Applied Thermal Engineering 141 (2018) 42–50

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Knocking behavior and emission characteristics of a port fuel injected hydrogen enriched compressed natural gas fueled spark ignition engine

S.M.V. Sagar, Avinash Kumar Agarwal*

Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India

HIGHLIGHTS

- HCNG is fast emerging to be an alternative to conventional liquid fuels.
- Experiments on a port fuel injected engine prototype using HCNG.
- HCNG emitted lower CO_2, HC and CO, but higher NO_X.
- Lowest knocking intensity exhibited by 30HCNG at all loads.
- HCNG particulates have no additional toxicity/ threat to human health.

ARTICLE INFO

Keywords:
HCNG
Particulates
Gaseous emissions
Knocking
Hydrogen engine

ABSTRACT

Natural gas has highest hydrogen-to-carbon ratio among hydrocarbon fuels, which helps in reducing greenhouse gas emissions. Blending natural gas with hydrogen decreases emissions even further because of superior combustion characteristics of hydrogen enriched compressed natural gas (HCNG) mixtures. This study focuses on measurement of carbon dioxide, nitrogen oxides, hydrocarbons, carbon monoxide and particulate emissions from HCNG mixtures and compare them with that of baseline compressed natural gas. Hydrogen enriched fuels are prone to higher knocking therefore, experiments were conducted on a single cylinder port fuel injected spark ignition engine prototype using variety of test fuels such as compressed natural gas, 10, 20, 30, 50, 70% HCNG mixtures and hydrogen for in-depth understanding of relative particulates and gaseous emissions, in addition to determining the engine's knocking characteristics. Experimental results showed that hydrogen enrichment of natural gas reduced emissions of carbon dioxide, hydrocarbons, and carbon monoxide however emissions of nitrogen oxides increased. Lowest knock intensity was observed for 30HCNG mixture. HCNG mixtures improved the engine out emissions and reduced the knocking tendency experienced with hydrogen fueling in internal combustion (IC) engines. Hydrogen enrichment of natural gas also reduced the carbon intensity of fuels, which in-turn reduced greenhouse gas emissions.

1. Introduction

World is currently facing multiple challenges of environmental pollution, rapid climate change and global warming, with increasingly severity. Emission of hazardous gases and particulate matter (PM) from internal combustion (IC) engines in vehicles are one of the prime anthropogenic causes for these issues. In order to control environmental degradation, stringent emissions norms have been adopted worldwide. In this context, the need for cleaner alternate fuels with fewer emissions compared to conventional fuels has been strongly felt. The number of engines/vehicles releasing hazardous pollutants is growing rapidly [1,2]. Conventional fossil-fuel generated emissions are a major source of hazardous pollutants that alter the climate and degrade the urban air quality [1,3], in addition to causing global warming. According to

Abbreviations: BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; bTDC, before TDC; BTE, brake thermal efficiency; CH_4, methane; CI, compression ignition; CNG, compressed natural gas; CO, carbon monoxide; CO_2, carbon dioxide; CR, compression ratio; EEPS, engine exhaust particle sizer; EGR, exhaust gas recirculation; GHG, greenhouse gases; H_2, hydrogen; H/C, hydrogen-to-carbon ratio; HC, hydrocarbons; HCNG, hydrogen enriched compressed natural gas; HRR, heat release rate; IC, internal combustion; KI, knock intensity; NDIR, non-dispersive infrared; NMHC, non-methane hydrocarbon; NOx, nitrogen oxides; PAH, polycyclic aromatic hydrocarbons; PN, particulate numbers; PN_{max}, maximum PN; PM, particulate matter; $PM_{2.5}$, PM smaller than 2.5 µm size; PM_{10}, PM smaller than 10 µm size; PPM, particles per million; RAFR, relative air-fuel ratio; RoPR, rate of pressure rise; SI, spark ignition; SoI, start of injection; SOx, sulfur oxides; TDC, top dead centre; TiO_2, titanium dioxide; THC, total hydrocarbons; v/v, volume-by-volume fraction

* Corresponding author.
E-mail address: akag@iitk.ac.in (A.K. Agarwal).

https://doi.org/10.1016/j.applthermaleng.2018.05.102
Received 13 February 2018; Received in revised form 22 May 2018; Accepted 27 May 2018
Available online 28 May 2018
1359-4311/

United States Environmental Protection Agency (USEPA), nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions from automotive sector are major contributors to the acid rain. Emissions from engines/vehicles also cause severe health hazards, when deposited on soil and waters bodies, through which they potentially enter the food chain. Health effects such as respiratory issues, cancer, heart and blood related diseases, asthma, inflammatory problems [4], lung diseases and various types of allergies are attributed to PM originated from IC engines/vehicles. Especially particle emissions with < 2.5 µm ($PM_{2.5}$) are known to trigger respiratory health issues [5]. Therefore emission norms adopted worldwide to counter this menace are increasingly becoming stricter with time. To comply with these emission norms, researchers are exploring/developing alternate fuels to replace conventional fossil fuels, which can be readily adopted with minimum engine hardware modifications.

Kalam et al. [6] conducted experiments on a 4-cylinder engine using gasoline and CNG. They reported that CNG exhibited lower brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), higher combustion efficiency and lower emissions of HC, CO_2, CO, but relatively higher NO_x emissions compared to baseline gasoline. Zarante and Sodre [7] also reported relatively lower CO and CO_2 emissions from CNG compared to gasoline. Roethlisberger and Favrat [8] performed comparative study of gasoline and CNG in direct and indirect (prechamber) spark ignition (SI) engines and reported that CO and THC emissions from CNG were lower by ~40% and ~55% respectively in case of indirect spark ignition engine. A delay in spark timing by 8°CA bTDC resulted in lower peak in-cylinder pressure, and lower NO_x, CO and THC emissions. Another study [9] exhibited that CO emission from CNG reduced from 10% (v/v) to 2% (v/v), while CO_2 emissions reduced from 12% (v/v) to 4% (v/v) under the same operating conditions, when the fuel was switched to baseline gasoline. However NO_x emissions increased from 700 ppm to 1000 ppm for CNG under identical operating condition compared to baseline gasoline.

In addition to environmental issues, fast depleting fossil fuel reserves [10] have also necessitated development of newer alternate energy resources for sustaining the global automotive sector. In India, fossil fuel demand is very high and this coupled with scarce locally availabile fuel reserves have pushed the fuel prices northward. Alternate fuels like CNG have become very attractive option, since CNG has the highest H/C ratio amongst all hydrocarbon fuels and it has huge reserves in the form of shale gas and gas hydrates worldwide, which are yet to be exploited. Table 1 shows typical fuel properties of hydrogen and CNG compared to conventional gasoline.

Relatively slower flame propagation speed of natural gas leads to higher cycle-to-cycle variations and larger ignition delay in SI engines. Hydrogen on the other hand suffers from the problem of very fast flame speed. Therefore hydrogen enrichment of natural gas reduces both cycle-to-cycle variations as well as the ignition delay of the resultant test fuel mixture, with engine cycle approaching closer to the air-standard thermodynamic cycle efficiency. Thus mixtures of hydrogen and CNG (referred as HCNG) have superior combustion properties compared to hydrogen and CNG, when both used individually [12]. Because of wider flammability limits and lower ignition energy requirement in case of hydrogen, knocking tendency of HCNG mixture also increases in the test fuel mixtures with higher hydrogen fraction. The shockwaves created during knocking increase peak in-cylinder pressure rapidly, resulting in possible damage to the engine hardware and vital moving components. Flekiewicz et al. [13] reported that optimal hydrogen percentage (HCNG ratio) in the test fuel mixtures was between 30% and 40% ((v/v)). They reported that addition of hydrogen > 40% ((v/v)) leads to knocking. However, hydrogen is not available in nature in free form to be used as fuel. It has to be produced from hydrocarbons and other natural resources using some specific energy intensive chemical reactions. Today, hydrogen is mainly produced from natural gas by 'steam reforming' process. Steam reforming doesn't provide any benefit in terms of net CO_2 released, since it merely shifts use of fossil fuels from the end use point to the hydrogen production point. However to reap benefits of hydrogen in totality i.e. in terms of cost, performance, reliability & environment viewpoint, it should be produced from non-fossil renewable resources such as water, on a large-scale in a commercially viable manner. At present, technologies for hydrogen production from water are not at par with steam reforming, which is a commercially viable technology. However, researchers are making efforts to develop commercially viable technologies for hydrogen production from water in order to exploit the benefits of this carbon-free fuel. From this viewpoint, this research study is quite relevant for finding out the potential of hydrogen as a fuel additive to an existing fuel 'CNG' because of its limited availability, with the hope that in foreseeable future, hydrogen will be commercially produced with near-zero carbon footprint and then the world can possibly switch over to hydrogen economy gradually [14].

Table 1
Properties of hydrogen, CNG and gasoline [11].

Properties	H_2	CNG	Gasoline
Limits of flammability in air, % (v/v)	4–75	5–15	1.0–7.6
Stoichiometric composition of air, % (v/v)	29.53	9.48	1.76
Minimum energy for ignition in air, mJ	0.02	0.29	0.24
Auto ignition temperature, K	858	813	501–744
Flame temperature in air, K	2318	2148	2470
Burning velocity in NTP air, cm/s	325	45	37–43
Quenching gap in NTP air, cm	0.064	0.203	0.2
Thermal energy radiated, %	17–25	23–33	30–42
Diffusivity in air, cm^2/s	0.63	0.2	0.08
Normalized flame emissivity	1.00	1.7	1.7
Equivalence ratio	0.1–7.1	0.7–4	0.7–3.8

Combustion of CNG leads to emissions of carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC) because of presence of carbon in the fuel molecules. Hydrogen is a carbon-free fuel therefore its combustion does not lead to carbonaceous emissions. Hydrogen enrichment of CNG increases overall H/C ratio of the HCNG mixture, resulting in significant reduction in GHG emissions. Hydrogen enrichment of CNG also helps reduce HC, CO and CO_2 emissions compared to baseline natural gas. Bauer et al. [15] achieved reduction in CO_2, total hydrocarbons (THC), non-methane hydrocarbons (NMHC), NO_x and particulate emissions by ~7, 23, 58, 50, and 90% respectively, by hydrogen enrichment of CNG. Ma et al. [16] reported 70% reduction in emission of CH_4, 84% reduction in emission of CO, and 93% reduction in emission of NO_x in an optimized HCNG engine, compared to baseline CNG engine. Park et al. [17] measured mass emissions (g/kwh) and reported 45% reduction in NMHC and 40–50% reduction in CO with HCNG, compared to baseline CNG. One of the main negative aspects of hydrogen enrichment of CNG was higher NO_x emission under identical engine operating conditions [18]. Hydrogen combustion results in very high peak in-cylinder temperature. Higher NO_x emissions are produced under higher peak in-cylinder temperature conditions. Hence, hydrogen fueled engines emit relatively higher NO_x compared to CNG fueled engines because the peak temperature encountered in hydrogen combustion is ~150 K higher than that in case of CNG fuelled engines. However, studies have shown that reduction in emissions of NO_x and other species can be obtained by retarding the spark timings. Park et al. [17] reported 80% reduction in NO_x emissions by retarding the spark timing for the HCNG mixtures. Khatri et al. [19] reported 31.74% reduction in CO_2 emissions, 92.4% reduction in CO and 62.6% reduction in HC from HCNG engine compared to baseline gasoline fueled engine. Effect of other parameters such as injection timing [20], compression ratio [21], spark timing [19], excess air ratio etc. have been experimentally investigated extensively. Serrano et al. [22] reported that an increase in compression ratios (CR) from 9.5 to 11.5 increased the brake thermal efficiency (BTE) and introduction of exhaust gas recirculation (EGR) reduced the NO_x emissions from HCNG mixtures.

Apart from regulated gaseous emissions, awareness about the