

Comparative Study of Unregulated Emissions on a Heavy Duty CNG Engine using CNG & Hydrogen Blended CNG as Fuels

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ABSTRACT

One of the most promising solutions to address the twin problems of transport related pollution and energy security is to use alternative fuels. Compressed Natural gas (CNG) has been widely used in India to address the menace of pollution from commercial vehicles in cities like Delhi. Hydrogen blended compressed natural gas (HCNG) as a fuel has potential for further reducing harmful emissions and greenhouse gases. Enriching hydrogen in CNG improves combustion characteristic of CNG and reduces carbonyl emissions. Due to growing concerns over un-regulated emissions and their effect on human health, it is imperative to estimate un-regulated emissions from such alternatives for assessing overall impact of such fuels.

Presently world over, emission legislations mainly addresses pollutants like CO, HC, NO_x, CH₄, NH₃, PM etc. Relatively higher quantity in exhaust qualifies these pollutants to be monitored and controlled. But as the consumption of alternative fuels becomes comparable to that of the liquid fuels, other unregulated emissions like Methanol (CH₃OH), Ethanol (C₂H₅OH), Formaldehyde (HCHO), Acetaldehyde (CH₃CHO), Formic Acid (HCOOH), Acetic Acid (CH₃COOH), Propene (C₃H₈), Ethylene (C₂H₄), Ethyne (C₂H₂) Benzene (C₆H₆), 1,3-Butadiene (1,3-C₄H₆), Toluene (C₇H₈), Butene (C₄H₈) etc. become significant.

This paper presents the study of unregulated emissions on a heavy duty six cylinder engine used in the transport buses with CNG and HCNG as fuels. A transient engine dynamometer set up was used along with Fourier Transform Infrared Spectroscopy Gas Analyzer (FTIR) for measuring unregulated emissions. It was observed from the test results that regulated emissions like CO, NO, HC and PM are considerably reduced with HCNG fuel. Also, unregulated emissions like Formic Acid (HCOOH), Propane (C₃H₈), Ethylene (C₂H₄), Ethyne (C₂H₂), Benzene (C₆H₆), 1,3-Butadiene (1,3-C₄H₆), Toluene (C₇H₈) and Butene (C₄H₈) are significantly reduced with HCNG fuel. Whereas, there is slight increase in Methanol (CH₃OH), Ethanol (C₂H₅OH), Formaldehyde (HCHO) and Acetaldehyde (CH₃CHO) with HCNG.

It can be inferred from the study that HCNG has reduced significant amount of unregulated emissions and it is the most promising fuel for transport sector in future. Beside this it is also observed that with HCNG Fuel, there is increase in NH₃ and NO₂ which create favorable condition for effective working of exhaust after treatment device like selective catalytic reduction (SCR) for Euro VI compliant vehicles.

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INTRODUCTION

Fossil fuels are major energy sources for meeting world energy demands. However, there are several disadvantages with use of fossil fuels including limiting resources, generating waste and depleting environment air quality. In recent years, there have been many studies about alternative fuels mainly concentrated on fuel economy and emissions. Several researches are being undertaken world over to reduce fast depletion of fossil fuels and improve the environment. Alternative fuels are promising fuels, which lead to energy independent of states and eco friendly energy resources. Nowadays, Natural gas is consider as a promising alternative fuel because of

wide availability, a clean fuel that features the lowest carbon content of all hydrocarbon fuels and easily adapted to conventional internal combustion engines.

Two fuels namely, Natural Gas (NG) and hydrogen are promising renewable fuels for meeting futuristic energy needs. Although, natural gas considered as fossil fuels, however, it can be produced from renewable resources. The natural gas has large content of methane, it is a low carbon fuel has high anti-knocking properties this means, the internal combustion engine may be run at higher compression ratio than the petrol engine without knocking, thus increase thermal efficiency of the engine. The natural gas can be stored in its compressed form (CNG). The CNG used as fuel for transport in

several countries. Several studies have reported that CNG is clean fuel thus reduce CO, HC and NOx emissions as compared to gasoline/ diesel powered vehicles [1]. However, the slow burning nature of CNG poses unstable combustion and misfires thus emits significant amount of un-burnt mixture of methane, it is important to note that the un-burnt methane is greenhouse gas of global warming factor of more than 20 as compared to global warming gas of carbon dioxide (CO₂).

In the last ten years, the number of natural gas (NG) vehicles worldwide has rapidly grown with the biggest contribution coming from the Asia-Pacific and Latin America regions [2]. As natural gas is the cleanest fossil fuel, the exhaust emissions from natural gas spark ignition vehicles are lower than those of gasoline-powered vehicles. Moreover, natural gas is less affected by price fluctuations and its reserves are more evenly widespread over the globe than oil. Ristovski et al. [3] performed an experimental activity on a passenger car converted to operate either on gasoline or on compressed natural gas (CNG). Fuelling the engine by CNG, both regulated (CO, NOx and HC) and unregulated emissions (PAHs and formaldehyde) were lower than gasoline.

One of the drawbacks of the NG fuel is the laminar burning velocity lower than gasoline, as a consequence, a higher spark advance. In order to increase the efficiency of natural gas engines and to stimulate hydrogen technology and market, hydrogen can be added to natural gas, obtaining Hydrogen - Natural Gas blends, usually named as HCNG.

Hydrogen is well known for its wide flammability limits and high flame propagation speed. Such characteristics of hydrogen enable ultra-clean burning, high efficiency and low exhaust emissions. Hydrogen is a clean and high-efficiency energy carrier with potential to be the alternative to fossil fuels [4,5]. Hydrogen for IC engines is considered as a future fuel due to carbonless structure. But several obstacles need to be overcome before commercialization of H₂ as an IC engine fuel for transport sector. Presently, lack of hydrogen infrastructure and refuelling stations prevent widespread introduction of hydrogen vehicles. To acquire the benefits of the unique properties of the hydrogen, the option of blending hydrogen in CNG has been studied; this reduces the demand of pure hydrogen. Also these blends can use the existing natural gas infrastructure [6] and existing CNG engine without any major hardware modification.

HCNG is short for hydrogen enriched compressed natural gas. HCNG has been considered as an automotive fuel without any major modification in the existing engines. As it can be seen in Table 1 [7,8,9], hydrogen is an excellent combustion improver to methane due to its unique characteristics. The important effects of hydrogen addition can be pointed out: the laminar burning velocity of hydrogen is nearly 7 times higher than that of methane. Hence, the hydrogen addition can increase the burning velocity of the mixture, and it brings some advantages such as shorter combustion duration, greater constant volume degree etc. Also, blending hydrogen with natural gas can allow the mixture to burn leaner, reducing the emissions. HCNG is a viable alternative to pure fossil fuels because of the effective reduction in total pollutant emissions and the increased engine efficiency.

Table 1. Comparison of properties of Hydrogen, CNG and HCNG blend [7,8,9]

Properties	Hydrogen	CNG	HCNG
Stoichiometric composition in air, vol %	29.53	9.48	22.8
Limit of Flammability in air, vol %	4-75	5-15	5-35
Auto Ignition Temp, K	858	813	825
Flame Temp in air, K	2318	2148	2210
Minimum energy for Ignition in air, mJ	0.02	0.29	0.21
Burning velocity in NTP air, cms -1	325	45	110
Quenching gap in NTP air, cm	0.064	0.203	0.152
Diffusivity in air, cm ² s ⁻¹	0.63	0.2	0.31
Percentage of thermal energy radiated	17-25	23-33	20-28
Normalized flame emissivity	1.00	1.7	1.5
Equivalence ratio	0.1-7.1	0.7-4	0.5-5.4

Since hydrogen laminar combustion speed is about eight times greater than methane, it provides a reduction of combustion duration when mixed with natural gas in small concentrations. Many studies have been carried out to measure the flame speed of hydrogen-methane air mixtures at different hydrogen concentrations and equivalence ratios. Ilbas et al. [10] performed the measurements at ambient temperatures with hydrogen-methane blends up to 100% hydrogen.

The reduction of combustion duration promoted by hydrogen addition results in increased engine efficiency respect to natural gas and enhances combustion stability, reducing cycle-by-cycle variation.

Nagalingam et al. [11] proved that the high burning rate of HCNG blends requires an ignition timing lower than natural gas to obtain the Maximum Brake Torque (MBT). The MBT spark advance versus the hydrogen content (Karim et al., 12), is noticeably affected by hydrogen addition, in particular for very lean air-fuel mixtures. It is concluded from the paper that for blends containing significant amount of hydrogen, small adjustments to the ignition timing are needed when the equivalence ratio is changed. The engine efficiency can be increased fuelling the engine by HCNG blends. Sierens & Rosseel [13] developed a fuel system which supplies hydrogen-natural gas mixtures in variable proportion to the engine. For low brake mean effective pressures high efficiency can be achieved by increasing the hydrogen content reducing throttling losses.

Ma et al. [14] investigated the effect of high hydrogen volumetric content, up to 55%, on the performance of a turbocharged lean burn natural gas engine. The authors found that the addition of hydrogen significantly extends the lean limit, decreases burn duration and yields higher thermal efficiency. It is concluded from the study that the engine efficiency versus λ , shows a negative trend in engine efficiency for natural gas for λ values greater than 1.3, while the blend with the higher hydrogen content shows positive trend up to $\lambda = 1.6$. The increased hydrogen/carbon ratio and engine efficiency bring a reduction of CO₂ emissions. By the way, as a consequence of a faster combustion, higher temperature are attained in the combustion chamber, increasing NOx emissions in HCNG fuelled engines compared to natural gas, for a given equivalence ratio ϕ .

NOx can be kept down and engine efficiency further improved if the engine is run with lean mixtures or adopting EGR at stoichiometric air-fuel ratio.

Larsen and Wallace [15] investigated emissions and efficiency of turbocharged lean burn HCNG fueled engine. 15 percent hydrogen enrichment in natural gas i.e., 85/15 CNG/ H₂ mixture by volume compared with pure natural gas. Test results at different speeds, different loads and different equivalent ratios indicated with respect to matrix and statistical analysis clearly demonstrated the potential of methane and hydrogen mixture to reduce the exhaust concentrations of regulated pollutants and increase the efficiency of SI engine. The emissions of primary concern in a lean fueled engine were HC and NOx. Exhaust treatment device has been used to control HC and NOx simultaneously.

Shudo et al. [16] studied HCNG fuel for combustion and emission and reported that increase of thermal efficiency and decrease of hydrocarbon emissions. NOx emissions tend to increased, however, the NOx emission maintained at lower levels with retard ignition timing. Current emissions standard would require extensive emission control system to achieve lower emission. Traditionally, Exhaust Gas Recirculation (EGR) system was used for control NOx emission with penalty on fuel economy and power.

HCNG blends can be distributed by the present natural gas refuelling stations, providing them with mixing equipment in order to obtain blends with the selected hydrogen content. The system must operate to assure a high accuracy of hydrogen percentage because the fuel composition influences engine performances hence requiring customized engine calibration. In particular, the increased combustion velocity requires a reduction of the ignition advance as the hydrogen concentration increases to obtain the maximum engine torque. Furthermore, the fuel supply system should be calibrated to compensate the variation of fuel properties caused by hydrogen addition. In fact, present natural gas vehicles requires stoichiometric air-fuel ratio to obtain a high conversion efficiency of HC, CO and NOx emissions in the three-way catalytic converter. HCNG fuels can be used in lean burn engines or with high EGR rates at stoichiometric conditions, exploiting their excellent combustion properties, with positive impact on engine efficiency and low exhaust emissions. Finally, the use of HCNG fuel can stimulate the development of the hydrogen technologies and market which are, nowadays, the main practical problems preventing it to be implemented.

Many research projects have been performed in the past and others are still going on to assess the potential benefits coming by using HCNG fuels in real-life applications. The U.S. Department of Energy Advanced Vehicle Testing Activity (AVTA) teamed with Electric Transportation Applications (ETA) and Arizona Public Service (APS) to develop a hydrogen pilot plant, where hydrogen is produced by means of PEM electrolyzer and is dispensed to vehicles that operate with different HCNG blends with hydrogen ranging from 0% to 100%. The project demonstrated the safety of operating vehicles on hydrogen and the reduction of exhaust emissions attainable with hydrogen and HCNG fuelled vehicles compared to gasoline [17]. A

hydrogen production plant with HCNG dispenser have been built in Malmö, Sweden, for project to improve engine efficiency and reduce emissions of a bus fleet [18].

Many researchers have studied the effect of the addition of hydrogen to natural gas on performances and emissions in the past few years. Blarigan and Keller investigated the port-injection engine fueled with natural gas-hydrogen mixtures [19]. Karim et al. [20] theoretically studied the addition of hydrogen on methane combustion characteristics at different spark timings. The theoretical results showed that the addition of hydrogen to natural gas could decrease the ignition delay and combustion duration at the same equivalence ratio. It indicated that the addition of hydrogen could increase the flame propagation speed, thus stabilizing the combustion process, especially the lean combustion process. Sierens and Rossel [21] determined that the optimal HCNG composition to obtain low HC and NOx emissions should be varied with engine load.

During the earlier studies by the author [22-23], experimental investigation were carried out to assess the regulated and unregulated emissions with the use of hydrogen enriched CNG fuel under various blend ratios (12, 18 and 30% v/v) on a three-wheeler. Also exhaustive field trial of 20,000 km was successfully completed on a fleet of three wheelers running on HCNG. Further, Government of India [24] declared that hydrogen blends in CNG upto 20 percent would be considered as alternative fuel to CNG. Similarly, parallel studies were carried out by the author on the effect of HCNG on small and heavy duty engine performance [7, 25]. Based on Government of India directives and earlier studies, it is concluded that the blend of 18 percent HCNG is best suited for engine performance and emissions with reference to Indian context.

The vehicular emissions such as CO, THC, NOx, sulphur oxides, particulate matter has been regulated through the legislation. The amount of un-regulated pollutant emitted to the atmosphere is continuously alarming with increase of vehicle population and use of fossil and alternative fuels. Information on un-regulated emissions from the use of hydrogen blended gaseous fuel is very scanty. Establishing emission limits for aldehyde is imperative in the light of the gaseous fuelled fleet growth, toxicity of these compounds, and their contribution as precursors in ozone gas formation reactions in low troposphere.

The objective of this paper is to assess un-regulated emissions with the use of CNG and hydrogen blended CNG fuels on 6-cylinder sequential gas injection based heavy duty CNG engine. The six cylinder engine was chosen due to its importance for urban bus transportation.

EXPERIMENTAL SETUP

A state of art test facility has been created for undertaking research on engines running on gaseous fuels. The test facility comprises of transient engine dynamometer, emission measurement system, utility services and safety controls. [Figure-1](#) shows experimental setup of test facility.