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Review Article

EMISSION AND PERFORMANCE OF DIESEL ENGINE USING DIRECT INJECTION CNG WITH SPARK IGNITION ENGINE- A REVIEW

Uttam R.B.

Address for Correspondence

PG Student, Department of Mechanical Engineering,
L.D. Engineering College, Ahmedabad – 15 (Ahmedabad– Gujarat – INDIA

ABSTRACT

The conversion of a single cylinder diesel engine to CNG fuelled SIDI engine has been performed with the intention of reducing harmful emissions. To do it, it is necessary to change the basic working cycle from compression ignition (CI) to spark ignition (SI), including mixture formation, ignition system and control system. A gasoline direct injection (GDI) injector and a spark plug were installed in the combustion chamber. The CNG was injected into the combustion chamber by the GDI injector and then ignited by the spark plug placed near the injector. The close arrangement of the injector and spark plug provided a stratified charge of CNG around the spark discharge position. Emission and performance tests on both the single cylinder diesel engine and the modified CNG fuelled SIDI engine has been carried out and analyzed.

KEY WORDS: CNG,Diesel engine, Emission, Performance

INTRODUCTION

After Independence of India, Delhi, the capital became major centre of commerce, industry and education. Rapid growth of Delhi resulted in significant increase in environmental pollution. Based on the ambient air quality monitored by the Central Pollution Control Board in 1998, it was found that the contribution from vehicles to the ambient air pollution of Delhi was about 65% of total air pollution. This could be understood from the fact that vehicle population increased from a number of 2,35,000 in 1975 to 21,00,000 in 1991 and further to around 37,00,000 vehicles by 1st January 2004 in Delhi. The sector-wise emission of pollutants in Delhi can be seen from the Table 1.

Table-1*Source: Central Pollution Control Board (CPCB), 1998

POLLUTANTS	TRANSPORT	POWER	INDUSTRY	DOMESTIC	TOTAL
UHC	310	2	6	2	320
SPM	13	50	60	12	135
NITROGEN OXIDES	157	143	20	3	323
SULPHUR DIOXIDE	11	121	35	12	179
CARBON MONOXIDE	810	8	128	117	1063
TOTAL	**1301**	**324**	**249**	**146**	**2020**

The above situation had given dubious distinction to Delhi as one of the most polluted city of the world. With the increasing number of pollutants in Delhi's air and with the background of increasing trend in the use of CNG in the other parts of the world, Public Interest Litigation (PIL) was filed in the Hon'ble Supreme Court of India in 1985 seeking intervention in this matter. The Hon'ble Supreme Court had directed the Government of India to take initiative in promoting the use of CNG, an established clean fuel in the world as transport fuel in Delhi to control the increasing levels of ambient air pollution.

CNG EMISSIONS

The gas fuelled SIDI engine (with the correct control and adjustment) has, in comparison with diesel engine, the following advantages:

- much lower particular matter (PM),
- lower gaseous pollutants (NOx, HC, CO),
- lower operating noise.

Gas fuelled engines are very important for urban transport, municipal good transport and other specificities such as garbage collection. Small cars and small transport vans could also benefit from the low pollution nature (and also low cost) of such technology.

At present the main interest for gaseous fuels lies with LPG and NG (in liquid or gas form – LNG or CNG). with a large number of small vehicles (cars) running in Europe, mainly in Holland [17,18], Italy and France.These gaseous fuels have different physical and chemical properties from the more usual liquid fuels: they have a simpler molecule structure which gives them a good chance for lower production of the exhaust pollutants, namely particulate and polycyclic aromatic hydrocarbon (PAH) emissions. For using as motor fuels, this type of fuels have advantages such as a very good ability for easy mixture formation, both outside and inside the engine cylinder, a wide range of air-fuel ratios (leading to lean or extremely lean mixtures), high heating value and antiknock resistance. These properties enable this SI engine to work with relative high compression ratios and therefore a higher total efficiency (but the efficiency SI engines will not be grater than a CI diesel). The lower mass content of carbon of the gas fuels further reduces CO2 emissions. Other advantages of the use of such gaseous fuels is the reducing emissions during vehicle refueling and operation and lower fire risk of the vehicle. The controlled exhaust emissions of gas fuelled engines are also very low (when compared against emission from more conventional liquid fuels) at low and very low ambient temperature (during cold start or low atmospheric temperature) and their dependence on temperature (engine and ambient) is very small.

SUITABILITY OF CNG AS DIRECT INJECTION SPARK IGNITION ENGINE

Alternative fuels are any materials or substances that can be used as fuels, other than conventional fuels. The benefits of these alternative fuels are that they emit less air pollutants and they are very economical compared to conventional fuels [1]. Natural gas is regarded as one of the most promising alternative fuels and it is composed primarily of methane (CH4) [2]. Compressed natural gas (CNG) is made by compressing natural gas to less than 1% of the volume it occupies at standard atmospheric pressure. CNG has a high octane number (RON=110-130) and therefore can be easily employed in spark-ignited (SI) internal combustion engines (ICEs). Due to the high

RON of CNG, engines could be operated with a higher compression ratio for better thermal efficiency [3]. Furthermore, since CNG has a low carbon/hydrogen (C/H) ratio, it produces less CO2 per unit of energy released. Therefore, CNG appears to be an excellent fuel for SI engines [4]. In order to meet the stringent automobile pollutant legislation and continuously improve the thermal efficiency of ICEs, the research work for the development of more efficient ICEs and more economical vehicles must be conducted [5,6]. In recent years, a direct CNG injected gasoline engine has been developed for automobile engines to improve fuel economy. This technology strongly increases the engine volumetric efficiency, which permits the engine to run at higher speed and produce more overall power. Such technology also allows decreasing the need for throttling for control purposes, thus reducing the cycle pumping loss. During low loads and engine speeds CNG direct injection engines operate with a stratified charge, and the charge stratification in the combustion chamber permits extremely lean combustion without high cycle-by-cycle variations and with high combustion efficiency, although it still retains the problem of high NOx and PM emissions [7-9].

The spark-ignited direct injected CNG engine is a kind of engine which adopts DI technology in a SI engine, and uses the alternative fuel of CNG. Up to now, studies of SI direct injected CNG engines have concentrated on the CNG homogeneous charge, and few reports can be found related to SIDI CNG engines with stratified charge [10-16].

REQUIRED MODIFICATION WHEN DIESEL ENGINE CONVERTED IN TO SIDI CNG ENGINE

The problem of air pollution around the globe is real and serious. Diesel exhaust emissions are a major source of pollution in most urban centers around the world and a major contributor to climate change. Trucks, buses, generators and ships burn millions of gallons of diesel fuel daily. Many countries are looking to alternative fuels to reduce diesel exhaust emissions, especially in urban centers. Furthermore, as the price of crude oil continues to increase, the use of alternative fuels becomes increasingly economical.

Compressed natural gas (CNG) has emerged as a perfect solution to the problems of high oil prices and high exhaust emissions. Readily available in many countries from indigenous sources, it is inexpensive and clean burning. In some countries, the price of CNG is 1/3rd the price of diesel fuel. Some countries have large reserves of natural gas but no technology to use it in engines. The conversion of diesel engines to natural gas would decrease the country’s dependency on foreign fuel and help them utilize the abundant natural gas resources.

Omnitek approaches the issue of 1.) replacing or 2.) converting high-polluting diesel engines to clean burning natural gas engines by offering two main options, which in large part are dictated by the level of technological capabilities within the country and financial feasibility. Omnitek may work with local companies in an effort to convert high polluting diesel engines to clean burning natural gas, or supply new dedicated Natural gas engines. However, to correctly convert a diesel engine to a low-polluting Natural Gas engine can be technologically challenging and time consuming.

- Under Solution 1 Omnitek will supply complete low-polluting natural gas engines in 4 and 6 cylinder configurations. This may be the better option when the existing engines are based on old and outdated technology and when long downtimes are not acceptable. Omnitek will help in the installation and service support. A strong local support team, service provider and spare parts supplier is needed. Engines can also be supplied to local natural gas truck and bus manufacturers. The engines can be certified up to the EURO 6 / US2010 emissions standard.
- Under Solution 2 Omnitek will supply engineering support, for a small per-vehicle royalty, to convert/rebuild the engines to natural gas locally to Omnitek specifications, on a "Technology Transfer" basis. This offers an economic benefit and boost to the local economy. The engines can be certified up to the EURO 5 / US2007 emissions standard. (Converting engines from diesel to CNG requires some good amount of expertise and may involve downtime.) Suggested engine modifications to assure engine reliability, optimized power, fuel consumption and emissions may include optimizing compression ratio, valve lift, valve timing, exhaust system and intake manifold. Special attention goes to engine cooling, engine lubrication and the potential issue of excessive oil consumption. A properly modified engine can make the same power as the base engine.

REQUIREMENTS WHEN DIESEL ENGINE CONVERTED INTO CNG SIDI ENGINE

- Engine Compression Ratio Must Be Lowered.
- Ignition System Must Be Installed.
- Cylinder Head Modification Are Needed To
- Installed Spark Plug and gas carburator.
- Crank Shaft Position Sensor Must Be Made.
- May Need To Improve Cooling System Efficiency.
- May Need Engine Oil Cooler.
- May Need New Piston And Rings.
- May Need A New Cam Shaft.
- May Need New Valve Seats, Guides And Seals.

TECHNICAL SPECIFICATION OF GL 400 TEST ENGINE:

Vertical, single cylinder, air-cooled, cold starting compression ignition, four stroke, high speed diesel engine. See tables 2 and fig.3 to 8.

Table 2: Technical specification of test engine

MODEL	GL - 400
Bore (mm)	86
Stroke (mm)	63
Displacement (cm³)	395
Compression ratio	18:01
RPM	3600
H.P. CMVR	7.5
Max. Torque – kgm	1.7@ 2200 (16.5 NM)
Consumption of fuel (S.F.C)-gn/h.p./hr.	220
Lub oil consumption-kg/hr.	0.011
Capacity of oil sump-Liter	1.2
Dry weight-Kg.	45

Figure 3: The actual photographs of test engine exhaust manifold.

Figure 4: The actual photographs of test engine configuration.

Figure.5: The actual photographs of test engine cng storage tank

Figure 6: Rope brake dynamometer set up

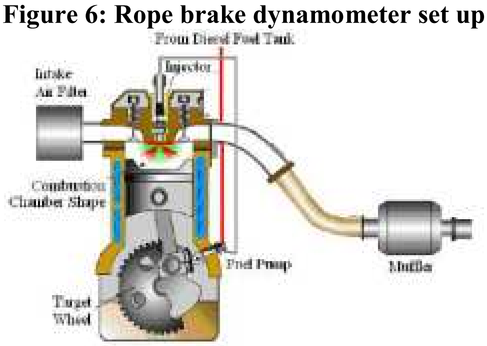

Figure 7: Detail schematic of diesel engine

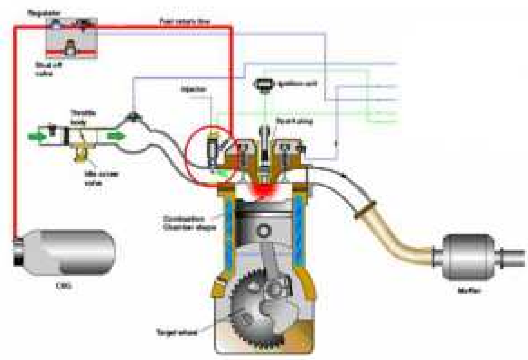

Figure 8: Detail schematic of sequential CNG engine.

SALIENT FEATURES OF GL 400 SINGLE CYLINDER DIESEL ENGINE:

- Direct injection.
- Gear pump forced lubrication.
- Full flow lub-oil filter.
- MIN-MAX governor for better acceleration.
- Rope starting.
- Fuel filter.
- Oil bath air cleaner for working in dusty environments. (Remote mounted dry type air filter can also be supplied)
- Automatic extra fuel device ensures easy starting of engine.
- Adequate capacity flywheel mounted fan ensures efficient cooling even at high ambient temperature.
- Decompression lever.
- Remote throttle and stop.
- Standard rotation of the engine is anticlockwise looking towards PTO.
- Magnetic oil drain plug.

CNG FUELLED SIDI ENGINE EXPERIMENTAL RESULTS OF EXHAUST EMISSION

M.K Hassan, I.Aris, S.Mahmod and R. Sidek

There are two types of natural gas engines have extensively investigated, in search of a clean fuel, which has attracted the public attention: (i) bi-fuel engine diesel-CNG or gasoline-CNG and (ii) mono-fuel engine dedicated CNG. All bi-fuel engines are using port fuel injection (PFI) and only one car manufacturing (ISUZU) successfully developed a mono-fuel diesel cycle direct injection (DI) system. Mono-fuel engines are largely implemented on heavy-duty vehicles, for instance public buses, garbage lorries, mini vans to substitute diesel engine. Most of bi-fuel engines are implemented on light-duty vehicles or passenger cars. However, the difference combustion characteristic of natural gas, gasoline and diesel in internal combustion engine requires a different set of engine parameters to optimize the engine performance. Thus, a short-term solution to resolve the puzzle for bi-fuel engine is to use a conversion kit, which requires two engine management system or sometimes-called master-slave system. Although, the conversion kits are available, the number of conversion vehicles until present day are not encouraging especially in Malaysia. These are due to the feedbacks that conversions vehicles are lack of power, difficult engine cranking in the morning, bulky storage tank and very limited refueling stations available. Conversion of originally gasoline or diesel engine gives lower fuel conversion efficiency and higher hydrocarbon emission. Therefore, a dedicated gas SIDI injected system will be the real solution to resolve the problems.

Most of researched on CNG carbureted SI engines are focused on diesel engine cycle but diesel engines emit high emission especially particulate matter. The diesel engine uses compression heating for ignition while the gasoline engine uses spark plug for ignition. The only car manufacturer that proposed and developed CNG SIDI diesel cycle engine is ISUZU. They developed CNG SIDI with glow spark plug ignition with hot surface system mounted on cylinder head, which will improve engine efficiency. Hence, CNG SIDI is a direction of natural gas engine technology for gasoline or Otto cycle combustion implementation. [19] from Nissan Diesel Motor Co. Ltd Experience has reported some of their findings on the development of stratified charge combustion CNG SIDI engine. Although there are few studies on SIDI -injected gas engines, more knowledge and information on the basic combustion characteristics is necessary. [20] has studied the combustion and emission characteristics in SIDI –injected natural gas engine using multiple stage injection. The main concerned is to study the stabilization of combustion and the possibility of reducing NOx emission using two-stage injection, which is a method for producing a stratified fuel-air mixture suitable for mixture in the vicinity of a spark plug by splitting gas injection into two stages per cycle. The investigation had been done on the modified single cylinder diesel engine. The influence was investigated under the condition that primary injection quantity is larger than the secondary one in order to reduce NOx emission. The result shows that implementing two-stage injection may reduce the NOx emission drastically. However, since the spark timing is after the top dead centre, the thermal efficiency drops sharply and THC and CO concentration rise as the fuel-air mixture becomes lean. The modeled that has developed have shown some potential of CNG implementing direct injection system.

All researchers gave little information in terms of injection timing influence in four cylinder CNG direct injection engine. The basic combustion characteristic of compressed natural gas engine was reported by [29] as comparison with gasoline combustion characteristics. The characteristics of stratified combustion and emission of natural gas and gasoline implementing SIDI -injected method at the optimum injection settings over a wide range of equivalent ratios were investigated. The result showed that, CNG stratified SIDI -injected produces more hydrocarbon (HC) than gasoline stratified DI at a low overall equivalence ratio. The effect of injection timing as reported by [28], also revealed some basic combustion characteristics of CNGDI. He used rapid compression machine (RCM) to investigate the effect of fuel injection timing relative to ignition on CNGDI. As a result of his experimental exercised, he stated three findings; (i) heat release pattern of early injection showed a slower burn in the initial stage and a faster burn in the late stage, which is similar with premixed gas. In contrast to late injection, the heat release pattern shows faster burn in the initial stage and slower burn in the late stage which is similar to diesel combustion. (ii) early injection leads to a longer duration of initial combustion, whereas late injection leads to a longer duration of the late combustion. (iii) late injection produces lower NOx at equivalent ratio greater than 0.5, while CO level is higher for the injection at high equivalence ratio greater than 0.9. The initial study for the CNG SIDI -injected engine, shown compression ratio 14:1 can be used because the property of CNG can withstand higher compression ratio. Fuel is injected at the central of the cylinder with 20-bar pressure.[27] have verified the potential of high-pressure injection of CNG into the cylinder in their paper. Their findings as in Figure 1 and Figure 2, verified that high-pressure injection will produce a higher torque and power compare with low pressure-injection. It also has an advantage of low fuel consumption.

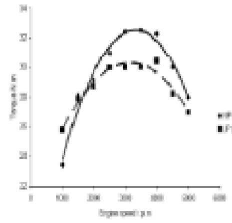

Figure 1: Variation of engine torque versus engine speed for two fuel injection types

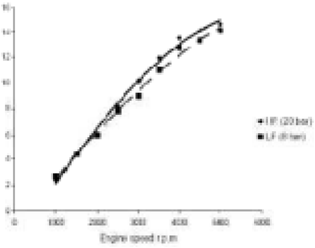

Figure 2: Variation of engine power versus engine speed for two fuel injection types.

A comprehensive reviewed by[21] concluded that to keep the output power and torque of natural gas engine comparable to those of their gasoline or diesel counterparts, high boost of pressure should be used. High activity of catalyst for methane oxidation and lean NOx system or three-way catalyst with precise air-fuel ratio control strategies should be developed to meet future stringent emission standards. However, there is still a limited resource of reference can be found for combustion characteristics of an experimental study of direct injection CNG with Otto cycle. Most of researches have done for gasoline based engine are of preliminary and theoretical study of CNGDI engine or modified diesel based engine or using single cylinder engine. This paper presents an experimental work of high compression direct injection system fuelled with CNG for spark ignition four cylinder engine. The experimental engine is based on 1.6 liter engine, with high compression ratio 14:1 as illustrate in Table 3.

Table 3 :Four cylinder spark ignition 1.6lit engine specification

Engine parameters	Value
Bore × Stroke (mm)	78 × 84
Connecting rod length (mm)	131
Displacement (cm^3)	1596 (4 Cylinders – Inline)
Compression ratio	14:1
Crank radius (mm)	44
Intake valve open (° CA)	12° before TDC
Intake valve close (° CA)	48° after BDC
Exhaust valve open (° CA)	45° before BDC
Exhaust valve close (° CA)	10° after TDC
Fuel Pressure (bar)	20
Valve Train	DOHC 16V & 4 cylinders in-line

PURPOSE OF CONVERSION

Isuzu Motors Limited Carried out this project with support from Westport Innovations (prototype fuel, ignition and associated control systems). Moreover, many of development expense were supported by the New Energy and Industrial Technology Development Organization and the Japan Gas Association.

Japan's transportation sector has a very strong dependence on oil, at 98%, compared to other sectors, and the growth rate for oil consumption is also high. It is crucial for Japan, an energy-importing nation, to introduce and develop alternative energies for oil. Urban air pollution problems are driving the need and the desire for clean natural gas vehicles. The currently available natural gas vehicles, however, are not comparable to conventional diesel vehicles in fuel consumption, a fact that is a major obstacle to their general acceptance. From the perspectives of alternative energy development, low emission and the prevention of global warming, it is therefore an important and urgent issue to develop a natural gas vehicle with fuel consumption comparable to diesel vehicles as well as ultra-low emission.

Based on the above, our objective was to develop a high-efficiency, ultra-low emission commercial natural gas vehicle that would be an alternative to commercial diesel vehicles.

FUEL SUPPLY AND STORAGE SYSTEM

The maximum pressure for in-cylinder direct injection of fuel was set at 25 MPa. The reasoning behind this is shown in Fig. 9: the maximum internal pressure of the cylinders of the engine during operation was 15 MPa; fuel can be injected during combustion; and, the injection pressure should be higher than the cylinder internal maximum pressure by 5 MPa at the minimum. The latter is to ensure the stable sealing capability of gas seal valves under the internal pressure of cylinders. Also considered was the fact that this was a technology under development and the possibility of testing the engine up to 18 MPa with EGR, etc.

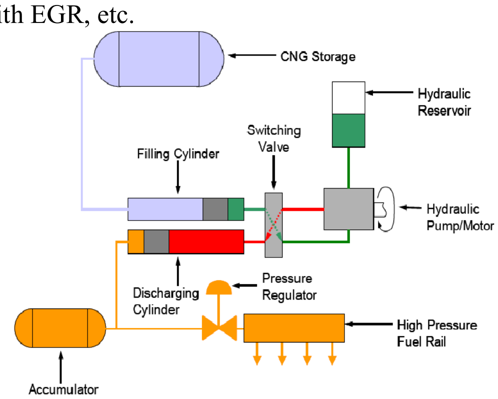

Figure 9 Fuel Storage And Delivery System[31

In order to maintain the desired system pressure, a booster-compressor is included in the vehicle fuel system. The booster-compressor raises pressure from the tank outlet pressure (5-25MPa) to the operating pressure of 25MPa. The booster-compressor is a compact 2-cylinder reciprocating unit with a novel free-floating piston design. The actuating medium is hydraulic pressure generated via an engine driven pump/motor unit. During the intake stroke, the work done by the incoming gas on the hydraulic fluid is recirculated in the system to assist in compressing the gas in the opposing cylinder. This operating principle increases compressor isentropic efficiency to up to 80%. A schematic of the Fuel Storage and Delivery System is given in Figure 9. The system is controlled by dedicated controls that schedule operation to ensure system pressure is maintained.This is one of significant features of the common-rail injection system employed in this engine, because one of the primary aims of this project is to control combustion. In other words, it was our strong desire to retain the feature of diesel engines: while the pre-mixing combustion is relatively difficult to control, the diesel combustion is controllable from the ignition timing to combustion conditions (diffusion combustion).

Diesel fuel is liquid, and the internal pressure of the common rail (injection pressure into the cylinders) is fully changeable as intended through a few repeated injections. Gaseous fuels are, on the other hand, compressive and difficult to control to produce the optimum common rail pressure even with rapid changes in the operating range on the engine side.

CONTROL SYSTEM

The HSI CNG-DI control system processes commands from the OEM diesel engine controller and coordinates the activities of the whole system. The control system functions include:

- Scheduling of injection events (quantity, timing and shape)
- Driving the injector actuators
- Maintaining correct fuel supply pressure
- Controlling the ignition system
- Controlling Exhaust Gas Recirculation (EGR) and turbocharger
- controller or embedded within the Westport system. A schematic diagram of the control system is given in Depending on the configuration of the system, some of these functions may be satisfied by the existing diesel Figure 10.

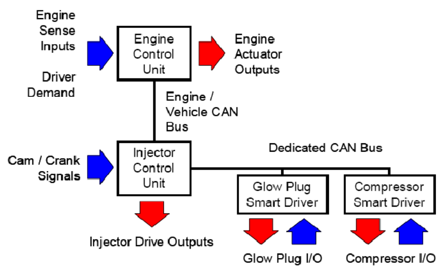

Figure 10 Control System Schematic

AIR INTAKE AND EXHAUST SYSTEM

An outline of the air intake/exhaust system. For the purpose of conducting different studies, an electric air intake controller was installed. The EGR system has its connecting passageways and the cooler doubled in size in order to allow up to twice as much volumetric flow as that of base diesel engine. Note that the EGR mixing point with intake is actually the inlet of the turbo because there is no black smoke generated. Fig. 11 illustrates the variable nozzle-turbo charger system, and a photo of the system is Fig. 12. The system controls the boost and has a feedback for VNT position.

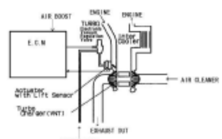

Figure 11 Variable Nozzle Turbo Charger

Figure 12 Appearance of Variable Nozzle Turbo (VNT) System[30] Charger (VNT)[30]

NOISE AND VIBRATION

[30]Latest diesel engines are common rail types and, combined with pilot injection and other technological advances, are far superior in vibration and noise to conventional diesel engines. Noise comparison between the latest diesel engine model under development at Isuzu and the engine studiedin this project. It was noted that our engine had a jarring noise (2000 to 4000 Hz), occurring every two revolutions The subsequent study found that the cylinder heads were acting as speakers for the injector's seating noise. Today it has been improved to a degree such that this noise is virtually inaudible. The combustion noise was demonstrated to be sufficiently low in comparison with that of diesel engines. Fig.12 shows one example. In fact, the noise heard at the start of the vehicle is quite mellow, without any resemblance to the noise of the diesel cycle. It is likely caused by the fact that CNG has one less physical transition as in gas _ ignition _ combustion than diesel as in liquid _ gas _ ignition _ combustion.

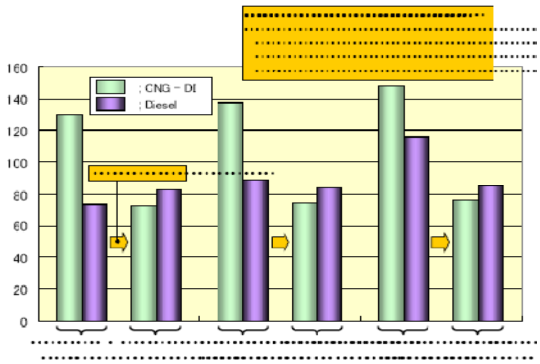

Figure 13 :Coefficient of Variation of Combustion (COV; Pmax) before Fine Tuning

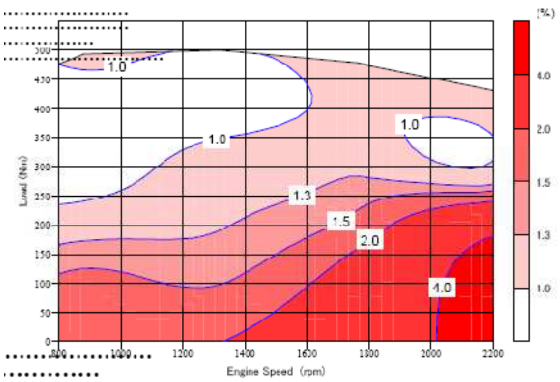

Figure 14 Differences of Combustion Noise

Fig. 14, on the other hand, shows the fluctuation of maximum combustion pressure, the factor affecting vibration, by coefficient of variation of Pmax (maximum peak cylinder pressure). As seen, there is no problem since fluctuation is within 5% over the entire range, thereby satisfying the target.

2.16 TYPE OF CNG STATIONS:

Four types of CNG stations have been developed in Delhi. These are as follows:

2.16.1 MOTHER STATION:

Mother stations are connected to the pipeline and have high compression capacity. These stations supply CNG to both vehicle sand daughter stations (through mobile cascades). Typically they have the facility of filling all types of vehicles – buses/autos/cars. The Mother station requires heavy investment towards compressor, dispensers, cascades, pipelines, tubing etc.

2.16.2 ONLINE STATION:

CNG vehicle storage cylinders need to be filled at a pressure of 200 bars. "On line Stations" are equipped with a compressor of relatively small capacity, which compresses low pressure pipeline gas to the pressure of 250 bar for dispensing CNG to the vehicle cylinder. The investment in an online station is midway between daughter station and mother station.

2.16.3 DAUGHTER STATION:

The "Daughter Stations" dispense CNG using mobile cascades. These mobile cascades at daughter stations are replaced when pressure falls and pressure depleted mobile cascade is refilled at the "Mother Station". The investment in a daughter station is least among all types of CNG stations. There is reduction in storage pressure at daughter stations with each successive filling. Once the storage pressure drops, the refueling time increases, while the quantity of CNG dispensed to vehicle also decreases.

2.16.4 DAUGHTER-BOOSTER STATION:

Installing a booster compressor can eliminate drawbacks of daughter stations. The mobile cascade can be connected to the dispensing system through a booster. Daughter booster (compressor) is designed to take variable suction pressure and discharge at constant pressure of 200 bars to the vehicle being filled with CNG. The investment in daughter booster station is slightly higher than that of daughter station.

2.16.5 MEGA CNG STATIONS:

Mega CNG stations have been conceptualized to cater to a large fleet of vehicles, particularly the buses. The objective is to provide comfortable filling experience to the consumers when they come to the station for refueling. Mega CNG stations are constructed on much larger plot of landthan that of conventional CNG stations, as a result of which more number of Compressors and Dispensers can be installed and more number of vehicles can be simultaneously refuelled at such stations. A Mega CNG station has been commissioned at Rohini, Sector 23 on July 13, 2003 and a similar station has been put into operation at Patparganj on June 30, 2003. At present, there are three Mega CNG stations in Delhi. The CNG Mega station at Patpargang has been constructed at a cost of around Rs.13.5 crores (USD 3 MM) to simultaneously refuel five buses and eight other vehicles (cars, autos, mini buses etc.). Built on a plot of size 75 m X 40 m, it has the capacity to comfortably refuel CNG to 800 buses and over 1500 other vehicles daily.

CONCLUSIONS

- The HSI CNG-DI concept achieves true natural gas Diesel cycle operation. This provides potential to significantly improve torque and efficiency when compared to current Otto cycle products. This combination of natural gas and high efficiency operation results a significant CO_2 benefit when compared to diesel and Otto cycle NGVs. [31]
- In many locations, natural gas is available at significantly lower cost than diesel fuel. Availability of a high efficiency NGV offers a real, low cost alternative to diesel, broadening

market appeal, and allowing penetration in new market segments.[31]

- We succeeded in the incorporation of an ISUZU and Westport hot surface ignition CNG-direct injection diesel cycle engine in a commercial vehicle and its operation as a complete vehicle for the first time in the world. As seen in the records at the Bibendum, it was demonstrated that the vehicle has satisfied all the parameters of a vehicle at a high level, indicating the high potential of this technology for commercialization in the near future. It is a significant milestone.[30]

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