ISSN 2395-0226

JOURNALOF SCIENTIFIC RESEARCHAND ADVANCES

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Review on performance and emission analysis of hydrogen blended Compressed natural gas on a bi-fuel engine

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Abstract— Considering the forsaken circumstance of rising fossil fuel costs combined with constrained accessibility and environment corruption created by routine fills, it is not shocking that the world has turned its thoughtfulness regarding utilization of option energizes. The continually expanding interest for biologically benevolent vehicles must be met by utilization of ultra clean energizes like Compressed Natural Gas (CNG) and Hydrogen (H_2). Lower carbon to hydrogen proportion of CNG makes it a cleaner fuel, because of this CNG is picking up prevalence as an inward ignition (IC) motor fuel in transport division. Hydrogen fuel for IC motors is likewise being considered as a future fuel because of its straightforward carbon less structure. Be that as it may, a few impediments must be overcome before commercialization of H_2 as an IC motor fuel for transport area. The hydrogen enhanced CNG fuel alluded to as HCNG can possibly lower emanations and is thought to be the initial move towards advancement of a Hydrogen economy.

Keywords: Lean Burning, Excess Air ratios, wide open throttle, higher flame velocity.

I. Introduction

HCNG is a vehicle fuel in which compressed natural gas is enriched with hydrogen, typically 5-20% hydrogen by volume fraction. Indian Oil HCNG testing facility has confirmed the fuel's potential to reduce nitrous oxide (NO_x), carbon dioxide (CO_2), and carbon monoxide (CO) emissions compared to baseline CNG.Resources are deteriorating at a tremendous rate, on the contrary energy demands are skyrocketing. Many factors are responsible but one of the major factors affecting this demand is availability of fuels.

Mineral fuels are categorised as solid (coal), liquid (gasoline, diesel, etc.) and gas (natural gas) and these contain two principal combustible elements: Carbon (C) and hydrogen (H) and of the two hydrogen is more efficient.

Fuel gets its efficiency from the calorific value it contains. The calorific value of pure Carbon is 3.56521 kcal and that of pure Hydrogen is 15.50793 kcal which clearly underlines the dominance of the latter in this field.

Many researchers have studied the effect of the blending of hydrogen to natural gas on performance and emissions on dedicated or retro fitted SI and CI engines, whereas less work has been carried out in Bi-Fuel SI engines, thereby resulting in limited knowledge in this area. This study contains major works done by highly reputed research scientists on their respective state of the art experimental setup:

Bauer and Forest [1] piloted an investigational study on natural gas–hydrogen combustion in a CFR engine and found astonishing performance and emission results that triggered

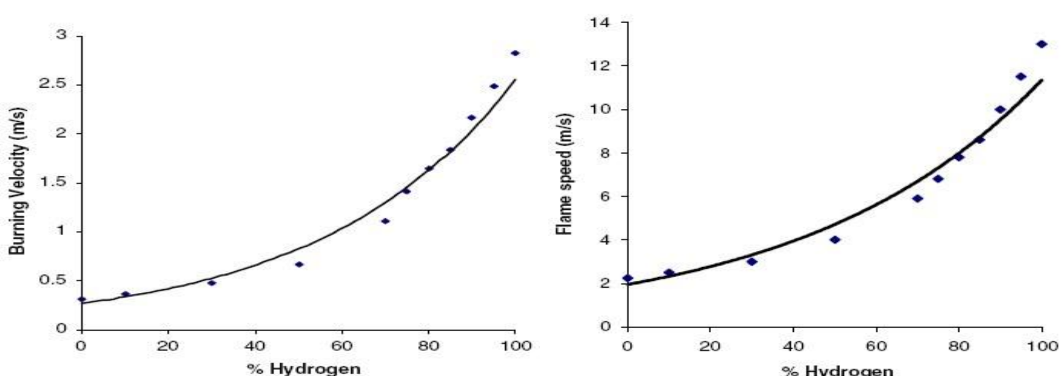


Figure 1: Burning velocities and flame speed for different percentages of hydrogen in methane (φ = 1.0) [3].

major research work in this field.

Karim et al [2] in theory studied the addition of hydrogen on methane combustion characteristics at different spark timings. The theoretical outcomes displayed that the addition of hydrogen to natural gas could decrease the ignition delay and combustion duration at the same equivalence ratio. It specified that the addition of hydrogen could upsurge the flame propagation velocity, thus stabilizing the ignition progression, particularly the lean combustion process.

Ilbas et al. [3] experimentally calculated the laminar burning velocities of hydrogen–air and hydrogen–methane–air mixtures. They concluded that increasing the hydrogen percentage in the hydrogen–methane mixture caused an increase in the subsequent burning velocity and produced broadening of the flammability limit (Figure 1).

Their outcomes proved that the ignition system attained higher thermal efficiency due to higher flame propagation velocity and lesser emissions. An increase in the amount of pre-mixed hydrogen steadies the combustion route to lessen HC and CO exhaust emission, and increases the degree of constant volume combustion and NOxexhaust emission. The growth in NOxemission can be retained at a lower side with retarded ignition timing minus the reduction in the elevated thermal efficiency.

Jungsoo Park et al [4] studied thatMass Fraction Burned (MFB) improved with H_{vf}(Hydrogen volume fraction), at Excess Air Ratio (EAR) of 1.5 the addition had a drastic effect

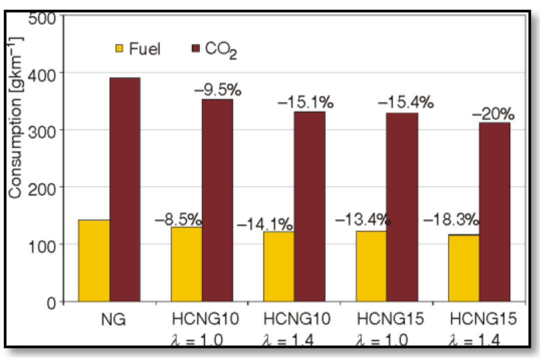


Figure 2: Fuel Consumption and CO_2 emissions at different Hydrogen volume fractions

on mass fraction burned. Also saw that NO_x usually increased with addition of H_2 under lean burn conditions and that better *de-NO$_x$*efficiency can be obtained under these conditions where in-cylinder temperature decreases.

Reji Mathai et al [5]stated thatBrake Specific Fuel Consumption is lesser in HCNG in comparing with CNG due to high Calorific Value and improved combustion efficiency. At 18% HCNG the flame speed stabilizes and accelerates the combustion process thus enabling the degree of Constant Volume of Combustion (CVC). At same H-to-CNG ratio: CO and HC drastically decrease whereas NO_x increases as compared to CNG.

M. Ayoub et al [6]at Excess Air Ratio, CO decreases and if hydrogen percentage increases then we can see progressive decrease in NO_x formation down to complete cancellation on pure H_2.

Raman et al[7] carried out an experimental study on Spark-Ignition engines fuelled with HCNG blends in a V8 engine. The authors observed a reduction in NOx emissions using specific ratio of hydrogen blends with some increase in HC emissions as a result of ultra-lean combustion.

Ma and Wang[8], experimentally examined the delay of the lean operation limit over hydrogen addition in a Spark-Ignited engine which was piloted on a six-cylinder throttle body injection natural gas engine. Four levels of hydrogen enhancement were used for comparison purposes: 0%, 10%, 30% and 50% by volume. Their results exposed that the engine's lean operation limit could be stretched by adding hydrogen and growing load level (intake manifold pressure). The outcome of engine speed on lean operation limit is less significant. At a low load level an upsurge in engine speed is advantageous in extending the lean operation limit but this is not correct at high load level. The effects of engine speed are even weaker when the engine is converted to hydrogen enriched fuel. Spark timing also impacts the lean operation limit and both over-retarded and over-advanced spark timing are not logical.

Genovese et al.[9] performed road test on urban transport buses, associating energy ingesting and exhaust productions for NG and HCNG blends with hydrogen content between 5% and 25% in volume fraction. The authors established that average engine efficiency through the driving cycle rises with

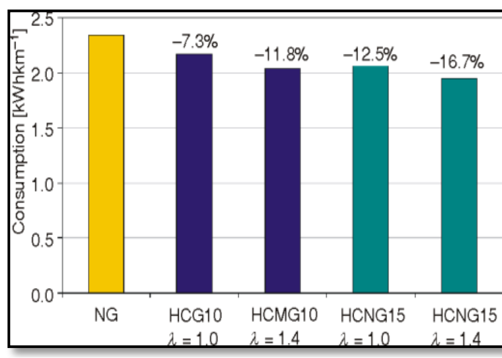


Figure 3: Fuel consumption at different Hydrogen Volume Ratios

Hydrogen content and NOx emissions were higher for blends with 20% and 25% of hydrogen, despite the lean comparative air fuel ratios (AFR) and delayed ignition timings implemented.

Zuo-yu Sun et al [10] proved that the emissions (NO_x, CO and HC) decreases with increase of Ignition Advanced Angle and increases with increase in Manifold Absolute Pressure (MAP). Adding Hydrogen will decrease NO_x and CO greatly at lean combustion condition. ϕ (Equivalence Ratio), Ignition timing and Mass Fraction Burned (MFB) greatly affect NOx emission in HCNG engine. Process of Exhaust Gas Recirculation (EGR) introduction decreases NO_x significantly and when EGR increases and Thermal Efficiency (η_{et}) first increases and then decreases, both NO_x and BMEP (Brake Mean Effective Pressure) decreases continuously and decrease of NO_x is more at higher Hydrogen Volume Fraction.At Wide Open Throttle (WOT) with higher Hydrogen Volume Fraction;

as the value of λ (Air-Fuel ratio) increases both maximal heat release rate and maximal cylinder pressure decreases and both early flame development period and flame propagation duration are extended. As ϕ increases both the Ignition Advanced Angle at MBT (Maximum Brake Torque) and Thermal Efficiency (η_{et}) decreases, but NO_x increases.

Table 1: Comparison of properties of hydrogen, CNG, and HCNG 5 with gasoline[12]

PROPERTIES	UNITS	H2	HCNG 5	CH4	GASOLINE
Limits of flammability in air,	*vol.%*	4-75	**5-35**	5-15	1.0 -7.6
Stoichiometric composition in air,	*vol.%*	29.53	**22.8**	9.48	1.76
Minimum energy for ignition in air,	*mJ*	0.02	**0.21**	0.29	0.24
Auto ignition temperature,	*K*	858	**825**	813	501-744
Flame temperature in air	*K*	2318	**2210**	2148	2470
Flame velocity in NTP[1] air,	*m/s*	3.25	**1.10**	0.45	0.37-0.43
Quenching distance in NTP[3] air,	*Mm*	0.64	**1.52**	2.03	2.0
Normalized flame emissivity		1.0	**1.5**	1.7	1.7
Equivalence ratio flammability limit in NTP air		0.1-7.1	**0.5-5.4**	0.7-4	0.7-3.8

Cheolwoong Park et al [11]investigation stated at λ =1 and MBT spark timing during H_2 addition decreases the combustion duration as there is increase in flame propagation. η_{et} attains maximum value at low percentage of Hydrogen addition whereas η_{et} decreases with the increase in Hydrogen percentage due to increased cooling loss.

Significant difference in cooling loss between CNG and HCNG induced a decrease in η_{et}. THC emissions decreases drastically but NO_x increases expressively with Hydrogen addition resulted by faster burning speed of Hydrogen. The suggestion was made to retard spark timing with respect to MBT spark timing while keeping other points identical to the peak efficiency conditions

Fanhua Ma et al [13]verified that Indicated Thermal Efficiency (ITE) increases at lean value of excess air ratio; the heat loss to the wall is 25% whereas at stoichiometric ratio the heat loss to the wall is 45% in an H_2 fueled engine. Thereby validating that lean burn can reduce heat loss and improve indicated thermal efficiency.

Yusuf M.J. et al [14] measured all engine-to-fuel configurations performed similarly over normal operating ranges. An important distinction occurred with rich mixtures. In addition, the blending of Hydrogen to Compressed natural gas at 20:80 ratios showed a small but noteworthy decrease in BSCO output.

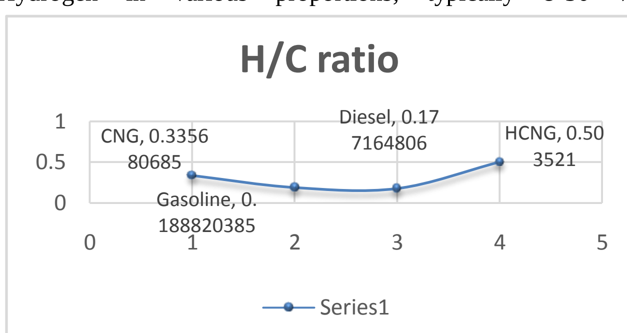
Zheng J et al [15] stated that NOx emission increases with increasing hydrogen fraction when the hydrogen fraction is less than 10%, and it decreases with the increase of hydrogen fraction when the hydrogen fraction is larger than 10% at various injection timings. HC emission decreases with the increase of hydrogen fraction. This is because the quench distance of the fuel blends is decreased and the lean flammability limit of the natural gas-hydrogen fuel blends is extended with hydrogen addition. Furthermore, the C/H ratio decreases with increasing hydrogen fraction and this also contributes to the decrease of brake HC emission with the increase of hydrogen fraction. CO emission decreases with increasing hydrogen fraction. As overall excess air ratio in the cylinder increases with hydrogen addition, and CO is strongly related to the air-fuel ratio, the sufficiency of oxygen in the

cylinder makes the CO emission low.

With majority of the literature survey based on dedicated gaseous fuel SI engines, limited work is been done on conventional SI engines with least or no modifications. So there exists a research gap on evaluation of HCNG on the engines that are used only for gasoline fuels, this dissertation report focuses on the tests done on a Bi-Fuel engine that for gasoline operation by design and not retrofitted for HCNG and accordingly interprets the performance and emission results of Gasoline with Hydrogen Blended Compressed Natural gas.

Hydrogen blended Compressed Natural Gas (HCNG)

HCNG is a vehicle fuel which is a blend of natural gas and Hydrogen in various proportions; typically 8-50 %



[1] NTP denotes normal temperature (293.15 K) and pressure (1atm)

Figure 4: Hydrogen to Carbon ratio in major automotive fuels

volumeIntroduction to Hydrogen blended Compressed Natural Gas (HCNG).

HCNG is a vehicle fuel which is a blend of natural gas and hydrogen in various proportions, typically 8-50 % volume hydrogen. Mixtures at 20% are referred to as Hythane™ [16]. HCNG can bridge the gap between traditional liquid fuels and hydrogen. By using HCNG as a transition fuel and taking advantage of the CNG prevailing substructure, there is a potential to initiate building a hydrogen infrastructure at a minimum cost. Besides the benefit as a transition fuel, HCNG has its own specific advantages in terms of pernicious emissions and, if in addition, the hydrogen is produced from renewable resources, HCNG could also contribute to reduced greenhouse gas (GHG) emissions [16].

In relation to climate change [17], sustainable growth, and policy valuation, sinking energy/fuel ingestion and carbon dioxide (CO_2) emissions remain the most vital challenges confronted by the policy makers, along with the automobile and petroleum industry. In this framework, it is important to analyze and forecast the efficiency of the policies that aim to shrink fuel consumption, accordingly resulting in CO_2 emissions reduction. Either Hydrogen or methane, taken separately, is a well characterized combustible gas. The blend of Hydrogen and methane (the principle constituent of regular gas) to shape Hythane is in a few ways self-evident: two combustible, non-dangerous gasses remain so when blended. Other properties of Hythane are not self-evident. This paper presents the present comprehension of the impacts of weaken centralizations of Hydrogen on the properties of common gas, including impacts on materials. The advantageous impacts for ignition motors are expanded warm productivity and lessening of NOx and HC by incitement of normal gas burning close to as far as possible (lean burn or broad fumes gas reuse). Lamentably, the expansion of Hydrogen to regular gas lessens vitality stockpiling thickness by 1) lower volumetric vitality thickness and 2) expanded super-compressibility element. Hydrogen shortly costs more than common gas also, accessibility of Hydrogen is restricted. Therefore, the goal of Hythane is to expand the advantage per unit of Hydrogen vitality devoured (expense viability).

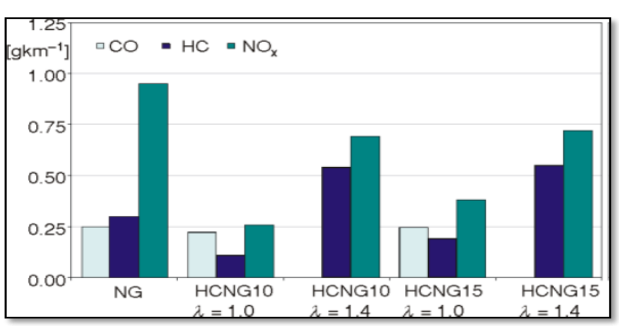


Figure 5: Fuel Consumption with CO, HC and NOx emissions at different Hydrogen volume fractions

The motivation behind Hythane is to upgrade and supplement characteristic gas—not to supplant it as we make our first strides toward a Hydrogen vitality future reference pointing these scrutinizes, as the reference in contrast to which the other scenarios are compared. Hence, the requisite of considering a baseline scenario that reflects accurately current trends in technical progress, public behavior, energy markets, and regulatory policies.

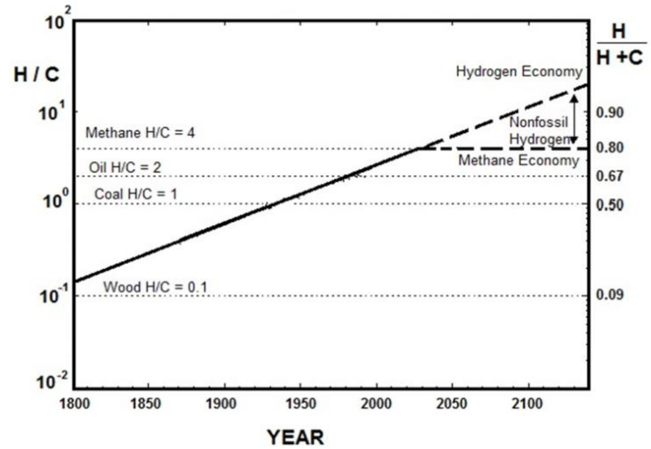


Figure 6: Decarbonization: Evolution of the Ratio of Hydrogen (H) to Carbon (C) in the World Primary Fuel Mix [24]

Furthermore, one major field of survey is the Hydrogen to Carbon (H/C) ratios, these ratios have greater impact factor than other fuel properties has led to the development of H-CNG as the new alternative fuel, which has comparatively best H/C ratio thereby imparting superior fuel quality?

Since the volumetric vitality thickness for air-Hydrogen blends is lower than air-methane blends at stoichiometry, no doubt safe to expect that Hythane blends would likewise have lower vitality thickness than methane, in extent to the Hydrogen content. Nonetheless, the air-fuel blend vitality thickness bend is definitely not direct with creation, as demonstrated in Fig. 5. At lower Hydrogen rates, the vitality thickness of a motor's admission blend is not really influenced there is an immaterial 0.45% hypothetical force misfortune for a stoichiometric motor utilizing Hythane (20% Hydrogen by volume) versus an unadulterated methane motor. Thus, little doubt remains safe to expect that air-Hydrogen blends will dependably have lower vitality densities than air-methane blends, even at air/fuel proportions leaner than stoichiometry. Shockingly, this suspicion is likewise false. In spite of the fact that methane creates more vitality per mole of fuel than Hydrogen, Hydrogen delivers more warmth than methane per unit of oxygen devoured, and at fuel/air proportionality proportions beneath around 0.7, this impact starts to rule the blend vitality thickness.

With majority of the research based on dedicated gaseous fuel SI engines, limited work has been done on conventional SI engines with least or no modifications. So there exists a research gap on evaluation of HCNG on the engines that are used only for gasoline fuels, this dissertation report focuses on the tests done on a Bi-Fuel engine that for gasoline operation by design and not retrofitted for HCNG and accordingly interprets the performance and emission results of Gasoline with Hydrogen Blended Compressed Natural gas. Substantial work being done on dedicated CNG or retrofitted engines. Also CNG in dual fuel mode has also been explored.

HCNG has shown various advantages:

From the review of literature available in the field of HCNG usage, many advantages are noticeable. The following are some of the benefits of using HCNG as fuel:

i. It is usable with the existing CNG infrastructure. It requires only small hydrogen storage and a column for the mixing of hydrogen with natural gas.
ii. Safety properties are similar to CNG. HCNG is safer to handle than hydrogen, because of lower risk due to very low energy content from hydrogen (only up to 30 vol.%).
iii. It extends the lean misfire limit of CNG.
iv. Minor modifications are required in the engine due to moderate concentration of hydrogen in the fuel mixture; the excellent anti-knock characteristics of CNG are not under-mined.
v. The phenomenon of hydrogen embrittlement does not occur with respect to the engine components. Hence, no major change is anticipated in the fuel system and engine components.
vi. Hydrogen addition to natural gas can decrease engine's unburned hydrocarbons and NOx emissions (by lean burn) and speed up the combustion process.
vii. It improves the engine efficiency and lowers fuel consumption.

However there are challenges of HCNG

From the review of literature available in the field of HCNG usage, many challenges are noticeable. The following are some of the arguments of using HCNG as fuel:

i. HCNG storage and supply infrastructure.
ii. Efforts to be concentrated on countering to fuel system performance, material compatibility.
iii. Emission analysis with more varieties of hydrogen in HCNG blends
iv. Continuous obtainability of HCNG needs to be guaranteed before boarding on its major use in IC engines.
v. Continued engine performance, emissions and durability testing in variety of engine types and sizes need to be developed to increase consumer and manufacturer's confidence [18].
vi. Development of less expensive quality tests

II. Conclusions

Future examination of the hydrogen enhanced packed characteristic gas fuel incorporate constant change on execution and discharges, particularly to decrease the hydrocarbon outflows (counting methane if vital) which are at present not intensely controlled but rather will most likely be all the more firmly directed later on:

i. A definitive objective of hydrogen economy is to dislodge fossil powers with clean burning hydrogen and CNG is the best course to guarantee the early presentation of hydrogen fuel into the energy demanding field.
ii. The incline burning capacity and fire vehement velocity of the natural gas engine is enhanced by mixing it with quick burning high velocity fuel, hydrogen.
iii. Dedicated HCNG engine are better than CNG engines from fuel economy, Power, and Torque perspective because of better ignition.
iv. The HCNG motor enhances control by 3 - 4 % and torque by around 2 - 3 % contrasted with the CNG motor. The HCNG motor works on the leaner side than the CNG motor which decreases fuel utilization by around 4% contrasted with CNG motor.
v. The HCNG fuel decreases CO outflows and NOx discharges more than the pure CNG operation. Henceforth making the HCNG fuel is all the more environmentally friendly.
vi. Compression ratio and equivalence ratio have a significant effect on both the performance and emission characteristics of the engine and have to be carefully designed to achieve the best engine performance characteristics.
vii. Higher engine rotational speeds can be used in lean mixtures to increase the power output of an engine operating on hydrogen while maintaining high efficiency and pre-ignition free operation.
viii. The expansion of hydrogen to methane gives a decent option fuel to hydrocarbon fills as it gives great fire security, wide combustible areas and generally higher smoldering speed.

In spite of the fact that the exhaust outflows from hydrogen-improved natural gas are as of now low, assist refinement must be done so as to further decrease discharges and to accomplish Enhanced Environmentally Friendly Vehicle (EEV) norms. In this manner discovering the ideal mix of hydrogen fraction, ignition timing and excess air proportion alongside different parameters that can be streamlined is surely a widespread obstacle. It is not just a test to find the perfect blend of hydrogen part, ignition timing, and overabundance air proportion, yet it can likewise be a huge test to control these parameters. In conclusion there is potential for execution changes with an increment in the pressure ratio [19]. Thus, today are confronted with natural issues, tomorrow hydrogen will tackle every single ecological issue because of street transports: Natural gas-hydrogen mixes may be a potential extension from today to tomorrow.

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