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Experimental study of the composition of hydrogen enriched compressed natural gas on engine performance, combustion and emission characteristics

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HIGHLIGHTS

- BTE, BSEC and BSFC improved with BMEP for HCNG mixtures.
- Engine performance characteristics (BSEC, BTE and EGT) improved for HCNG.
- P, RoPR, HRR and CHR improved for HCNG mixtures.
- MBF_{10} and combustion duration shortened, flame speed increased for HCNG.
- With hydrogen addition, HC, CO and CO_2 reduced, while NO_x emission increased.

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ABSTRACT

Depletion of petroleum reserves and prevailing stringent emission legislations have motivated the researchers to develop and introduce alternative automotive fuels with an objective of reducing global emissions and reducing consumption of conventional fuels such as gasoline and diesel. Natural gas has emerged as a widely accepted and used alternative automotive fuel in last couple of decades. However many properties of compressed natural gas (CNG) limit its use in high performance engines. CNG has relatively lower diffusivity, lower lean limit, requirement of high ignition energy, high coefficient of variation (COV) of indicated mean effective pressure (IMEP), low flame speed and high flame quenching distance compared to gasoline. These properties can be effectively improved by addition of hydrogen to CNG. In this experimental study on a single cylinder prototype hydrogen enriched compressed natural gas (HCNG) engine, investigations were done to explore the potential benefits of HCNG mixtures of different compositions on engine performance, combustion and emission characteristics. Results proved that HCNG is a superior fuel compared to CNG and it increases power output and torque in addition to lowering emissions. Hydrogen addition to CNG improved brake thermal efficiency (BTE), reduced brake specific fuel consumption (BSFC), brake specific energy consumption (BSEC) and enhanced the combustion stability. Combustion parameters such as in-cylinder pressure, rate of pressure rise (RoPR), heat release rate (HRR) and combustion duration also improved. Combustion pressure increased with hydrogen addition to CNG. Addition of hydrogen raised RoPR, HRR and CHR compared to CNG. Emissions such as hydrocarbons (HC), carbon-monoxide (CO) and carbon-dioxide (CO_2) reduced while nitrogen monoxide (NO) increased with hydrogen addition at a given brake mean effective pressure (BMEP). 30% HCNG (mixture of 30% (v/v) Hydrogen and 70% (v/v) natural gas) showed most optimum performance and emission benefits amongst the tested HCNG mixtures.

1. Introduction

U.S energy information administration [1] projected sharp rise in fossil fuel demand for three large countries namely United States, China and India. This is in sharp contrast to rapidly depleting crude oil reserves across the world including gulf, which is demanding introduction of alternative fuels on large scale to sustain global mobility. These alternative fuels must replace conventional fossil fuels and reduce global emission footprint simultaneously. Many alternative fuels have emerged such as alcohols and biofuels however none of these are commercially viable

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except compressed natural gas (CNG). Major constituent of CNG is methane. Due to lower exhaust gas emissions and easy adaptation in the existing engines, CNG has been widely accepted. International Association of Natural Gas Vehicles (IANGV) has reported increasing number of natural gas vehicles (NGV) and projected 65 million [2] NGV by 2020 compared to 1.7 million in 2001.

Irrespective of CNG's commercial advantage, it suffers from certain drawbacks due to its distinct physical, chemical and combustive properties such as higher quenching distance, narrow flammability range, higher ignition energy, lower calorific value and lower burning speed. These properties can be improved by hydrogen addition. The mixture of CNG and hydrogen is referred as hydrogen enriched compressed natural gas (HCNG). HCNG delivers benefits of both hydrogen and CNG because of its improved properties. Use of HCNG also paves way for application of hydrogen in engines, which is challenging and unsafe with the present state of infrastructure. Addition of hydrogen to CNG reduces its quenching distance and lowers overall carbon-to-hydrogen (C/H) ratio, resulting in more complete combustion of fuel, leading to lower HC and CO emissions. Hydrogen addition also broadens the flammability limits of CNG and improves lean combustion so as to reduce nitrogen oxides (NO_x) emissions. Hydrogen addition to CNG leads to rapid formation of OH− and H+ radicals, which improve burning speed of CNG by enhancing the reaction rates. In view of the benefits offered by hydrogen addition, this research focuses on quantifying benefits of HCNG over CNG. For this study, a single cylinder engine (Kirloskar; DM10) was suitably modified to operate as port fuel injected HCNG engine. Performance, combustion and emission characteristics were analyzed for different HCNG compositions with variations in engine load.

Application of HCNG as potential engine fuel was conceptualized in 1989 by Hydrogen Components Incorporation (HCI). For initial studies, researchers modified a conventional engine to operate on gaseous fuel. This was followed by scientific studies on a wide range of single cylinder and multi-cylinder engines [3,4]. HCNG has been studied using direct injection, port injection and throttle injection techniques of fuel induction. Effect of various parameters on HCNG engine performance such as ignition timing, injection timing, compression ratio, excess air ratio etc. have been investigated extensively. Use of turbocharging [5,6], exhaust gas recirculation (EGR) [7] and variable compression ratio using a Cooperative Fuel Research (CFR) engine [8] have been investigated for HCNG. Nanthagopal et al. [9] explored the application of HCNG as an alternative fuel to liquid diesel and gasoline with an objective to minimize emissions and slow down depletion of hydrocarbon fuel resources. They indicated that HCNG engines have potential to comply with Euro-V norms. Akansu et al. [10] concluded that HCNG is a sustainable fuel based on environmental, economic and technical criterions. They concluded that engine efficiency improved by hydrogen addition to methane and emissions reached ultra-low emission vehicle (ULEV) levels, while increased NO_x was controlled by three-way catalytic converter. However, they also raised concerns related to higher production and operational costs due to high cost of transportation and storage infrastructure of hydrogen. Thipse et al., Patil et al., Helmut et al. and Midun et al. [11–14] enlisted various essential modifications required for engine operation on CNG and HCNG. Patil et al. [12] showed improvement of 3–4%, 2–3% and 4% in power, torque and BSFC respectively for 5% HCNG compared to baseline CNG, in addition to 20–30% reduction in NO_x, 40–50% reduction in CO and 45% reduction in NMHC emissions. Kavathekar et al. [15] applied computational modeling and experimental approaches for development of 6-cylinder HCNG engine and tried to comply with Euro IV emission legislations. Increasing hydrogen fraction in HCNG above critical limit led to knocking in conventional SI engines. Knocking was observed above 40% hydrogen addition by Flekiewicz et al. [3]. Helmut et al. [13] reported that engine power output and torque reduced for 100% hydrogen due to use of leaner air-to-fuel ratio (AFR) mixtures since richer AFR caused backfire and this was improved by HCNG. Turbocharging was not found to be effective for hydrogen engines because of lower exhaust gas energy due to leaner combustion however it was found to be effective for HCNG.

Ma et al. [16] investigated variations in indicated thermal efficiency (ITE) with ignition timing in a turbocharged engine. In their study, hydrogen addition improved ITE and maximum ITE was obtained with retarded ignition timings i.e. close to top dead center (TDC) for higher HCNG mixtures. They suggested that with increase in hydrogen volume percentage, ignition timing had to be retarded for optimum engine performance and lower emissions. They concluded that combustion duration shortened by 1 °CA for every 10% (v/v) increase in hydrogen fraction and ignition delay reduced. In another study, Ma et al. [17] compared the results of online mixing system and pre-bottled mixture. Pre-bottled mixture was prepared using Dalton's law of partial pressures. They found results to be in close range for both methods. Ceper et al. [18] carried out experiments for variations in in-cylinder pressure at different excess air ratios and different hydrogen fractions. They reported that peak pressure increased with hydrogen addition and the peak shifted towards TDC, with the highest efficiency observed when peak pressure occurred at 10–15 °CA after top dead center (ATDC). They reported trend of lower HC with increasing excess air ratio while CO_2 variation vs. excess air ratio initially increased and then gradually reduced. Formation of CO_2 reduced with hydrogen addition due to reduction in overall C/H ratio. Xu et al. [19] carried out experiments in a single cylinder port fuelled engine and reported almost similar in-cylinder pressure trends but relatively higher heat release rate (HRR) for hydrogen-methane mixtures. Peak pressure location and HRR curve peak shifted towards TDC with increasing hydrogen fraction in the HCNG. CO reduced with increasing excess air ratio, while CO_2 increased with increasing excess air ratio up to 1.2 and then reduced. On the other hand, HC emissions reduced to minimal and then increased with increasing excess-air ratio. Hydrogen addition showed lower CO_2 and HC emissions compared to CNG due to higher combustion temperature and relatively lower C/H ratio of the HCNG mixtures. Moreno et al. [20] performed experiments in a spark ignition (SI) engine at higher engine speeds (2500 to 4500 rpm) and compared experimental results with baseline gasoline. Pressure curve peak shifted towards TDC at same equivalence ratio for hydrogen fractions of 0–50% in their study. Peak pressure and rate of pressure rise (RoPR) increased with increasing hydrogen fraction at 3250 rpm. In addition, flame development duration and rapid combustion duration reduced with increasing hydrogen percentage at each speed due to higher burning velocity.

Bauer and Forest [8] achieved reduction of 90%, 50%, 58%, 23% and 7% in particulate matter (PM), NO_x, non-methane hydrocarbons (NMHC), HC and CO_2 respectively. They also reported that NO_x could be further reduced by dilution with air i.e. with lean engine operation or EGR dilution and retarded ignition timing. Park et al. [21] reported 80% reduction in NO_x emissions with retarded ignition timings for 30% (v/v) HCNG. Ma et al. [22] reported 70%, 83.57%, 93% and 5% reduction in methane (CH_4), CO, NO_x, and BSFC respectively for optimized HCNG engine vis-à-vis baseline CNG engine. Khatri et al. [4] tested a vehicle with a four-cylinder engine on a chassis dynamometer under idling and varying load conditions. Large reduction in CO down to 15 ppm, HC to 25 ppm and CO_2 by 31.74% compared to 198 ppm CO and 67 ppm HC from baseline gasoline were reported. Ma et al. [23] reported increased NO_x emissions with increasing hydrogen fraction in HCNG mixture. 3000 ppm NO_x was reported for 25% (v/v)