbon Monoxide

The variation of CO emission as a function of speed for the pressure of 2.6 bar is shown in figure 10.It is seen that CO emission are very less in lean mixture and is observed that at 2500 rpm emission are less for CNG compared to gasoline .At 2500 rpm, it is 42 gm/kW-hr for CNG and for gasoline it is 100gm/kW-hr. As the speed is increased emissions reduces.

9. Hydrocarbon

Fig 11 shows the emission of hydrocarbon from the engine outlet for the fuels CNG and gasoline in comparison for 2.6 bar. As the speed increases, HC Emission increases. But it is less than gasoline engine. At 2500 rpm, HC Emission is about 0.1gm/kW-hr and that for gasoline at same speed is 0.25 gm/kW-hr. At 4500 rpm, Difference between HC Emission for CNG and gasoline is quite is less.

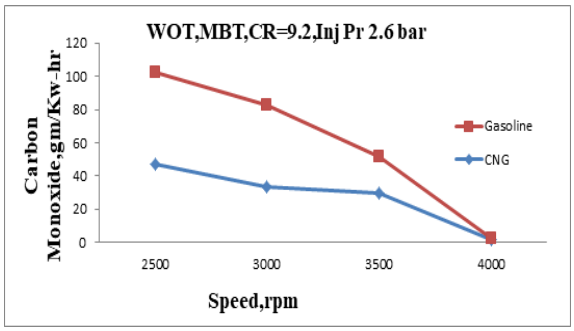

Fig 10: Carbon Monoxide with Variation in speed

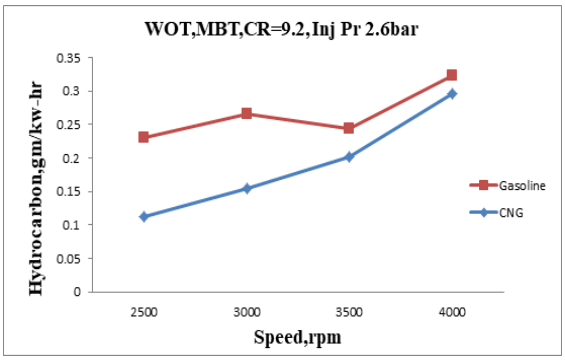

Fig 11: Hydrocarbon with Variation in speed

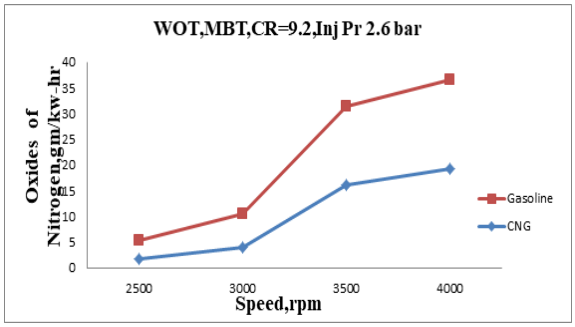

Fig: 12 Oxides of Nitrogen with Variation in Speed

10. Oxides of Nitrogen

Fig 12 shows the emission of nitrogen oxide with respect to the speed at 2.6 bar. At 2500 rpm emission from CNG fueled engine is 5gm/kW-hr. As the speed increases, emission from CNG increases. At 4500 rpm CNG have NOx emission of 18 gm/kW-hr whereas for gasoline at same speed is 36 gm/kW-hr which is exactly double.

VII. CONCLUSION:

All trials are performed at MBT with sequential injection system for compression ratio 9.2:1 in SI Engine. Maximum volumetric efficiency of 92% is observed with 15° BTDC at MBT spark timing for injection pressure of 2.8 bar. The brake specific fuel consumption at 2.6 bar is 0.3 kg/kW-hr. Maximum brake thermal efficiency of 22.5 % was observed at 3000 rpm. Carbon based emission reduced with optimum injection pressure of 2.6 bar of CNG. NOx emission increased with increase in fuel injection pressure.

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