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HCNG fueled spark-ignition (SI) engine with its effects on performance and emissions

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ABSTRACT

The usage of natural gas in internal combustion engines involves various difficulties, like weak lean-burn ability, low flame speed and ignitability, which demand deep studies for its usage in IC engines. For compressed natural gas (CNG) in SI engines, there is an engine efficiency sacrifice at low loads and high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions which cannot be solved without using after-treatment equipment. This equipment, however, is very expensive. Therefore, an additional fuel can enhance the characteristics of the combustion of natural gas, which can be added in the intake charge. Hydrogen is an effective gas for enhancing the flame rate regarding combustion in an SI-CNG engine, in addition to increasing engine stability. Small amounts of hydrogen improve performance and reduce exhaust emissions. Thus, a number of investigators have carried out research studies on SI engines with different ratios of HCNG. This paper is comprehensive overview of CNG, H_2 and HCNG blends. The main topics discussed consist of the combustion fundamentals of natural gas, hydrogen and hydrogen-natural gas mixture. Natural gas and hydrogen usage as fuels and their characteristics have been analysed. The storage of hydrogen and HCNG is still challenging researchers and, therefore, their storage has been taken into consideration. Moreover, a comprehensive review has been performed of HCNG blends in order to understand the effect of hydrogen enriched CNG on performance and the emissions of SI engines. The combustion characteristics of HCNG engines are strongly dependent on the conditions of the engine. The air-fuel ratio, the time of injection, the compression ratio and speed play a major role in blending HCNG in an SI engine and have been discussed in this article.

1. Introduction

The world is facing various issues in the 21st century. Some of the most important of these are the decreasing availability of low-cost sources of fuel, the growth of the population of the world, and the growth of energy demand in all sectors of industry. Fossil fuels, like coal, diesel, and gasoline, are depleting at a fast pace. Moreover, they pollute the environment and thus are not regarded as sustainable and permanent solutions to the world's energy requirements [1]. Furthermore, any shortage in these types of energy sources might result in the fluctuation of oil prices and is regarded as a threat to the energy security of the world and the global economy [2]. With the global increase of fossil fuel usage, the quality of local air deteriorates and the amount of greenhouse gas (GHG) emission increases. Transportation (marine, air, road, etc.) encompasses 33% of the USA's emission; of which more than one third are from road transport. Power stations are responsible for 41% of the emissions in the USA, agriculture and industry emit 16% and the remaining 10% is emitted by other sources [3].

Employing NG as a substitute fuel is one of the solutions that has been accepted and has spread throughout the world. NG, whose main constituent is methane, provides great environmental and economic advantages like lower emissions, along with enhanced availability and efficiency. The use of natural gas in internal combustion engines involves various difficulties like methane's ignitability, poor lean-burn capability and low flame speed [4]. Based on past research studies, hydrogen is a green fuel that can be used in vehicles as an alternative to conventional fuel [5,6]. Compared to compression ignition (CI)

Abbreviations: A/F, Air fuel ratio; CAD, Crank angle degree; TDC, Top dead center; ATDC, After top dead center; SI, Spark ignition engines; CI, compression ignition; IC, Internal combustion; CNG, Compressed natural gas; NGVs, Natural gas vehicles; LPG, Liquefied petroleum gas; CO, Carbon monoxide; CO2, Carbon dioxide; HC, Hydrocarbons; PM, Particulate matter; NOx, Nitrogen oxides; BTE, Brake thermal efficiency; LHV, Lower heat value; BMEP, Brake mean effective pressure; HRR, Heat Release Rate; SOC, Start of combustion; CR, Compression ratio; CA, Crank angle; EGR, Exhaust gas recirculation; λ, Exceed air (1/4 air-fuel ratio); η, Molar fraction of methane

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Table 1
Air pollutants, their sources and health effects [36].

Pollutants	Source/formation	Human health effects
Carbon monoxide (CO)	IC engine, industries and waste incineration	When inhaled CO enters the bloodstream and disrupts the supply of oxygen to the body's tissues.
Hydrocarbon (HC)	Evaporative emissions from vehicle fuel system, or in exhaust emissions	Exposure can cause headaches or nausea, while some compounds may cause cancer.
PM and soot	IC engine (e.g., cars and trucks) and Industry	Long term exposure may cause to lung cancer, heart disease, and asthma attacks.

engines, SI engines are more appropriate for adopting hydrogen since hydrogen's auto ignition temperature is rather high (around 858 K [7]) [8–12]. Hydrogen has various combustion characteristics that are unique and beneficial in emission performance and engine efficiency [13,14].

Mixing hydrogen with natural gas is one of the most effective ways of handling this issue since the burning velocity of the mixture is substantially high, the ignition energy is low, and the lean-burn capability is satisfactory. There is a rise of interest in the research on pollutant emissions and the performance of the hydrogen-enriched, CNG-fueled, conventional internal combustion engine [13,15,16]. These studies indicate that mixing hydrogen with natural gas enhances the combustion stability and reduces the hydrocarbon emissions; however, it results in the production of more nitrogen oxides (NO_x). The impact of different CNG-hydrogen blend combustions on the combustion traits in direct-injection SI engines has also been examined by different researchers [13,15,17,18]. These studies have proposed an optimum hydrogen volumetric fraction CNG-hydrogen blend that results in a balanced compromise in the emission and performance of the engine. It is expected that natural gas combustion with hydrogen will enhance the lean-burn traits and reduce the engine emissions (particularly CO, HC, and CO_2); however, the main concern is the possibility of a rise in NO_x emissions [19]. The addition of hydrogen enhances the process of combustion with the added possibility of developing engines that have a lower environmental effect and higher performance. Hydrogen is entirely carbon-free and can be produced with relative ease; these are characteristics that make it a good alternative choice to conventional fuel. But, there are some disadvantages in using pure hydrogen, like the low calorific value per unit volume, the high adiabatic flame temperature, and pre-ignition phenomena caused by contact with the residual gas or the hot spots resulting from lower ignition energy [20–22]. Employing NG/hydrogen mixtures which contain H_2 provides an opportunity to exploit the positive aspects of using hydrogen without the considerable alteration of the natural gas engines that already exist [23]. Moreover, employing hydrogen as an element that complements natural gas results in the extension of the lean-burn limit to the hydrogen's extended flammability range. Lean-burn ability decreases the knock coincidence (a serious condition which is threatening to spark ignition (SI) engine's safe performance), enhances the thermal efficiency, and decreases the combustion temperature and the emission of NO_x [24,25]. Hydrogen's anti-knock characteristic enables it to enhance the compression ratio (CR), which results in the further enhancement of thermal efficiency [25]. Adding hydrogen can also result in a significant decrease of IMEP (the coefficient of the indicated mean effective pressure variation) and reduces the duration of combustion leading to better thermal efficiency and a decrease in fuel consumption [26,27].

In this article, past studies examining hydrogen-enriched CNG as a fuel used in a reciprocating spark-ignited (SI) piston engine have been reviewed in detail. There are several review papers on this subject. Several reviews have discussed the effect of natural gas on SI engines and CI engines in dual-fueling [28–34]. The effect of hydrogen on SI engines and on CI dual fuel engines was reviewed by several others [1,34–41]. For hydrogen-enriched CNG, a few papers [26,42–44] contained short discussions about its influence on the performance and emissions of the engine, with their main focus being on other topics. Some of them focused on the effect of HCNG on diesel engines only. In the present work, there is firstly a discussion of the necessity for alternative fuels with regards to the current state of pollution and fossil fuel reserves. How natural gas is implemented in IC engines and its economic aspects are then discussed. Hydrogen fuels in an IC engine, its production and its storage are presented in a sub-section of this paper. In the main section of the article, using hydrogen and natural gas blends in an SI engine are considered, as well as the effect of HCNG on the engine performance, combustion and emission characteristics. Lastly, the overall conclusions and future recommendations are presented.

2. The usage of alternative fuels in an SI engine

Harmful emissions (like PM, soot, NO_x, HC and CO) are emitted by fossil fueled (like LPG, CNG, diesel, and gasoline) vehicles. These emissions eventually become part of the environment and pollute the earth's atmosphere. During combustion, CO and CO_2 are emitted from the carbon that existed in the fuel. CO_2 and water vapour are formed as a result of a perfect combustion which is illustrated by Eq. (1). However, in the actual combustion, other species (like N_2O, NO_2, NO, HC, CO) are generated, as shown in Eq. (2). These pollutants are generated by various sources; however, transportation vehicles contribute the most. Human health is affected by the increase of pollutants in the environment [36]. Table 1 illustrates various pollutants and their health impact.

$$C_xH_y + a(O_2+3.76N_2) \rightarrow bCO_2 + cH_2O + a\times 3.76N_2 \tag{1}$$

$$C_xH_y + a(O_2+3.76N_2) \rightarrow bCO_2 + cH_2O + dCO + eC_xH_y + fNO + gN_2O + a\times 3.76N_2 \tag{2}$$

The level of pollution in urban areas can be controlled through the use of hybrid vehicles, battery-operated vehicles, and fuel change. Zero emission is produced by battery-operated vehicles on the road. However, a number of factors contribute to the limited use of electric vehicles, e.g. the short travel range, the lower battery life, and the lower ratio of power to weight. Hybrid technology can be regarded as intermediate to fuel change and battery mode. It needs a battery and a traditional power train, resulting in higher maintenance and capital expense. After observing road transportation vehicles' future needs, fuel change seems like a more convenient solution [36]. Alternatively, biofuels, hydrogen and CNG can fuel IC engines. High emissions, such as nitric oxides, carbon dioxide, hydrocarbons, and carbon monoxide, are produced from engines operated using petroleum, and this problem is still a challenge to researchers [45]. Alternative fuel is one of the new technologies used to reduce emissions in CI engines. Natural gas, propane, and methanol have been used since the year 2000 as alternative fuels for vehicles [6]. Due to their clean burning nature and their ever-increasing usage in the automobile industry, alternative fuels might be termed as future fuels. Hydrogen, natural gas and mixtures of natural gas and hydrogen have been taken into consideration as alternative fuels in recent years in order to reduce the pollution from vehicles [14,46].