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Full Length Article

Effects of compression ratio and hydrogen addition on lean combustion characteristics and emission formation in a Compressed Natural Gas fuelled spark ignition engine

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HIGHLIGHTS

- Study to optimize compression ratio and hydrogen addition on lean combustion of CNG fuelled SI engine.
- Higher compression ratio resulted in improved power output and brake thermal efficiency.
- Hydrogen addition to CNG extended the lean misfire limit and enhanced combustion rate.
- Hydrogen substitution leads to lower HC and CO emissions and reduced NOx emission.
- Stable combustion of hydrogen lowers cycle by cycle variations.

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ABSTRACT

A single cylinder diesel engine was modified to operate as a Compressed Natural Gas (CNG) fuelled lean burn Spark Ignition (SI) engine. The engine was tested at 1500 rpm under wide open throttle condition at different compression ratios over varying equivalence ratios. The optimized compression ratio for CNG operation was found to be 12.5:1 which was further investigated for hydrogen substitution at 5% and 10% on energy basis to study and compare the performance, emission and combustion behavior of CNG fuelled lean burn SI engine. The brake thermal efficiency and brake power output increases with rise in compression ratio and achieved a peak brake thermal efficiency of 30.2% with 12.5:1 compression ratio and above a critical value of 12.5:1, the improvement was small when compared to the increase in emissions. Wide flammability limits of hydrogen enable ultra-lean combustion thereby extends the lean limit of operation to an equivalence ratio of 0.42 with 10% hydrogen addition as compared to 0.50 with neat CNG operation and its anti-knock enhancement makes it advantageous compared to increasing the compression ratio under low load conditions. Hydrogen addition also enhanced the combustion rate, heat release rate and reduced cyclic variations. On the emissions front, hydrogen addition showed reduction in hydrocarbon emissions from 65 g/kWh to 6.9 g/kWh at an equivalence ratio of 0.5 alongside carbon monoxide and carbon dioxide reduction. Due to retarded ignition timing to avoid knock, the Oxides of Nitrogen (NOx) emission increase was not significant.

1. Introduction

Nowadays, with rapidly depleting petroleum based fuel reserves, various alternative fuels have to be opted for reducing the dependency and for environmental protection. Never ending discussions on the emissions point of view, with more emphasis on cleaner automobile fuels led researchers to investigate alternate fuels such as biodiesel, CNG, hydrogen, alcohols, Liquefied Petroleum Gas (LPG) for a variety of conventional Internal Combustion (IC) engine applications [1,2]. Among the available fuel contenders, gaseous fuels are more attractive because of their wide ignition limits, capability to form homogeneous mixtures and their high hydrogen to carbon ratio leading to lesser emissions. Lately, CNG fuel has been regarded as a promising transportation fuel because of their clean nature of combustion [3–5]. CNG has been primarily used as a fuel in SI engines rather than Compression Ignition (CI) engines due to their lower cetane number, lower molecular weight and high vapour pressure suited for attaining homogeneous fuel/air mixtures followed by premixed gaseous combustion. Also, the

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Nomenclature

BDC	Bottom Dead Centre
BSFC	Brake Specific Fuel Consumption
CDI	Capacitive Discharge Ignition
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COV	Coefficient of Variation
DI	Direct Injection
ECU	Electronic Control Unit
FID	Flame Ionization Detector
HC	Hydrocarbon
HCNG	Hydrogen enriched Compressed Natural Gas
IC	Internal Combustion
IMEP	Indicated Mean Effective Pressure
LML	Lean Misfire Limit
LPG	Liquefied Petroleum Gas
NDIR	Non-Dispersive Infra-Red
MBT	Minimum advance for Best Torque
NO	Nitric oxide
NOx	Oxides of Nitrogen
OH	Hydroxyl
SI	Spark Ignition
TDC	Top Dead Centre

higher octane rating of the fuel exhibits trend towards lesser emissions, usage of higher compression ratio and its tendency for lean combustion makes it a favourable solution in SI engines [6–8]. Considering SI engine operation, the parameters of interest are generally the torque, power output and fuel consumption along with their efficient combustion characteristics. But usage of gaseous fuels in SI engines has always been reported with lower power output and considerable engine out emissions under stoichiometric combustion of the fuel [9–11]. Also on the emissions side, NOx emission level is particularly high under stoichiometric operation owing to higher exhaust gas temperature leading to durability setback and lower thermal efficiency. These factors strike a blow to the conventional stoichiometric operation of SI engine with gaseous fuels and to rise above these limitations, the stoichiometric CNG SI engine should be considered for effective lean burn operation [12,13].

Generally, stoichiometric operation of engines provide stable combustion than lean burn engines but leaner charge mixture aids in higher fuel conversion efficiency [14,15]. This corresponds to the presence of excess oxygen and reduced in-cylinder temperature where the burning of lean mixture requires advanced ignition timing to afford additional period for combustion reaction because of the excess air present. Even though the formation of emission is reduced under lean burn conditions, burning velocity is significantly lower as excess air hinders the flame propagation thereby increasing the overall combustion duration [16]. Thus, reduced flame travel decreases the overall efficiency with leaner mixtures. In addition, a few properties of CNG are not suitable for efficient lean combustion including necessity of high ignition energy, lower quenching distance and relatively lower flame speed. Obviously, lower flame speed guides to engine misfire causing eclipsed cyclic variations with increased hydrocarbon (HC) emissions. To compensate for these undesirable properties and extend the lean limit operation of CNG, hydrogen addition to CNG is being suggested on all terms because of its superior combustion characteristics [17,18]. However, certain combustion challenges had to be addressed first in utilizing the maximum out of these recommended fuels. Supporting the aforesaid statement, previous works suggest that addition of hydrogen with CNG even in smaller quantities helps in stable combustion with lesser emissions and improved performance. Thipse et al. [19] proved the benefits of hydrogen enrichment in natural gas and explained that because of excellent combustion properties of hydrogen fuel, ultra lean combustion could be achieved with optimized hydrogen-CNG blend. This could be evidently seen from the desirable properties of hydrogen fuel as shown in Table 1. For instance, Xu et al. [20] studied the effect of hydrogen addition on engine performance and emissions fuelled by CNG and showed that a relatively higher brake thermal efficiency can be achieved under certain fixed engine conditions when adding more than 20% of hydrogen by volume basis. Efficiency showed a drastic improvement based on suitable ignition timings and possible varying hydrogen fractions even under idle operating characteristics [21].

Addition of hydrogen to CNG enhances the reactivity of the gaseous fuel blend as it advances the formation of hydroxyl (OH) radicals together with CO and CO_2 amid combustion. Dandy et al. [22] investigated that addition of 20% hydrogen in methane would report similar percentage of increase in OH radical concentration and would enhance the oxidation rate of intermediate products. Kahraman et al. [23] showed that maximum brake thermal efficiency was obtained at 30% hydrogen when added to natural gas. Previous literature works suggest that addition of hydrogen with CNG improves the overall performance and helps in reducing toxic out emissions [24–26]. Apart from performance and emissions, studies also suggest that hydrogen enrichment of CNG improves combustion characteristics as well. In fact, variations in the cylinder pressure for different fractions of hydrogen blended with CNG report that peak cylinder pressure increased and the pressure

Table 1
Important properties of test fuels [26,29,37].

Property	Compressed Natural Gas	Hydrogen
Stoichiometric composition of air (% vol.)	9.5	29.5
Density (kg/m^3 @ STP)	0.74	0.085
Lower heating value (MJ/kg)	50	120
Flame speed (cm/s)	34	320
Flammability limits (% vol. in air)	5–15	4–75
Octane number (Research)	120	<130
Auto ignition temperature (°C)	540	600

Table 2
Engine specifications.

Type	Kirloskar TAF1, air cooled, single cylinder CI engine
Displacement	661 cc
Stroke	110 mm
Bore	87.5 mm
Connecting Rod	231 mm
Compression ratio	17.5:1 (CI version) 10.5,11.5,12.5:1(SI version)
Rated Power	4.4 kW @ 1500 rpm
Inlet Valve Open	4.5° bTDC
Inlet Valve Close	35.5° aBDC
Exhaust Valve Open	35.5° bBDC
Exhaust Valve Close	4.5° aTDC