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Experimental investigations of combustion, performance and emission characteristics of a hydrogen enriched natural gas fuelled prototype spark ignition engine

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HIGHLIGHTS

- Effect of hydrogen enrichment of natural gas on engine performance.
- Fuels with different H/C ratios (4, 4.22, 4.5, 4.85, 5.33 and ∞) were investigated.
- Brake thermal efficiency was superior for test fuel with H/C: 4.5.
- P_{max} increases with increasing H/C ratio of the test fuels.
- HRR was highest for hydrogen along with shortest ignition delay.

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ABSTRACT

In this study, spark ignition of hydrogen enriched natural gas (HCNG), a fast emerging alternative gaseous fuel, was experimentally investigated in a suitably modified single cylinder spark ignition (SI) engine. Port fuel injection of the HCNG engine using a high volume flow rate solenoid injector, controlled by a customized injector control unit and electronic control unit (ECU) was done and the fuel injection timings and duration were controlled for each load. Fuels with different H/C ratios in the final HCNG mixture were investigated for their engine performance, emissions and combustion characteristics. Engine investigations were carried out at constant engine speed of 1500 rpm for different H/C ratios (4, 4.22, 4.5, 4.85, 5.33 and ∞). Spark timing was kept constant (32° bTDC) for all test blends. Relative air–fuel ratio (RAFR) was kept constant for all loads during the experiments in order to avoid misfire at lower engine load. Hydrogen exhibited higher pressure peak (P_{max}) but lower maximum brake torque (MBT) compared to other test fuels due to lower knocking limit. Brake thermal efficiency (BTE) was superior for test fuel with H/C: 4.5. NOx emissions were higher for test fuel with H/C: 4.22 and relatively lower for hydrogen compared to baseline natural gas.

1. Introduction

Rapid increase in energy demand and resulting consumption of conventional fossil fuels has led to rapid depletion of underground carbon energy reserves and increasing fuel prices. This has increased dependency of all major global economies on gulf countries. In addition, it has also adversely affected air quality significantly, resulting in severe environmental degradation and climate change. Conventional fossil fuels are responsible for emission of harmful species such as unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), particulate matter (PM) and carbon dioxide (CO_2). These pollutants have severe health effects on human body and the global environment. Therefore commercialization of prominent low carbon or carbon free alternative fuels such as natural gas and hydrogen is necessary for the survival of humanity. These fuels have potential to reduce harmful green-house gas (GHG) emissions and could displace a portion of conventional liquid fossil fuels.

Both these fuels however offer different challenges for their utilization in internal combustion (IC) engines. For example, hydrogen requires very low ignition energy therefore utilization of hydrogen in IC engines can potentially cause pre-ignition and backfire [2]. Use of hydrogen also leads to low power output and constraints the operating load range of the engine because of very low density of hydrogen, which in-turn reduces the volumetric

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efficiency of the engine significantly. Therefore use of 100% hydrogen as a total replacement of gasoline in a spark ignition (SI) engine is rather challenging and difficult. On the other hand, natural gas is being used as an alternate fuel to conventional gasoline for last few decades. It is utilized either in the form of compressed natural gas (CNG) or liquefied natural gas (LNG). Natural gas resources have been discovered in various forms worldwide. There is tremendous interest in using natural gas on a large scale worldwide because it is relatively cleaner fuel due to its highest H/C ratio (4:1) amongst all hydrocarbon fuels. However natural gas suffers from poor lean-burn capabilities, low flame speed and poor idle stability [3], which makes CNG engine relatively low efficiency engine due to its longer combustion duration [4] and less agility. Engine's lean operation could be extended by increasing H_2 fraction in the test fuel and also by increasing intake manifold pressure [5]. In summary, both hydrogen and CNG have their own merits and disadvantages. The important properties of hydrogen and CNG are given in Table 1.

It can be seen from Table 1 that addition of hydrogen to CNG can significantly improve combustion characteristics of CNG by increasing its lean limits and flame burning velocity. Therefore in this study, performance, combustion and emission characteristics of a prototype SI engine, fuelled by various formulations of hydrogen enriched natural gas (HCNG), were experimentally investigated. This study is expected to clarify the behavior of engine fuelled with HCNG blends, in which H/C ratio was increased from 4 to ∞, or in other words, hydrogen fraction was increased from 0% (v/v) to 100 (v/v), through 10%, 20%, 30% and 40% (v/v).

Several researchers carried out investigations on hydrogen–CNG blends as IC engine fuel. Lim et al. [6] conducted experiments using 30HCNG in an engine with compression ratios of 11.5 and 10.5. They reported significant reduction in NOx emissions ($\sim$75%) and improvement in thermal efficiency ($\sim$6.5%) compared to baseline CNG. They also reported that anti-knocking tendency increased with fuel increasingly enriched in hydrogen. Significant effects of compression ratio, excess-air ratio and ignition timing were observed on NOx emissions. NOx and CO emissions increased with increased compression ratio. This increase in NOx emissions could be reduced by retarding the ignition timing or using lean combustion. Liu et al. [7] also reported similar trend and suggested that excess air ratio had a significant effect on the HC, CO, NOx, and CO_2 emissions for both, natural gas and hydrogen enriched natural gas. They reported that in lean burn operation, HC emissions decreased with increasing hydrogen fraction for a specified excess-air ratio. NOx emissions increased with increasing hydrogen fraction in the HCNG mixtures, and NOx attained its peak concentration at an excess-air ratio of 1.1. CO_2 emissions decreased with increasing hydrogen fraction in the HCNG mixture. It emerged that the addition of hydrogen in natural gas extended the lean burn limit. Thus, an engine fuelled with HCNG operating under lean mixture conditions produced fewer emissions of HC, CO, CO_2, and NOx. Ma et al. [8] carried out experiments in a turbocharged engine, introducing hydrogen fraction (0–50% v/v) in CNG at different ignition timings. They reported that increased hydrogen fraction led to decreased maximum brake torque (MBT), and increased indicated thermal efficiency (ITE). The NOx, HC and CO emissions decreased with advancing spark timing and increasing engine load. With hydrogen enrichment, NOx and CO emissions increased for same ignition timing but HC emissions decreased. If spark timing was retarded to MBT, NOx emissions exhibited no increase but thermal efficiency increased with increase in H_2 fraction in the HCNG mixture [9]. Akansu et al. [10] also studied emission characteristics of hydrogen and natural gas blends in an IC engine and reported that HC, CO and CO_2 concentrations decreased with increasing hydrogen fraction in the test fuel. However NOx emission increased as more hydrogen was added to the test fuel. Thipse et al. [11] proved the benefits of hydrogen enrichment of natural gas. Because of its excellent combustion characteristics, such as higher laminar flame speed and wider lean flammability limits, ultra-lean combustion could be achieved in HCNG. HCNG engine could comply with the NOx regulations upto EURO-6, while maintaining low levels of HC and Greenhouse gas (GHG) emissions, without use of any NOx after-treatment system. Park et al. [12,13] compared the engine experiment results of HCNG and CNG combustion. They reported that addition of 30% (v/v) hydrogen to CNG (30HCNG) was most appropriate to comply with NOx regulations of EURO-6 emission norms without affecting overall engine performance, HC and CO emissions. Moreover, the use of 30HCNG allowed sufficient range of the vehicle, compared to higher levels of hydrogen enrichment. Wang et al. [14] introduced nitrogen in the engine cylinder to reduce NOx emissions from CNG. They reported an inverse relationship between nitrogen dilution ratio and engine out emissions. Higher nitrogen dilution ratio exhibited lower NOx ($\sim$17–81%) emissions, but higher THC ($\sim$3–78%) and CO ($\sim$1–28%) emissions. Nitrogen dilution had a significant influence on combustion and exhaust emissions [8].

Table 1
Important fuel properties of hydrogen and natural gas.

Properties	H_2	CNG
Relative air–fuel ratio (Stoichiometric)	34.3	17.2
Density (kg/m^3) @ stp	0.085	0.748
Octane number	<130	120
Lower calorific value (MJ/kg)	120	50
Auto-ignition temperature (°C)	536	600 [1]
Laminar burning velocity (cm/s) @stp	265–325	37–45
Flame quenching distance (mm)	0.64	2.03
Flammability in air (%v/v)	4–75	5.3–15

Tangoz et al. [15] performed experiments using 5HCNG, 10HCNG and 20HCNG at different CRs and CR = 12 was found to be optimum. The maximum in-cylinder pressure (P_{max}) increased by addition of hydrogen to CNG for all CR. As CR decreased, torque increased upon addition of hydrogen to CNG. Lee et al. [16] reported reduction (>25%) in fuel consumption rate, while using HCNG as fuel at idle, compared to CNG. THC and CO emissions decreased with HCNG at idle, because of the low carbon content and enhanced combustion characteristics of the test fuel. Lower HCNG quantity used at idling also continuously decreased NOx emissions with an increase in lambda. Huynh et al. [17] performed experiments on a modified engine by controlling valve overlap. They reported that with hydrogen, it has no significant effect on engine performance compared to fixed valve timing. However they

Table 2
Technical specifications of the test engine.

Specifications	Before modifications	After modifications
Model/make	DM 10/Kirloskar	ERL1/IITK
Ignition type	Compression ignition	Spark ignition
Bore × stroke (mm)	102 × 116	102 × 116
Connecting rod length	232 mm	232 mm
No. of cylinders	1	1
Displacement	948 cc	948 cc
Compression ratio	17.5	11
Inlet valve opening time	4.5° bTDC	4.5° bTDC
Inlet valve closing time	35.5° aBDC	35.5° aBDC
Exhaust valve opening time	35.5° bBDC	35.5° bBDC
Exhaust valve closing time	4.5° aTDC	4.5° aTDC
Cooling system	Water cooled	Water cooled
Fuel injection type	Direct injection	Port injection
Fuel injection pressure	220 bar (in-cylinder)	3 bar (port)