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A comprehensive review on utilization of hydrogen in a compression ignition engine under dual fuel mode

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ABSTRACT

Compression ignition (CI) engines emit high levels of particulate matter (PM) and oxide of nitrogen (NO_x) emissions due to combustion with heterogeneous air fuel mixture. The PM emission could be reduced significantly along with thermal efficiency improvement using hydrogen in the engines under dual fuel mode (diesel-hydrogen). In hydrogen dual fuel engines, other emissions including hydrocarbon (HC), carbon monoxide (CO) and smoke decrease to near zero level whereas greenhouse gas emissions (carbon dioxide (CO_2) and methane (CH_4)) from CI engines decrease substantially. However, the literature review indicates the maximum hydrogen energy share in the dual fuel engines at rated load is limited from 6% to 25%. This is mainly due to higher in-cylinder peak pressure and rate of pressure rise, knocking and autoignition of hydrogen-air charge. In addition to this, NO_x emission in the engine under dual fuel mode is higher (about 29–58%) than conventional diesel mode due to high localized in-cylinder temperature. The suitable strategies for improvement of maximum hydrogen energy share (up to 79%) and NO_x emission reduction (up to a level of conventional mode) in CI engines under dual fuel mode are discussed in detail.

1. Introduction

Compression ignition (CI) engines are widely used in various sectors including transportation, agriculture, civil construction and small scale electrical power generation due to its high thermal efficiency, high fuel economy and low carbon based emissions (carbon monoxide (CO), hydrocarbon (HC)). However, these engines emit high level of smoke/particulate matter (PM) and oxides of nitrogen (NO_x) emissions due to combustion with heterogeneous air fuel mixture. In addition to this, carbon dioxide (CO_2), one of the major greenhouse gas (GHG) emissions, is included in current emission regulation standards along with the other regulated emissions. For example, European Union sets CO_2 emission regulation of 95 g/km by 2020 [1,2]. The EPA (Environmental Protection Agency) implemented CO_2 emission regulation as 820 g/kWh for light, medium and heavy duty vehicles [2–4]. On the other hand, energy efficiency improvement is one of the major concerns for sustainability of CI engines. The current available technologies such as exhaust gas recirculation (EGR), retardation of injection timing etc. could not provide both the efficiency improvement and the emissions reduction benefits. However, utilization of gaseous hydrogen (H_2) in CI engines is a viable option to resolve both the problems of energy efficiency improvement and emissions reduction simultaneously.

Hydrogen has unique physical and chemical properties which are best suitable for its successful widespread adoption as a fuel (energy carrier) for internal combustion (IC) engines [5]. As hydrogen is a carbon free fuel, it's utilization in IC engines leads to zero carbon based emissions such as carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC) and smoke/soot/particulate matter. Hydrogen has the highest energy content per unit mass among all fuels and it has many advantageous properties such as a high flame speed, short quenching distance, high heating value and high diffusivity which

Abbreviations: 32/40DF and 51/60DF, Engine models from M/S MAN Diesel; 34DF and 50DF, Engine models from M/S Wartsila; BDC, Bottom dead centre; BMEP, Brake mean effective pressure; C-10 DFNG, C-12 DFNG, and C-15 DFNG, Engine models from M/S Caterpillar; CA, Crank angle; CH_4, Methane;; CI, Compression ignition; CNG, Compressed natural gas; CO, Carbon monoxide;; CO_2, Carbon dioxide; CR, Compression ratio; CV, Calorific value; C_xH_y, Hydrocarbon; E_a, Activation energy; EGR, Exhaust gas recirculation; EHI, End of hydrogen injection; EPA, Environmental Protection Agency; EVC, Exhaust valve closing; EVO, Exhaust valve opening; GHG, Greenhouse gas;; GWP, Global warming potential; H_2, Hydrogen; HC, Hydrocarbon; HCCI, Homogeneous charge compression ignition; HFCP, High frequency component of in-cylinder pressure; IC, Internal combustion; IVC, Inlet valve closing; IVO, Inlet valve opening; k_1, k_2, k_3, Constants; m, Mass flow rate of species; MI, Manifold injection;; N_2O, Nitrous oxide; Nc, Number of cylinders; NO_x, Oxides of nitrogen; O, H, and OH, Oxygen, hydrogen and hydroxyl radicals; P, Brake power; PHCCI, Partial homogeneous charge compression ignition;; PI, Port injection;; PM, Particulate matter; QSK50, KTA38-G2A, and KTA50-G3, Engine models from M/S Cummins; rpm, Rotations per minute; RPR, Rate of pressure rise;; RR, Reaction rate; Ru, Universal gas constant; SHI, Start of hydrogen injection; SI, Spark ignition; T, In-cylinder temperature; TDC, Top dead centre; TPE, Total premixed charge energy

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could lead to high combustion efficiency [6]. Theoretically, hydrogen produces water as by-product during its combustion in IC engines. It is therefore not only an energy carrier but also a clean and green fuel.

1.1. Hydrogen utilization in internal combustion engines

Hydrogen as a fuel is best suitable for spark ignition (SI) engines due to its high octane number of about 120 [7]. Hydrogen utilization in SI engines would give zero carbon based emissions due to high localized in-cylinder temperature. However, hydrogen utilization in the SI engines is limited due to power de-rating (throttling losses), low thermal efficiency, low volumetric efficiency and high level of NO_x emission [8]. In order to overcome these negative aspects, a major engine hardware modification or new technology need to be developed. On the other hand, if the hydrogen is used in CI engines under dual-fuel mode, thermal efficiency would improve significantly due to high compression ratio, no power de-rating due to no throttling losses, fuel economy would improve due to constant volume combustion, and HC CO, smoke and greenhouse gas emissions (CO_2, CH_4, N_2O) would decrease significantly. However, hydrogen could not be utilized in conventional CI engines as the hydrogen is having the properties of low cetane number and high autoignition temperature. But hydrogen can be used in CI engines under dual-fuel (diesel-hydrogen) mode. A small amount of diesel (pilot fuel) could be used as an ignition source and hydrogen (main fuel) as the major energy contributing fuel in a CI engine under dual-fuel mode.

1.2. Driving forces for hydrogen utilization in CI engines in Indian context

- India, one of the fast economic development countries, is known as diesel driven economy as the consumption ratio of diesel to gasoline is about 5.6:1 [9]. This significant diesel demand could easily be satisfied with hydrogen due to its abundant availability (common element in the universe), could be drawn from wide variety of sources/methods and renewable in nature.
- The utilization of hydrogen as an energy carrier is proposed in most of the governmental strategic plans for a sustainable energy system. The Indian Ministry of New and Renewable Energy, the US Department of Energy (DOE), the European Commission's Directorate-General for Research, the Japanese Ministry of Economy, Trade and Industry; and many others formulated vision reports for hydrogen programs. For example, in India, a National Hydrogen Energy Roadmap has been formulated by Ministry of New and Renewable Energy in the year 2007 [10], and it is envisaged in the Roadmap that one million hydrogen fuelled vehicles and 1000 MW hydrogen based electrical power generation would be targeted in the country by 2020.
- As hydrogen is available as a by-product from Chloro-Alkali industries, it could be used in diesel engines under dual-fuel mode for in-house electrical power generation.
- As thermal efficiency of a CI engine is higher than a spark ignition engine due to its high compression ratio, hydrogen utilization in CI engines would be more beneficial.
- Particulate matter (PM) emission from CI engines would decrease drastically with the use of gaseous hydrogen, which is otherwise a major concern for sustainability of CI engines.
- Natural gas based dual-fuel engines are already commercialized by original engine manufacturers (OEMs) (Table 1). In the world, Delhi (India) is one of the largest vehicle fleet fuelled with natural gas. In a significant step towards adopting green fuel, the Indian railways launched its first CNG (compressed natural gas) train in 2015. The railways modified a CI engine (rated power: 1400 hp) to run on dual-fuel mode through fumigation technology with 20% CNG substitution [11]. However, natural gas availability for meeting the future huge global energy demands is uncertain. In addition to this, natural gas based dual-fuel engines emit high levels of unburned HC (methane hydrocarbon and non-methane hydrocarbon) and CO emissions at part loads. Engine-out methane (CH_4) emission effect the environment adversely as global warming potential (GWP) of methane for 100 years time horizon is higher (21) than GWP of CO_2 (1). In order to resolve these issues, replacement of natural gas with hydrogen could be a viable option as there is no such problem of hydrogen availability. Hydrogen is one of the most available elements on the earth. However, it is not available in its actual form (H_2), it is combined with other molecules including water (H_2O) and hydrocarbons (C_xH_y) [7]. So, the hydrogen element needs to be dissociated from the feedstock/energy source. The significant energy sources and suitable production methodology is given in Fig. 1. Moreover, hydrogen utilization in CI engines could produce almost zero HC, CH_4 and CO emissions, and low CO_2 emissions along with an additional benefit of high thermal efficiency.

Table 1
Current scenario of dual-fuel engine manufacturers (OEMs) [2,11–13].

OEMs/Applications	Fuels used	Engine models
Cummins	Diesel and natural gas	QSK50, KTA38-G2A, and KTA50-G3
Caterpillar	Diesel and natural gas	C-10 DFNG, C-12 DFNG, and C-15 DFNG
Wartsila	Diesel and natural gas	34DF and 50DF
MAN Diesel	Diesel and natural gas	32/40DF and 51/60DF
Indian Railways	Diesel and CNG	1400 HP engine
HUNDAI	Diesel and CNG	VERNA (Under progress)
Mahindra & Mahindra	Diesel and CNG	SCORPIO (Under progress)

The existing natural gas infrastructure (storage, transportation and dispensing) could also be used for hydrogen blended natural gas fuel. The government of India is also taken further amendment by formulating fuel policy for implementation of hydrogen blended natural gas (hydrogen: 18% by volume) as a fuel for internal combustion engines/vehicles [10].

1.3. Dual fuel technology

Typically in a dual-fuel engine, gaseous hydrogen fuel (main fuel) is supplied to the engine during suction stroke and diesel fuel (pilot fuel) is directly injected in to the combustion chamber at the end of compression stroke to initiate the ignition as shown in Fig. 2[14]. Dual-fuel engines can operate either on dual-fuel mode if gaseous hydrogen fuel is available or on single diesel fuel mode in the absence of the gaseous fuel (fuel flexibility). Valve timing and process diagram of hydrogen and diesel are shown in Fig. 3. Hydrogen was injected into the intake manifold after the outlet valve closed (43° CA after TDC) in order to avoid scavenging losses [15]. Start of hydrogen injection (SHI) was maintained constant as 43° CA after TDC throughout the experimentation whereas the end of hydrogen injection (EHI) was varied with respect to the engine loading [15]. These injection timings were optimized based on better performance and lower emissions for diesel-hydrogen dual-fuel operation [15].

The hydrogen fuel could be added into a CI engine using three

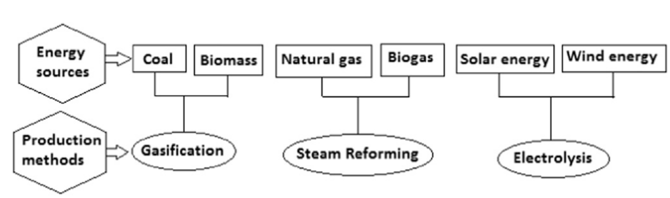

Fig. 1. Energy sources and production methodologies for hydrogen.