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

Hayder A. Alrazen\textsuperscript{a,b,*}, K.A. Ahmad\textsuperscript{b}

\textsuperscript{a} Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
\textsuperscript{b} Technical Institute/Qurna, Southern Technical University, Qurna, Basra, Iraq

\textbf{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 fuel 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 a comprehensive overview of CNG, H\textsubscript{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 security of the world and the global economy [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)
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 (NOx). 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 CO2); however, the main concern is the possibility of a rise in NOx 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 H2 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 NOx [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, NOx, 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 CO2 are emitted from the carbon that existed in the fuel. CO2 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 N2O, NOx, 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.

$$C_nH_m + a(O_2+n.36N_2) \rightarrow bCO_2 + cH_2O + a\times3.76N_2$$  \hspace{1cm} (1)  

$$C_nH_m + a(O_2+3.76N_2) \rightarrow bCO_2 + cH_2O + dCO + eC_nH_p + fNO + gN_2O + a\times3.76N_2$$  \hspace{1cm} (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].
3. Natural gas

3.1. CNG Used as a fuel

Natural gas vehicle usage is the same as is employed for heating and cooking in the domestic sector [47]. To produce CNG, natural gas (which is mostly made up of methane –CH₄) is compressed to below 1% of the volume it occupies at standard atmospheric pressure. A rigid container with 200–248 bar (2900–3600 psi) pressure is used for storing and distributing it; this is often in the form of a metallic cylinder. The physiochemical properties of gasoline, propane and hydrogen are compared with those of CNG (CH₄) in Table 2.

The number of natural gas vehicles in the world is increasing at a fast pace, which is why consistent information on their quantity is not available. But, based on the latest authentic sources, Iran is (currently) the leader in NGVs with as many as 4.07 million [28,52]. China follows available. But, based on the latest authentic sources, Iran is (currently) Iran closely with 3.99 million NGVs. Based onFig. 1, the NGV popu-

<table>
<thead>
<tr>
<th>Properties</th>
<th>Hydrogen</th>
<th>Methane</th>
<th>Propane</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>H₂</td>
<td>CH₄</td>
<td>C₃H₆</td>
<td>C₇.6H₁₆.2</td>
</tr>
<tr>
<td>Molecular weight (a.m.u.)</td>
<td>2.016</td>
<td>16.04</td>
<td>44.09</td>
<td>107.0</td>
</tr>
<tr>
<td>Density at Nkg/m³</td>
<td>0.0824</td>
<td>0.643</td>
<td>1.767</td>
<td>730</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>120</td>
<td>50</td>
<td>46.3</td>
<td>44.8</td>
</tr>
<tr>
<td>LHV (MJ/m³)</td>
<td>9.9</td>
<td>32.6</td>
<td>81.2</td>
<td>32.704</td>
</tr>
<tr>
<td>Heat of combustion (MJ/kgmol)</td>
<td>3.48</td>
<td>2.90</td>
<td>3.14</td>
<td>3.05</td>
</tr>
<tr>
<td>Specific heat (Cₜ) at NTP gas (MJ/kg K)</td>
<td>14.89</td>
<td>2.22</td>
<td>–</td>
<td>1.62</td>
</tr>
<tr>
<td>Specific heat ratio (γ) at NTP gas</td>
<td>1.383</td>
<td>1.308</td>
<td>–</td>
<td>1.05</td>
</tr>
<tr>
<td>Diffusion co-efficient in air at NTP (cm²/s)</td>
<td>0.61</td>
<td>0.16</td>
<td>0.1</td>
<td>0.005</td>
</tr>
<tr>
<td>Viscosity of gas at NTP (10⁻³ g/cm s)</td>
<td>0.0875</td>
<td>0.110</td>
<td>–</td>
<td>0.052</td>
</tr>
<tr>
<td>Flammability limits (vol% in air)</td>
<td>4.75</td>
<td>4.15</td>
<td>2.2–9.3</td>
<td>1.4–7.6</td>
</tr>
<tr>
<td>Flammability limits</td>
<td>0.1–7.1</td>
<td>–</td>
<td>–</td>
<td>0.7–3.8</td>
</tr>
<tr>
<td>Minimum ignition energy (mJ)</td>
<td>0.02</td>
<td>0.29</td>
<td>0.3</td>
<td>0.24</td>
</tr>
<tr>
<td>Auto ignition temperature (°C)</td>
<td>585</td>
<td>540</td>
<td>495</td>
<td>228–470</td>
</tr>
<tr>
<td>Flame velocity (m/s)</td>
<td>2.65–3.25</td>
<td>0.37–0.45</td>
<td>0.42–0.48</td>
<td>0.37–0.43</td>
</tr>
<tr>
<td>Stoichiometric composition in air (vol%)</td>
<td>29.53</td>
<td>9.48</td>
<td>4.03</td>
<td>1.76</td>
</tr>
<tr>
<td>Stoichiometric air-fuel ratio (mass basis)</td>
<td>34.12</td>
<td>17.23</td>
<td>14.75</td>
<td>14.7</td>
</tr>
<tr>
<td>Adiabatic flame temperature with air (K)</td>
<td>2318</td>
<td>2148</td>
<td>2267</td>
<td>2470</td>
</tr>
</tbody>
</table>

3.2. CNG economics

Providing an affordable source of energy is among the main advantages of CNG. The low-cost CNG provides a glimpse of hope amid continuous consumption of costly fuel like gasoline and diesel. Even though the main reason for the use of CNG in road transportation, particularly in big cities, was its emission control and environmental aspects, today, with the sharp increase in oil prices, the economic advantage of CNG usage is becoming more evident and attracts the attention of new users [54]. In most of the countries in the world, CNG costs much less than diesel and gasoline (per gallon equivalent) even when taking the compression costs into account. Thus, despite having a lower thermal efficiency than gasoline and diesel, CNG usage as a transportation fuel has substantial economic advantages. Natural gas needs to be slightly processed from the production field to the vehicle to become appropriate for transportation fuel usage, whereas gasoline and diesel need to be separated from crude oil and undergo an intricate refining process. Moreover, CNG resource is more evenly distributed throughout the world in comparison to oil and it has lower vulnerability to price fluctuation [55]. The natural gas price advantage over gasoline and diesel has been regarded as the most significant factor in attracting consumers and encouraging the change from traditional fuel to CNG [56–60].

Retail prices in the top 15 CNG user countries during the 2011–2012 fiscal year have been compared and illustrated in US Dollars in Table 3. It can be seen that the pumping price of CNG is 50% lower than the diesel and gasoline price on average in the majority of countries with successful NGV penetration. The rapid pace with which the numbers of CNG vehicles have increased in the past decade, particularly in the Asia-Pacific area, is mostly due to the lower price of CNG compared to gasoline and diesel [28]. The economic metrics for running a vehicle on CNG, as opposed to operating it on diesel or petrol, have been calculated based on the 2011–2012 fiscal year’s average global fuel price. The results of these calculations are illustrated in Fig. 3 and Table 4.

Based on the reports of the US Department of Energy’s Alternative Fuel Comparison for Jan-Mar 2011, CNG was one-third less expensive in comparison to gasoline. According to the U.S. Energy Information Agency’s reports, CNG costs 42% less on average in comparison to diesel (on an energy equivalent basis); it is expected to reach 50% by 2035. In a similar vein, the Republic Services, which is the USA’s second largest waste management services company, has managed to reduce its fuel cost by 50% with the effective deployment of CNG across various fleets [61]. In recent years, the US Department of Energy has carried out a survey on the subject of “alternative transportation fuels” and has discovered that using CNG, instead of conventional gasoline as the fuel of the transportation fleet, will result in a 50% cost reduction [28].

A comparative assessment of the Washington Metropolitan Area Transit Authority (WMATA) operated transit buses’ emissions was conducted by the USA’s NREATA (National Renewable Energy competition) in 2004. The results of the study showed that besides the CNG buses’ emission benefits, CNG buses had remarkable fuel economy outputs in comparison to diesel buses [62]. Clear strategies have been explicitly established to ban the usage of diesel in city buses (for instance in India) or to preserve CNG’s cost benefits compared to diesel (for instance in Pakistan) in the areas within which the government plans to replace diesel with CNG [63–69].
3.3. Natural gas composition

Natural gas is composed of different hydrocarbon molecules. The composition of commercial natural-gas differs from 85% methane to 96%. In addition, NG is comprised of heavier hydrocarbons like ethane (C₂H₆), propane (C₃H₈) and butane (C₄H₁₀) along with inert diluents like carbon dioxide (CO₂) and molecular nitrogen (N₂) [14]. Table 5 shows the average natural gas composition in different countries. NG also contains other hydrocarbon species and sulphur compounds. The level of these species is greatly influenced by the time of year, the geographical source, and the treatment used during the transportation and production stages [32,70–73]. Thus, it can be said that NG does not have a narrow range of traits nor does it refer to a single kind of fuel.

In comparison to traditional liquid fuels like gasoline and diesel, NG can be described as a clean-burning fuel. Its high level of octane makes it an appropriate choice for engines whose compression ratios are

![Fig. 1. Worldwide NGVs growth [28.](image)](image)

![Fig. 2. Worldwide NGVs growth by region [31.](image)](image)

![Fig. 3. Cost advantage of CNG fuel over gasoline and diesel [28.](image)](image)

### Table 3

<table>
<thead>
<tr>
<th>Rank</th>
<th>Country</th>
<th>Gasoline</th>
<th>Diesel</th>
<th>CNG per liter gasoline equivalent</th>
<th>CNG per liter Diesel equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iran</td>
<td>0.42</td>
<td>0.17</td>
<td>0.30</td>
<td>0.34</td>
</tr>
<tr>
<td>2</td>
<td>Pakistan</td>
<td>1.02</td>
<td>0.79</td>
<td>0.72</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>Argentina</td>
<td>1.44</td>
<td>1.44</td>
<td>0.33</td>
<td>0.39</td>
</tr>
<tr>
<td>4</td>
<td>Brazil</td>
<td>1.72</td>
<td>1.11</td>
<td>0.92</td>
<td>1.05</td>
</tr>
<tr>
<td>5</td>
<td>China</td>
<td>1.05</td>
<td>0.98</td>
<td>0.56</td>
<td>0.63</td>
</tr>
<tr>
<td>6</td>
<td>India</td>
<td>1.38</td>
<td>0.85</td>
<td>0.60</td>
<td>0.69</td>
</tr>
<tr>
<td>7</td>
<td>Italy</td>
<td>2.03</td>
<td>1.85</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td>Colombia</td>
<td>1.31</td>
<td>0.96</td>
<td>0.80</td>
<td>0.92</td>
</tr>
<tr>
<td>9</td>
<td>Uzbekistan</td>
<td>1.03</td>
<td>0.98</td>
<td>0.30</td>
<td>0.34</td>
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<tr>
<td>10</td>
<td>Thailand</td>
<td>1.25</td>
<td>1.06</td>
<td>0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>11</td>
<td>Bolivia</td>
<td>0.83</td>
<td>0.66</td>
<td>0.30</td>
<td>0.29</td>
</tr>
<tr>
<td>12</td>
<td>USA</td>
<td>1.02</td>
<td>1.12</td>
<td>0.60</td>
<td>0.68</td>
</tr>
<tr>
<td>13</td>
<td>Armenia</td>
<td>1.31</td>
<td>1.19</td>
<td>0.49</td>
<td>0.56</td>
</tr>
<tr>
<td>14</td>
<td>Bangladesh</td>
<td>0.79</td>
<td>0.56</td>
<td>0.27</td>
<td>0.29</td>
</tr>
<tr>
<td>15</td>
<td>Egypt</td>
<td>0.33</td>
<td>0.20</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1.13</td>
<td>0.93</td>
<td>0.49</td>
<td>0.56</td>
</tr>
</tbody>
</table>

### Table 4

Cost comparison of CNG vs other fuel [28.]

<table>
<thead>
<tr>
<th>Description</th>
<th>CNG</th>
<th>Gasoline</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle type</td>
<td>Bus</td>
<td>Bus</td>
<td>Bus</td>
</tr>
<tr>
<td>km travelled per annum per vehicle</td>
<td>80,000</td>
<td>80,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Total annual consumption of fuel in liters (consider unit of ‘Nm³’ in case of CNG)</td>
<td>36,184</td>
<td>39,400</td>
<td>32,000</td>
</tr>
<tr>
<td>Retail fuel price per liter US $ (consider unit of ‘Nm³’ in case of CNG)</td>
<td>0.52</td>
<td>1.02</td>
<td>0.92</td>
</tr>
<tr>
<td>Annual fuel cost (US $)</td>
<td>18,816</td>
<td>40,188</td>
<td>29,440</td>
</tr>
<tr>
<td>% Fuel cost saving CNG vs gasoline</td>
<td>113%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Fuel cost saving CNG vs diesel</td>
<td>57%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Hydrogen

Hydrogen (H) is the lightest of all the elements with an atomic weight of 1.00794 a.m.u. and an atomic number of Z = 1. The name hydrogen was made by combining two Greek words - “hydro” and “geinomai” - with the former meaning ‘water’ and the latter meaning ‘to bring forth’ as in “the element that brings forth water”. Cavendish discovered hydrogen in 1766 in England and Lavoisier named the atom [88]. Hydrogen is one of the crucial elements of water and more than 60% of the surface of the earth is covered in it. Hydrogen can be found in hydrocarbons and fossil fuels (like propane, natural gas and methanol), and in biomass, organic compounds, and water [46,89]. However, hydrogen in its elemental form is not naturally available. In normal pressure and temperature conditions, hydrogen is a flammable gas that is tasteless, odourless, and colourless.

4.1. Hydrogen production

Various sources and methods can be used for manufacturing hydrogen gas. Due to the lightness of the hydrogen molecules, the gravitational forces of the Earth have difficulty in retaining hydrogen gas within the atmosphere. This is why hydrogen can only be found in compound with other elements, e.g. several types of organic material, various types of hydride, hydrocarbons, and water. Thus, to use hydrogen as a fuel, it has to be manufactured and produced from other materials that contain hydrogen like biomass, water, fossil fuels or other biological sources. Hydrogen has been manufactured and employed for industrial usage for many years. Currently, approximately 90% (45 billion kg) of hydrogen is produced from fossil fuels [90–93].

Direct production of hydrogen from fossil fuels is possible through using processes such as coal gasification (CG), partial oxidation (POX), thermo-cracking (TC), and methane reforming (SMR). Thermochemical and biochemical processes are the main ways of manufacturing hydrogen from biomass. Moreover, hydrogen can be manufactured through photo-biological processes, water thermolysis (WT) (also known as thermochemical water splitting), photoelectrolysis (PHE) or photolysis (also known as photocatalytic water splitting or photoelectrochemical), and dissociating water with electrolysis (HE) [1].

The storage and production of hydrogen gas have been issues which prevent adoption of hydrogen thus far. Currently processes used to produce hydrogen require high energy typically coming from conventional fuels, negating the environmental benefits of the otherwise pollution-free fuel and carbon-free.

4.2. Hydrogen storage

Prior to any potential usage, the issue of a cheap system for storing hydrogen, which is both efficient and safe, remains a major problem. Moreover, risks of leaks or explosions and expensive tanks are prevent on face of storing hydrogen as liquid or compressed gas because they require extremely high pressures. It would be regrettable if this problem were to hinder the creation of a clean, renewable energy system, which is necessary for the safe survival of animals, plants and human beings in the long-run [94]. At 293 K temperature and 20 MPa pressure, gaseous...
hydrogen has a density which is five-times lower than the density of liquid hydrogen [95–103]. Therefore, compared to liquid hydrogen, a tank with approximately 5.5 times greater volume is required [94]. Different onboard options of hydrogen storage have been summarised in terms of the weight requirements in Table 6 (It has to be noted that 5 gal. of the gasoline was used as a reference. With this amount, a vehicle can drive up to 300 miles distance).

5. Using of CNG and H₂ blend in SI engine

5.1. CNG/hydrogen mixtures

Hydrogen can be employed as a fuel in various ways; it can be employed as an only fuel in the presence of air or as an addition in a mixture of hydrocarbon. If hydrogen is to be introduced commercially, it can be employed in hydrocarbon mixtures at low density and with a minimum need for adaptations and adjustments in IC engines [104–111]. The enrichment of hydrogen in fuel made of hydrocarbons is encouraged as a strategy to boost the performance, along with enhancing the emissions, of combustion engines. Similarly, a number of researchers have tested the performance of SI engines using H₂-CNG [112,114,115] and H₂-gasoline fuels [112,113]. Moreover, these investigators have reported that hydrogen is a good choice for enhancing performance in SI engines. This is due to the increase in the ratio of the hydrocarbon in the fuel and this reduces the duration of combustion. This is because hydrogen has a high flame speed compared to other fuels [116,117].

Even though NG mainly consists of methane, the precise composition differs regionally and seasonably. Instead of NG, pure methane (with 99.5% purity) was employed to ensure comparability. Three variations of premixed-fuels were employed which are methane with 25 vol% hydrogen, CH₄ with 15 vol% H₂, and CH₄. Methane-hydrogen mixtures, and the stoichiometric and calorific properties are illustrated in Fig. 5. The LHV per volume of stoichiometrically mixed fresh gas is quantified by the heating value of the stoichiometric intake mixture [18]. The higher this amount, the greater is the chemical energy that can be delivered to the PFI engine that is naturally aspirated in WOT circumstances. Pure hydrogen’s stoichiometric intake mixture heating value is reduced by approximately 6% in comparison to pure methane. By comparison, with the addition of 15 or 25 vol% H₂ to CH₄, the heating value of the stoichiometric intake mixture reduces by just 0.3% and 0.6%, respectively [18]. This creates the expected result, which is that the WOT torque is not significantly affected by the addition of relatively small amounts of hydrogen.

5.2. Onboard HCNG storage

Storing hydrogen in high-strength steel tanks involves the issue of hydrogen embrittlement, where the crystal structure of the steel is penetrated by the hydrogen atoms resulting in elasticity deterioration [118]. With the increase of hydrogen’s partial pressure and steel alloy’s strength yield, this condition becomes more notable. High-carbon steels are especially susceptible. Therefore in high-strength steel tanks, which are generally employed in the low-cost storage of CNG at the 250 bar standard pressure on board vehicles, a high density of hydrogen must not be permitted. Even though hydrogen embrittlement can be achieved with HCNG, the hydrogen partial pressure is lower than that of pure hydrogen. For instance, the hydrogen partial pressure will be only 7.5 in a 30% HCNG mixture in a 250-bar storage tank. HCNG-converted F150 trucks were demonstrated in a long-term exhibition carried out by the Arizona Public Service Company. OEM fibre-reinforced 4130 steel was used as the storage tank. A destructive test was conducted on these tanks after they finished 1 year of service in which no trace of hydrogen embrittlement could be found [119,120]. If the objective is to completely remove the risk of hydrogen embrittlement, aluminum and composite construction tanks must be alternatively employed since they are not susceptible to hydrogen embrittlement. Composite tanks also have the advantage of being lighter; however, their cost is almost twice as much as their high-strength steel counterparts. With the current developments in materials and the increasing volumes across the hydrogenc N₂ G markets, their price is decreasing. Based on successful field experiences, it is possible for all other parts - like engine fuel systems, regulators, valves, sensors, and plumbing - to be identical to the generally used standard of CNG 250 bar [120].

5.3. Effects of HCNG on the combustion of SI engines

5.3.1. In cylinder pressure

In cylinder pressure has been measured with some parameters by Luigi et al. [23]. Their study was tested with two blends of NG/H₂ with respect to the NG case. For H₂, a shorter combustion results in a higher pressure rise (Bar/CAD). The H₂ content will lead to a decreased incubation time and main combustion duration. For NG/H₂ 20%, the main combustion was up to 5% shorter. Moreover, for NG/H₂ 40%, it was about 10–15% shorter. As such, for NG/H₂ 40%, a 30–40% higher maximum rate of pressure rise was measured; and with NG/H₂ 20%, there was a 5–15% higher rise. It is evident that there is a peak pressure increase and it switches from NG to NG/H₂ 40% as a result of the partly faster heat release [23]. Hora and Agarwal [119] carried out work at different BMEP for baseline CNG and HCNG mixtures. Their outcomes showed that an increase in BMEP will result in a peak cylinder pressure increase. The peak cylinder pressure will be increased by a higher fuel quantity generated at a higher engine load. The crank angle position matches the peak pressure for a given fuel. It shifts towards TDC, as a result of the decreased combustion duration with an increase in BMEP. This improved fuel use, therefore, leads to a BTE increase. With an increase in the hydrogen percentage in the HCNG, the peak cylinder pressure shifts towards TDC at a given BMEP. This is as a result of the higher flame speeds with HCNG, which makes the combustion duration shorter and results in the comparatively earlier start of combustion (SOC). At the same BMEP, a rather higher peak cylinder pressure is
delivered by HCNG [121]. On the other hand, if the hydrogen content in HCNG increases, a knock’s tendency would increase due to an increase in the rate of burning. Unusual combustion features, such as knocking, backfire or pre-ignition, can be caused by the higher hydrogen content of the test fuel. Moreover, the engine efficiency will be reduced due to the higher hydrogen content of the test fuel. However, in the fuel-air mixture, an optimum hydrogen content would bring about higher thermal efficiency in comparison to CNG. This is caused by hydrogen's lower ignition energy need, which decreases the ignition delay as well. In the case of higher speeds, loads and compression ratios, the influence of hydrogen knocking would be detrimental. According to Flekiewicz et al. [122] knocking happens when adding hydrogen beyond 40%.

Many researchers have challenged themselves with solving the problem of knocking and the undesired characteristics of the engine. Kamil and Rahman [15] performed a research study to determine the profiles of in cylinder pressure with engine speeds under the stoichiometric condition for various hydrogen-gasoline and hydrogen-methane fractions. For gasoline-hydrogen blends, the different peak cylinder pressures with engine speed are illustrated in Fig. 6(a). The reduction in the peak pressure of the cylinder is noticed. This reduction is not desired because of the inherent dependence of the acquired work on the pressure inside the cylinder. When 20% hydrogen is added, there is a decrease of 4.6 bars at 5000 rpm. In the engine speed area, the maximum cylinder pressure's trend caused by methane-hydrogen combustion is shown in Fig. 6(b). Based on this figure, when hydrogen fractions are added, the peak cylinder pressure reduces. However, compared to the decrease of gasoline-hydrogen blends, this reduction is small [15]. This is due to the fact that hydrogen, as well as methane, are gaseous fuels and the distinction among their energy densities is very small compared to gasoline. The profiles of pure methane and the 5% hydrogen appear to be identical. The maximum decrease in the peak pressure at 7000 rpm was 2.6 bars. This shows only 4% of the peak pressure in the base methane engine [15]. Studies by Ceper et al. [123] and Kahraman et al. [124] show that the highest peak pressure values are acquired when 30% (by volume) of hydrogen is added to the mixture of methane-air. The focus of their studies was on examining the pollutant emissions when hydrogen fractions (by volume) were added. Friction, the gases flowing to the exhaust and the heat transfer to the cylinder walls caused the loss of a significant part of the energy released from the combustion of the blends. The major part increases the pressure to perform the work of use. The energy content is reduced when hydrogen gas is added to methane or gasoline as a result of its low energy content. This decrease results in the reduction of the peak pressure [125]. Moreover, the presence of the hydrogen fractions causes the fix spark timing (at the MBT) to move from its place. The combustion is accelerated due to the presence of the methane-air or gasoline-air mixture. Moreover, the related crank angle for the highest pressure is advanced as a result of the presence of the methane-air or gasoline-air mixture. In this situation, the expected highest pressure occurs in a larger cylinder volume place, which causes the pressure to disappear and decreases its peak [124].

Meanwhile Lim et al. [25] reported that the excess air ratio affected the boost pressure. Also they reported that at the same compression ratio (CR), no pressure distinction could be found. However, when the CR was altered to 11.5 with the same excess air ratio and fuel, the pressure reduced. This reduction in the boost pressure can be due to improved thermal effectiveness. The boost pressure is directly matched with the throttle valve’s opening. Since for a CR of 11.5 with the same power output, less air and fuel were required, the throttle value was opened with a CR of 10.5 [25]. An increase in CR results in the decrease in the volumetric efficiency [126,127]. The decrease in the boost pressure can be controlled and abated for the purpose of extending the limit of lean operation with a low pumping function. As such, the excess boost capability from the improved thermal efficiency can cause the alteration in the surplus air ratio that displayed the better efficiency with an 11.5 CR [25]. In the meantime, the boost pressure can be limited by the reduction of exhaust gas temperature under the full load situation [128]. The decrease in the exhaust gas energy linked to the rise in the TE can cause the limitation of the boost pressure.

5.3.2. Heat release rate

The difference in the heat release rate is affected by blending hydrogen with natural gas during combustion. Tangöz et al. [129] investigated the alteration in the heat release rate with the increase of the compression ratio and the hydrogen fraction in the blends. The increase in hydrogen and CR leads to the advance of the heat release’s rate. According to their outcomes, the highest rates of heat release of 84, 88.19, 85.18 and 78.06 J/0 CA are obtained at 17.0, 15.3, 13.4 and 11.6 CA, as well as ATDC at λ = 1.01 for 9.6 CA. Moreover, the values of 89.56, 102.06, 90.69 and 80.36 J/0 CA are achieved at 13.4, 13.4, 11.3 and 9.8 CA, as well as ATDC at λ = 1.0 for 12.5 CR for CNG, HCNG5, HCNG10 and HCNG20, respectively [129]. This is due to the fact that an increase in the CR and adding hydrogen can cause the blend’s burning velocity to be increased, which makes the phase of ROHRMAX level with the reach of the top dead center [130-132]. In this context, Hora and Agarwal [123] also examined HRR under different ratios of HCNG fuels with various BMEPs. As shown in Fig. 7, they reported that higher engine loads inducted a higher fuel quantity. It will burn quickly and this results in higher HRR. An increase in the engine load can cause the HRR peak curve to move towards TDC. For HCNG, the heat release rate was higher. This was due to the higher flame speed caused by adding hydrogen. For 6.18 bar BMEP, the highest HRR acquired for CNG, 10HCNG, 20HCNG and 30HCNG were 59.3 J/0CA, 69.2 J/0CA, 72.4 J/0CA and 77.7 J/0CA, with the matching crank angle places for the HRR peak being at 8.5°, 5°, 2.5° and 0.5°.
ATDC respectively [121]. The HRR trends, which were perceived at various hydrogen contents and BMEPs at broad open bottle, were much the same as found by Moreno et al. [133]. This was noted at various hydrogen contents and BMEPs at broad open bottle, were much the same as found by Moreno et al. [133].

This was noted at various hydrogen contents and BMEPs at broad open bottle, were much the same as found by Moreno et al. [133]. According to Wang et al. [130], at a part throttle (10%) engine state. Therefore, earlier in the expansion stroke, a large fraction of chemical energy was released as heat and this was lower after burning occurred.

Combustion stability corresponds to combustion duration. The cycle by cycle differences are decreased by shorter combustion phases and shorter ignition delay. Biffiger and Soltic [18] stated that the combustion event can be divided into three phases, which are shown in Fig. 8. Phase one is the period between 5% of the fuel mass burnt and ignition. Phase two refers to the period from 5% to 50% of the fuel mass burnt. Phase three refers to the period from 50% to 90% of the fuel mass burnt. Biffiger and Soltic [18] determined that the turbulent kinetic energy and the charge stratification at the ignition’s moment are increased by direct injection. Based on the HR analysis, the direct injection direction and injection time affect the early phase of combustion, whereas fuel composition and global stoichiometry affect mainly the late stage of combustion (phase 3). Methane’s combustion in stoichiometric situations is not slower than H2-enriched CH4, while the effect of H2 at surplus 1.3 air ratio is considered to be quite strong. The early combustion phases are affected strongly by hydrogen’s direct injection into port-injected methane through changing the injection direction and time. When the injection is put towards the spark plug, particularly at higher surplus air ratios, the maximum effect can be seen. In these situations, later injection results in shorter combustion durations with the exception of EOI at 50° CA before TDCF in which the mixing time is expected to be too short [18]. A minor dependence on the injection timing and direction is shown in the combustion of phases 2 and 3. This is due to the fact that the influences of stratification and turbulence have already degraded. Phase 3 demonstrates that the influence of adding hydrogen is inclined to decrease when using late injection. Methane direct injection’s behaviour into premixed methane is considered to be interesting. As demonstrated by various authors, the direct injection of 9% (i.e., energy, mass, volume) of CH4 is capable of accelerating the combustion to the same degree as by adding H2. Adding methane and hydrogen affect the early phase of combustion significantly. A Phase 1 prolongation can be seen by adding hydrogen, which is through setting the injection timing from 70° CA to 50° CA EOI before TDCF. This behaviour cannot be seen when methane is added [18]. Therefore, it can be concluded that the best method of accelerating the early combustion phase is through delaying the direct injection of CH4 towards the spark plug.

5.3.3. In cylinder temperature

The influence of cylinder peak temperature on the creation of undesired emission, particularly NOx, and on the losses of heat transfer is the basis of its importance [136,137]. Kamil and Rahman [15] conducted a comparison between gasoline and gasoline-hydrogen, as well as between methane and methane-hydrogen, in SI engines, in order to examine the effect of peak temperature under different engine speeds. The peak cylinder temperature’s variation for the considered hydrogen fractions is shown in Fig. 9. Fig. 9(a) shows the trends of the gasoline-hydrogen blends. The peak temperature is increased through adding 5% hydrogen. The reports show an increase of 34 °C with this fraction at 6000 rpm. The peak temperature will not be increased through adding more hydrogen (10%). Nonetheless, the peak temperature is still more than that of the base gasoline engine (the difference is now 28 °C at 6000 rpm). The peak temperature will be back and become identical to that of the base engine when a 15% fraction is added. Therefore, the temperature will be reduced to below that of the base engine with any further enrichment. A temperature decrease to 25 °C at 6000 rpm is in order to go with the 20% fraction. This behaviour continues for the whole speed range reviewed [15]. Similar trends can be observed for methane-hydrogen blends which are illustrated in Fig. 9(b). The peak temperature will be increased by the hydrogen’s adiabatic flame temperature. The quick flame speed of hydrogen plays a part in increasing
the peak temperature as well. This is because the enriched mixture is capable of burning much faster than pure gasoline or methane, which signifies that the combustion is increased after adding hydrogen [138].

Lee et al. [139] also made a comparison of peak in-cylinder combustion temperatures between CNG and HCNG idle operations. It is shown very clearly in Fig. 10 that the peak temperature was kept at less than 1500 K for both cases. This was due to idle's near-zero load condition and the larger portion of residual gas in the cylinder. Despite the general perception that the highest combustion temperature of H₂ enriched fuel is increased by the higher adiabatic temperature of H₂, the final level of the peak combustion temperature in HCNG operations was lower than in CNG operations [80,139,140]. This is due to the fact that the amount of fuel provided for a stable idle was much lower in the HCNG engine operation in comparison with CNG. A decrease in the in-cylinder pressure throughout the combustion procedure was brought about by less fuel and finally the lower peak combustion temperature was induced. Much the same trend occurred when the spark ignition timing was delayed towards TDC for each air/fuel ratio. The peak temperature was increased due to the enhanced fuel consumption rate close to TDC. The increase in EAR for each timing spark ignition caused the combustion temperature to be decreased due to the increased influence of surplus air dilution. Therefore, for both fuels, the maximum peak combustion temperature occurs at the lower right corner [139].

5.4. Effects of HCNG on performance of SI engine

Engine thermal efficiency is important for assessing an engine's economics and its general performance. Optimising the fuel properties or the combustion system can lead to its improvement. Moreover, after adding hydrogen, brake thermal efficiencies are enhanced slightly. This also varies easily with the surplus air ratio, which shows that adding hydrogen caused the engine lean burn ability to be improved effectively [13]. The engine performance correlative surplus air-fuel ratio (λ) together with the exhaust gas temperature (EGT) at various loads (BMEP) for 4 different structures of HCNG mixtures was examined by Hora and Agarwal [121]. The overall chemical energy's conversion efficiency of fuel into mechanical energy, which is accessible at the engine shaft, is displayed in Fig. 11. In comparison with HCNG mixtures, CNG displayed a lower brake thermal efficiency. An increase in the hydrogen content in HCNG leads to an increase in BTE at all loads as a result of the higher combustion stability and higher combustion efficiency. 25.7% BTE was shown by CNG at 5.3 bar BMEP, whereas 27.2%, 28.1% and 28.5% BTE values were shown by 10HCNG, 20HCNG and 30HCNG respectively. Likewise, BTE values of 28%, 28.6%, 29.3% and 29.7% were shown by CNG, 10HCNG, 20HCNG and 30HCNG respectively at...
Based on the findings, an increase in BMEP led to the consumption of a greater fuel quantity for the purpose of producing a higher power output. This reduced the excess air-fuel ratio (\(\lambda\)) and caused the fuel-air mixture to become quite rich (Fig. 11). Similar power can be generated at lower BMEP using a leaner mixture of HCN-g-air in comparison with the CNG-air mixture, whereas a richer mixture of fuel-air was needed at a higher BMEP. This showed that the CNG operation's lean limit increases as a result of adding hydrogen to the CNG. The engine is going to operate very near to the stoichiometric condition (\(\lambda = 1.01, 1.02, 1.01\) and 1.0 for CNG, 10HCNG, 20HCNG and 30HCNG respectively) at 5.3 bar BMEP [121].

The ratio between the fuel heating power and the effective power, as studied by Diéguez et al. [141], corresponds to the thermal efficiency as shown in Fig. 12. They conducted their test at 4300 rpm, optimum spark advance and full load. Based on their findings, when the air-to-fuel ratio is enhanced up to 2.5, the efficiency decreases from 34–35% to 28–30% for \(\lambda\) values of 1.6–2.0. Their results also showed that an increase in the methane content of the fuel causes a trend towards lower efficiencies. The effect of the operating conditions on the mechanical efficiency can be described concerning the combustion temperature's effect for the engine torque [13,15,121,141]. An increase in the methane content of the fuel causes the combustion temperature to decrease. Therefore, the maximum efficiencies are achieved when pure hydrogen is utilised. Likewise, as the fuel mixture comes to be leaner, the combustion temperature reduces. Therefore, as \(\lambda\) increases, the mechanical efficiencies decrease.

Engine thermal efficiency can be improved by an increase in the mixture burning speed [142]. The hydrogen-\(\text{CH}_4\) mixture has an extended flame limit and faster burning velocity compared to \(\text{CH}_4\), due to the large flame speed of hydrogen which is five times larger than that of \(\text{CH}_4\), and also the wide flammability range of hydrogen which is much greater than \(\text{CH}_4\), which can lead to more complete burning and a shorter burning duration [13]. Concerning the hydrogen methane mixtures, the fuel composition at full load, 3400 rpm, the brake torque as a function of \(\lambda\) and the optimum spark advance are shown in Fig. 13. As can be seen, the brake torque changes with fuel composition to a certain extent. However, it obviously reduces as the air-to-fuel ratio enhances. This behaviour can be explained concerning the influence of combustion temperature as it is much the same as the adiabatic flame temperature's evolution, as shown in Fig. 14. Diéguez et al. [141] examined the brake torque connected to the gases' power cycle in the cylinder, which in turn is based on the engine speed, spark advance, load, and fuel nature. Hydrogen combustion carries the risks of backfiring and knocking, which are an impedance to operation at low values of \(\lambda\). [141]. From another point of view, combusting methane at the stoichiometric condition (\(\lambda = 1\)) will cause no problems. As such, from the engine performance perspective, adding methane to hydrogen has the positive influence of enabling a more fuel rich operation, which leads to an increase in the engine torque [141]. HCNG mixtures have a higher brake thermal efficiency compared to CNG. Bauer and Forest [113] showed much the same trend at various BMEP and HCNG blends at lower engine speeds (700 rpm and 900 rpm) and equivalence ratios.

Specific fuel consumption (BSFC) refers to the ratio of the mass fuel consumption to the break power [8,143]. According to Açıkgoz et al. [13], as the surplus air ratio, a decrease in the BSFC and an increase in the BTE were noticed through an enhancement of the hydrogen fraction in the fuel blends of more than 20%. Adding hydrogen was not useful for improving the efficiency when the excess air ratio was less than 1.4 [13]. As shown in Fig. 15, the influences of spark timing together with the air/fuel ratio on the rate of fuel consumption for CNG and HCNG idle operations were examined by Lee et al. [153]. In their study, HCNG was compared with CNG. They found that the utilisation of HCNG had a lower rate of fuel consumption for all \(\lambda\) and spark timing conditions. A more than 25% reduction in energy consumption was obtained throughout HCNG operations [139]. Low cyclic variation and closer-to
constant volume combustion were the reasons for these improvements. The flame propagation speed of the HCNG/air mixture was much faster in comparison with the speed of the in-cylinder volume change through changing the position at idle and as a result it comes to be closer to constant volume combustion due to adding H₂ [144]. Based on the findings, the fuel consumption rate reached the lowest level at roughly \( \lambda = 1.1 \) (for CNG) and between 1.1 and 1.2 (for HCNG) for each spark ignition timing. For higher \( \lambda = 1.1 \) (for CNG) and between 1.1 and 1.2 (for HCNG) for each spark ignition timing. For higher \( \lambda = 1.1 \) out of HCNG20 for 9.6 CR [129], Mariani et al. [135] tested different lower heating values and mixing fuels of HCNG and reported that (as Fig. 16 shows) the influence of the fuel on engine efficiency can be determined, taking into account the fuel consumption in MJ/km. There were no significant variations among HCNG15 and CNG, whereas a decrease has been seen when fueling the engine with HCNG30. The SFC that was achieved with this blend was 2.33 MJ/km for the NEDC. This was 6% lower than CNG. For urban, road and motorway, the SFC values were 3.41, 2.04 and 1.86 MJ/km for the Artemis cycles. They were 6%, 3% and 7% lower than CNG [135]. Faster combustion move up through adding hydrogen is the reason behind the enhancement of the engine's average efficiency for HCNG30 with respect to natural gas. The air-fuel ratio's estimation was enabled by exhaust gas analysis. This caused close to stoichiometric values for the whole of the conditions of operating.

**5.5. Effects of HCNG on the emissions of an SI engine**

**5.5.1. Hydrocarbon emissions (HC)**

Incomplete combustion can lead to the production of unburned hydrocarbon. Due to a big valve overlap angle, CH₄ is the source of THC (Total Hydrocarbon) emission for the HCNG engine. Moreover, hydrocarbon emission can be caused by both misfire and abnormal combustion. The wall quenching influence and incomplete combustion are the main sources of HC emission for the combustion procedures [147]. The unburned HC emission was decreased as a result of adding hydrogen, signifying improved combustion efficiency [13]. The decrease of heat transfer as a result of the fast burn speed can be eliminated through the higher in-cylinder temperature, together with the shorter quenching distance induced by adding hydrogen, can be the reasons behind this phenomenon [143,148]. Lima et al. [25] did a comparison between CNG and HCNG30 with two compression ratios to test the emissions of THC and CH₄. As shown in Fig. 17, the emission of THC with HCNG30 and CR of 11.5 reduced in comparison with 10.5 CR and HCNG30 in the lean combustion condition. The THC emissions with a high temperature of combustion are reduced by the high efficiency combustion. From the other point of view, CR in the CNG case did not affect the THC emission. Fig. 18 shows that the increment in CR at the same air ratio leads to a decrease of CH₄ emission with HCNG30. CNG shows the same trend. Nevertheless, the decrease in the CH₄ emission was greater than that of the THC emissions with 11.5 CR [25]. Hu et al. [149] found much the same result in lean premixed CH₄-H₂-air flames at enhanced temperatures and pressures. The results of Hu et al. [149] were similar to this for lean premixed CH₄-H₂-air flames at high temperatures and pressures. Based on their findings, the dominant chain branching reaction was (R38), whereas the chain recombination reaction in the combustion of HCNG was (R52) and (R35).

\[
\text{H} + \text{O}_2 \rightarrow \text{O} + \text{OH} \quad \text{(R38)}
\]
Based on the findings of the research, the recombination reactions are considered to be pressure sensitive and the reactions of chain branching are temperature-sensitive. The division of CH₄ into various radicals is promoted by the increase in the combustion temperature. As such, the decrease in CH₄ emission when CR is increased can be associated with the chain branching reaction, which a high combustion temperature activates, instead of an enhancement in the pressure [25].

Lee et al. [139] studied in idle operations and stated that the residual gas fraction can be described as high and the combustion temperature as low that lead to the production of a high level of THC emissions which means that it is not easy to fulfill the emission rules. As such, each operation’s THC emission against spark timing and air/fuel ratio are compared in their study. For HCNG engine operations, the overall level of THC emissions was much lower than that of CNG operations. This was due to the low carbon content in HCNG together with the outstanding combustion features of H₂. At first, the emission of THC reduced with an increase in λ (until λ almost = 1.1), then it increased for both fuels. THC emissions were enhanced for CNG as well as HCNG operations with an increase in the spark ignition timing. This enhanced the in-cylinder pressure; therefore, there was an increase in the charge density captured in the crevice volume. An increase in THC levels is caused by high spark retardation in CNG operation due to bulk quenching close by the wall throughout the expansion procedures. Therefore, the spark timing for the lowest level of THC emissions occurred at 2 CAD, BTDC for λ = 1, 8 CAD, BTDC for λ = 1.5 and among these values for 1.1 ≤ λ ≤ 1.4. However, since spark timing was set back toward TDC in HCNG operations, there was a high possibility of oxidising the HC released from the crevice volume throughout the early step of the expansion procedure. This happened due to the smaller quenching zone and shorter combustion duration. Therefore, when λ was less than 1.3, the emission of THC continued to decrease [139].

5.5.2. Carbon monoxide emissions (CO)

Carbon monoxide is formed as a result of the fuel’s incomplete burning in the engine. Incomplete burning happens when the combustion cannot be completed as a result of insufficient oxygen [16,150,151]. Based on the studies of Gharehghani et al. [154], with the decrease of the equivalence ratio, the CO emission is reduced and then it began to increase rapidly after a minimum value as a result of a misfire in the huge lean mixture. The addition of hydrogen did not have a significant effect on the formation of CO before the misfiring limitation for pure CNG (Φ ~ 0.6); however after this, adding hydrogen resulted in a greater decrease of CO, and on the basis of estimated outcomes, misfiring was delayed [152]. The engine’s operating range could be extended to that of a leaner mixture with no impact on the CO concentration through enhancing the percentage of hydrogen. The differences in the engine’s CO emissions at various engine speeds and different fuel mixtures were investigated by Açıkgoz et al. [13]. The entirety of the fuel cannot be burned by the engine even though there is excess air in the cylinder to complete the combustion. The hydrogen fueled engine was expected to have zero CO emission. A small amount of CO could still be found in the results. This resulted from the burning of the lubricating oil film inside the engine cylinder. CO emission diminishes with the increase of the engine speed. The addition of hydrogen increases the CO emission when the excess air ratio is almost stoichiometric; however it decreases when hydrogen is added under lean conditions. The oxidation reaction of CO into CO₂ is stimulated by the enhanced in-cylinder temperature after the addition of hydrogen [13]. The in-cylinder CO mass fraction distribution for different hydrogen fractions with an equivalence ratio of 0.625 at EVO is shown in Fig. 19. The fuel’s incomplete combustion within the combustion chamber results in CO emission. The incomplete combustion is highly dependent on the blend’s combustion temperature. Gharehghani et al. [152] believed that, based on the observation, the CO emissions produced at 30% and 50% hydrogen fractions were insignificant in comparison to pure natural gas fuel combustion.

Diéguez et al. [141] accomplished a research study which tested the air-fuel ratio at full load, 3400 rpm engine speed and optimum spark advance as shown in Fig. 20. They reported that there is a high increase in the emission of CO with λ. For instance, for η = 0.10 (10 vol% methane) the CO emissions at λ = 2.5 (3.6 g/kW h) are almost 7 times higher than when λ = 1.6 (0.5 g/kW h) [141]. This unexpected outcome can be explained by the fact that despite the decrease of the air/fuel mixture’s carbon content with the increase of λ, a greater decrease in the power is produced which results in the increase of specific emissions. This is in line with the findings of Moreno et al. [153] where a similar trend was found in a naturally aspirated two-cylinder SI engine, which was fueled with methane and hydrogen mixtures at full load, in its specific CO₂ emissions. Diéguez et al. [141] also reported that the specific CO emissions for η = 0.20 under stoichiometric conditions and at λ = 2 are almost coincident (about 2.2 g/kW h) and 3 times higher than at λ = 1.6 (about 0.8 g/kW h). Based on this, stoichiometric conditions are unfavourable for minimum carbon monoxide emissions in this situation because there is not enough oxygen available. Therefore, the level of CO emission is notably lower than that generated at the intermediate λ value of 1.6, compared with λ = 1 or 2 [141]. Hora and Agarwal [121] examined CO emissions with BMEP. They stated that with the increase of BMEP, the CO emission decreases since the higher peak cylinder temperature at higher BMEP is
favourable for CO to CO₂ oxidation. The CO emission of HCNG blends is less than baseline CNG since the HCNG mixtures’ C/H ratio is lower, and they have higher peak cylinder temperatures which is in favour of CO oxidation. According to the study, a higher CO emission was observed at 6.18 bar BMEP because the blend in the combustion chamber was richer and lower levels of oxygen were available for combustion [121]. Ma et al. [154] observed similar trends for the discussed emission at various BMEP for wide open throttle from HCNG mixtures at various ignition timings and Xu et al. [130] observed it at part throttle conditions.

5.5.3. Carbon dioxide emissions (CO₂)

When the degree of hydrocarbon fuel’s combustion has been completed, this is indicated by the engine exhaust’s CO₂ formation. Lower CO and higher CO₂ indicate the efficient utilisation of fuel and better combustion quality. HCNG has a low emission of CO₂ because the C/H ratio decreases with the increase of the hydrogen content [33,121,150]. To investigate the impact of adding hydrogen and the effect of the air/fuel ratio on the emission of CO₂, various mixtures of natural gas and hydrogen were examined including HCNG with hydrogen fractions from 10% to 90%, with an air/fuel ratio within reasonable operating limits, and CNG [155]. The flame propagation speed of hydrogen is high and its ignition energy is low, which makes it easier to work with leaner blends compared to natural gas. The lean air-fuel mixtures have a limit, which if reached, causes the combustion to become incomplete and unstable. The combustion speed decreases and the air-fuel mixture’s ignition energy increases when operating close to this limit. This results in cycle-by-cycle variations which decreases the thermal efficiency. Navarro et al. [155] investigated the effect of hydrogen addition and air/fuel ratio on CO₂ emissions at various engine speeds as shown in Fig. 21. It can be observed from the figure that there is a decrease in particular CO₂ emissions when there is an increase in the crankshaft rotational speed, when there is an increase in the air/fuel ratio, and when the employed fuel mixtures have increasing hydrogen content [155]. The reduction of specific CO₂ emissions and the increase of H₂ content in the fuel mixture can be caused by the progressive reduction of the carbon content and the combustion process’ advancement. Various aspects have to be considered in explaining this behaviour of CO₂ emissions, which is observed with an increase in the air/fuel ratios.

5.5.4. Nitrogen oxides emissions (NOₓ)

Coal burning creates nitrogen oxides (NOₓ), which are essentially nitrogen dioxide (NO₂) or nitric oxide (NO), and are generally referred to as NOₓ. NOₓ is created by ignition and is comprised of NO (90–95%) along with lesser (5–10%) amounts of NO₂ [46]. Nitric oxide’s arrangement in the burning zone results from two elements which are the
prompt system (Fenimore system) and the thermal system (Zeldovich system). High-temperature ignition, i.e. the point at which the burning temperature is above 1400 K, sets up the development of thermal NO. With the increase of the burning temperature, the development rate of the NO increases rapidly, and with the decrease of the burning temperature, the development rate decreases in this component [151]. The brief development of NO occurs within the rich, low-temperature burning zones where a reasonable amount of dynamic radicals can be accessed [150,156,157]. Because of the dominant impact of temperature, the formation of NO is favoured by fuel-rich mixtures (with low values of $\lambda$) [133,158–160]. However, by controlling the spark advance (SA), the temperature and, as a result, the combustion temperature that is reached within the cylinders, can be modified. Wang et al. [161] have studied the impact ignition timing on the lean combustion limit in the cases where natural/hydrogen gas is used as a fuel.

Diéguez et al. [141] performed a research study to examine the spark advance and molar fraction of methane ($\eta$) in the HCNG mixture as a function, with the specific NOx emissions at full load, $\lambda$ of 1.6 and speed of 3400 rpm. Spark advance increases the emission of particulate NOx, while the methane content decreases it significantly because of the combustion temperature decrease. This is one of the positive impacts of the addition of methane to hydrogen fuel. As illustrated in Fig. 22, when the spark advance is optimal, only the air-to-fuel ratio governs the specific emission and it is fairly unaffected by fuel composition at a specific value of $\lambda$ in the limits set by their study. In stoichiometric conditions ($\lambda = 1$), the fuel mixture that has the maximum methane content ($\eta = 0.20$) can only be combusted. The other fuels, like pure hydrogen, demonstrated a tendency to knock which prevented the use of a $\lambda$ value less than 1.6. In stoichiometric conditions, the emission of NOx was high and reached 3.05 g/kW h, despite the significantly low availability of oxygen. The emissions were near 1 g/kW h when $\lambda = 1.6$ was used and when the air-to-fuel was enhanced to 2–2.5, it decreased to 0.3–0.4 g/kW h [141].

HCNG mixtures have relatively higher NOx emissions, the formation of which is dependent on the oxygen content and the combustion temperature. This results from a comparatively higher in-cylinder temperature caused by the addition of hydrogen to CNG, which favours the formation of NOx. There was an increase in the flame-front temperature when the hydrogen fraction of the HCNG mixtures increased [25]. Diluting the mixture with exhaust gases or excess air is a typical method employed in decreasing the peak temperature of combustion and, consequently, the NOx emission. Biffiger and Soltic [18] accomplished work under various excess air ratios and injection strategies in the case of premixed combustion vs NOx emissions. They reported that at higher excess air ratios, the NOx was decreased. Likewise, they reported that when the excess air ratios are higher, there is a less notable decrease in the split injection. Furthermore, in methane into methane cases, there is an increase in the emission. This can be regarded as a better understanding of employing charge stratification. Since premature direct injection is more like the premixed combustion case, less NOx is shown at lean combustion while late rejection results in charge stratification. The mixture that is nearer to the spark plug becomes heterogeneous in a stratified combustion and prompts a higher flame temperature and consequently a higher NOx emission [18].

Hora and Agarwal [121] tested the NOx emissions with different BMEP and various HCNG mixtures. They reported that when the BMEP is low and is at 2.98 bar, an insignificant difference in the formation of NOx was found in the entirety of the tested fuels. This resulted from comparatively lower peak cylinder temperatures and the leaner fuel-air mixtures which were outside the NOx formation window. According to Wang et al. [135], less NOx is formed when HCNG is injected directly; however, insignificant differences were reported due to the addition of hydrogen at BMEPs. But there was a change in this pattern at higher loads when there was a higher formation of NOx. With an increase in BMEP and the enhancement of the hydrogen fraction within HCNG mixtures, the brake specific NOx emission and raw emissions increase [121]. Based on the report of Diéguez et al. [141], who also reported at various engine speeds, the specific NOx emissions were found to increase when the engine speed increased. For instance, at $\lambda = 2$, full load, $\eta = 0.2$ and optimum spark advance, the emissions increased from 0.32 to 0.39 and finally 0.47 g/kW h when the engine speed increases from 3400 to 4200 and finally 5000 rpm [141]. The turbulence intensifies with the increase in the speed of the engine, which results in higher NOx emissions and combustion temperatures, and enhanced mixing. Despite this, the effect of the engine speed on the emission of nitrogen oxides is significantly less notable than that of the spark advance or air-to-fuel ratio.

Tangöz et al. [129] have examined the compression ratio (CR) in a diesel engine fueled by different mixture ratios of HCNG. The NOx emissions at various CR and HCNG are illustrated in Fig. 23. Because of hydrogen’s high flame speed and high flame temperature, increasing the hydrogen fraction of HCNG results in an increase of the mixture’s temperature as well as the residence time of air in the hot zone. Thus, adding hydrogen to CNG increases the NOx [145]. The maximum NOx values obtained at $\lambda = 1.15$ for 9.6 CR fueled by CNG, HCNG5, HCNG10 and HCNG20 are 18, 19.8, 21.5 and 25.5 g/kW h respectively. In a similar fashion, the maximum values obtained at $\lambda = 1.16$ and $\lambda = 1.21$ for 12.5 and 15 CR fueled by the same fuels are 18.4, 19.1, 20.7 and 22.1 g/kW h and 18, 19.2, 21.7 and 25.8 g/kW h respectively. It can be observed from the figure that with an increase in the CR, the emission values reach maximum values at higher $\lambda$. Furthermore, these NOx values are greater than the Euro VI standard (0.4 g/kWh) [162] for a gas engine. Thus, in order to reach the Euro VI standard, the NOx values need to be reduced. It can be noticed in the figure that with excess air ratios, the emission values of NOx reach a maximum level and then decrease. The NOx emission values gained at $\lambda$ of 0.96, 1.15 and 1.3 for 9.6, 12.5 and 15 CR fueled by HCNG10 are 4, 21.5 and 16.7 g/kW h; 4, 20.5 and 17 g/kW h; 3.7, 21 and 18.6 g/kW h respectively [129]. As a matter of fact, the oxygen environment is close to lambda 1.1 and the combustion temperature is high in the cylinder. Thus it can be said that with the gradual lean out of the engine, there is a rapid increase in the NOx emission which reaches a peak and then experiences a rapid decrease to a fairly small value. The high combustion temperature is aided by the growth of the compression ratio. Thus, NOx emission worsens with an increase in the compression ratio [163].

The emission can be reduced through various methods, which include internal engine measures like various injections, exhaust after-treatment, and EGR or water treatment. On the basis of an engine operation strategy, either the conventional 3-way catalysts or the lean

Fig. 22. Evolution of the specific NOx emissions as a function of $\lambda$ and fuel composition at full load, 3000 rpm and optimum spark advance [141].
NOx must be used [46,164,165]. With regards to NOx, in spite of the promising outcomes such that the emission level was reached by 3-way catalysts, various studies have tried to elaborate on and investigate the lean NOx after treatment systems. This was due to the fact that for the actual operation of 3-way catalysts, particular stoichiometric conditions were required which resulted in a great decrease of the engine's efficiency in comparison to the lean mode. Methods that were employed in decreasing the NOx emissions consisted of 3-way catalysts, selective catalytic reduction (SCR) and a lean NOx trap. There have also been patents of concepts where the additional injection of the decreasing agent in the exhaust was prevented through altering the operation procedure from lean to fuel-rich using EGR in purifying the lean NOx trap [165–167]. Moreover, the measurements to decrease the engine's internal nitrogen oxide emissions include reducing the temperature inside the cylinder using water injection and EGR [168]. Water injection decreased the NOx emissions significantly and had little negative effect on the efficiency of the engine [169,170]. Even though water injection is regarded as a suitable process for decreasing the NOx emissions, its functional application is based on an effective way of providing the liquid (for instance, through restoring and liquefying it from the engine exhaust) [171,172].

6. Challenges of HCNG utilisation

To use HCNG as an engine fuel, hydrogen/natural gas ratio optimisation is the most challenging. This is due to abnormal combustion behaviour, such as pre-ignition and knock, and backfire for imbalanced ratios of the two mixtures. This means that it is important to adjust the spark timing and the fuel-air ratios to within the acceptable ranges. The hydrogen percentage is directly proportional to the lean operation limit, while at the same time it is inversely proportional to the maximum brake torque (MBT). From here, a relationship among the three (of hydrogen fraction, excess air ratio and ignition timing) can be improved, the determination of which means solving the hurdle to finding the optimum ratios.

In order to specify whether or not a fuel is a suitable alternative fuel, the most important parameter to be considered is the emission level, which mostly refers to NOx emissions. In the case of CNG, the excessive hydrogen causes an enhancement in the NOx levels while it reduces the emissive hydrocarbons. Due to this contrast, the hydrogen ratio needs to be adjusted in such a way as to keep both the NOx and hydrocarbon emissions as low as possible. Such a challenge is a huge limitation. The largest impact is usually noted if the injection can be delayed towards the spark plug. Using HCNG fuel confirms a reduced energy consumption rate for all excess air and spark timing conditions. In particular, an greater than 25% reduction in fuel consumption was obtained when using HCNG blends compared to CNG. This specific development was assigned to closer-to constant volume combustion along with minimal cyclic differences. However, some authors observed that when the hydrogen fraction is increased in natural gas with different CRs, the BSFC is advanced. This is a result of the combined consequences of volumetric emissions as low as possible. Such a challenge is a huge limitation to researchers. Natural gas, which in turn generally includes methane, gives considerable monetary as well as environmental advantages, including much better productivity and availability, as well as lower emissions. However, the weak lean-burn ability, the low flame speed and the ignitability of methane demand deep studies for its usage in an IC engine. When using natural gas in SI engines, there is an engine efficiency sacrifice at low loads and a higher level of some of the emissions such as HC/CO, which cannot be solved without using the after-treatment equipment. This equipment, however, is expensive. Therefore, an additional fuel can enhance the characteristics of combustion of NG - which could be used in the intake charge. H2 is an efficient gas for enhancing the flame rate regarding combustion in an SI-CNG engine, together with decreasing the COV and increasing engine stability. Tiny amounts of H2 improve performance and reduce exhaust emissions. Thus, many investigators have performed research studies on SI engines with different ratios of HCNG. Many studies have found that the combustion characteristics of HCNG engine are strongly dependent on the conditions of the engine. The air-fuel ratio, the time of injection, the compression ratio and the speed play a major role when blending HCNG in an SI engine. Adding hydrogen to natural gas increases cylinder pressures and temperatures. These increments were obtained due to enhancing the rate of heat release (the burning speed) of HCNG, leading to a shortened combustion duration. For this, a large proportion of chemical energy was emitted before the power stroke because of heat production and comparatively less after-burning happened. With stoichiometric operation, the combustion of natural gas is not significantly slower when compared with hydrogen-enriched CNG, although the effect associated with hydrogen from air-fuel (\(\lambda\)) of 1.3 is pretty strong. Additionally, the injection of hydrogen into port-injected CNG affects the early combustion stages of development rather highly through diverse injection timing along with position. The largest impact is usually noted if the injection can be pointed to approach the spark plug, particularly from higher excess air percentages. In most of these conditions, shortened combustion durations result from later injection. The authors have shown that the early combustion phases are accelerated when the method of direct injection is delayed towards the spark plug. Using HCNG fuel confirms a reduced energy consumption rate for all excess air and spark timing conditions. In particular, an greater than 25% reduction in fuel consumption was obtained when using HCNG blends compared to CNG. This specific development was assigned to closer-to constant volume combustion along with minimal cyclic differences. However, some authors observed that when the hydrogen fraction is increased in natural gas with different CRs, the BSFC is advanced. This is a result of the combined consequences of volumetric
effectiveness as well as the lowering of volumetric heat worth. Regarding brake thermal efficiency and power, CNG showed a lower BTE compared to the HCNG blend. At all loads, the power and BTE were enhanced when improving the hydrogen particles with HCNG, due to the somewhat larger combustion efficiency and remarkable combustion stability. The increment in the burning velocity of the mixture has an optimistic relation to improving the TE of the engine. Because the flame speed regarding H$_2$ is 5 times greater than that regarding CNG and the inflammability selection of H$_2$ is quite broad compared to CNG, the particular H$_2$-CNG mixture can have a quicker ignition and also a delayed flame control compared to CNG, which can mean a quicker burning and a fairly complete combustion.

The level of THC emissions with regards to the HCNG engine has been reduced, compared to that involving the CNG engine, due to the lower carbon formation inside HCNG, along with the exceptional combustion of hydrogen. As engine speed and loads increase, CO/CO$_2$ emissions tend to minimise. However, CO emission improves along with hydrogen improvement if the air-fuel ratio is stoichiometric, but it reduces with the help of H$_2$ beneath the lean-condition. The elevated in-cylinder temperature after the enrichment of hydrogen likewise is engaged to revitalise the particular oxidation reaction of CO into CO$_2$. HC and CO emissions are usually a direct result of the incomplete combustion associated with the fuel inside the combustion chamber and are also powerfully dependent on the mixture temperature. It is noticed that each of the 30% and 50% hydrogen fraction cases makes minimal CO/HC/CO$_2$ emissions in comparison to natural gas combustion.

NOx emissions, whose formation are determined by the combustion temperature and air formation, are comparatively larger for HCNG blends. This is on account of the comparatively larger temperatures in the cylinder due to the hydrogen supplement helping CNG, which often meant desired NOx formation. The temperature of the flame front improved with the addition of hydrogen in the HCNG blends. Also the air-fuel ratio, the loads and the engine speed affect NOx emissions with the HCNG blend. It has been discovered that the particular NOx emissions improve with changing engine speeds and loads. When the engine speed rises, the turbulence tends to enhance resulting in improved mixing and higher combustion temperatures, in addition to NOx emissions. On the other hand, the impact of the engine speed on the NOx emissions is much less noticeable as compared to that on the air-fuel percentage or even the sparks timing. So we can see that as the engine tends to lean operation, NOx formation expands quickly until it reaches its highest value, and afterwards it diminishes to a comparatively low value. With increasing compression ratio, the temperature of combustion will also be high, thus a higher compression ratio produces greater NOx emission. A typical approach is to diminish the top ignition temperature, and in this way likewise the NOx outflows to weaken the blend with abundant air or with exhaust gaseous. Also the increment of NOx could be managed by numerous injections, exhaust after-treatment as well as exhaust gas recirculation (EGR) or water injection. However, hydrogen ignition exhibits the dangers of reverse knock and backfire that prevent working at low estimations of λ and using a high value of it.

8. Future work suggestions

HCNG is a well-known technology emerging from the wide applications of CNG in engines and its existing production facilities. In this part, those advantages of HCNG which make it a suitable alternative fuel for the future have been reviewed. HCNG technology deploys the hydrogen market before it is consumed by hydrogen fuel cells for application in hydrogen fuel infrastructures. As the H$_2$ concentration in HCNG increases, the fuel storage density decreases which allows a higher onboard energy storage density. This privilege widens the HCNG on-board energy storage applications for IC engine vehicles and small fueling infrastructures such as local transportation, in comparison to hydrogen fuel cells. However, HCNG storage has limitations for fuel cell powertrains and short range IC powertrains at larger scales such as airport shuttles and local delivery trucks.

The second advantage is the overall cost effectiveness of HCNG. The optimum H$_2$ value to deploy the maximum usage from both the range and the emissions point of view is 30% H$_2$. Utilising this value, the methane combustion will be close to complete, meaning that the after combustion exhausts are near to zero. This leads to not only a reduction of after-treatment exhaust equipment costs, but also a reduction of space and design complexity as well as weight considerations. Due to this reduced amount of H$_2$ the hydrogen energy content is equal to 11%, which makes it easier for renewable sources to meet the emerging HCNG market demands. This is as the applications of fuel cell vehicles increase, and the hydrogen price lowers, from which HCNG could benefit.

As for the challenges HCNG is facing, a number of topics can be discussed. In terms of GHG, another alternative for hydrogen could be biogas. There is a possibility that by adding locally derived biogas to CNG, its performance could improve in such a way as to be considered a better treatment over adding hydrogen. As for the engine's compatibility, the engine should be designed in such a way as to operate on both HCNG and CNG as per necessity in the case of HCNG fueling system breakdown. Although the HCNG-fueling station is much more expensive than either of the CNG or hydrogen fueling stations, developing an HCNG flex-fuel system is more affordable based on current price and availability as it will enable the combustion of any mixture of any of the named gases even on a random basis. Such flexi-fuel equipment will therefore make it possible to utilise hydrogen from all sources, thus expanding the hydrogen market. From the other side, any expansion of HCNG relies on the expansion of current international standards for receptacle and nozzle design for more HCNG blends. The standards would consist of different mixing ratios of HCNG blends such as 20% and 30% or any other percent. Promoting such standards will motivate manufacturers to produce dispensing products to match the requirements of HCNG engines.

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