INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–13

Available online at www.sciencedirect.com

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Combustion and emission characteristics of a hydrogen-diesel dual-fuel engine

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ARTICLE INFO

Article history:
Received 23 January 2018
Received in revised form
5 April 2018
Accepted 10 May 2018
Available online xxx

Keywords:
Hydrogen
Hydrogen-diesel
Compression ignition engine
Dual-fuel engine
EGR

ABSTRACT

Hydrogen generated from renewable sources is an eco-friendly fuel that can be used in automotive industry or for energy generation purposes. Hydrogen is a high-energy content gas and its carbonless chemical structure can provide significant benefits of high thermal efficiency and near zero or very low carbon emissions when combusted with other fuels.

In this study, the implementation of hydrogen fuel was tested at low and medium operating loads in a heavy-duty hydrogen-diesel dual-fuel engine. The paper provides a detailed experimental analysis of the effects of hydrogen energy share ratio and various combustion strategies such as exhaust gas recirculation, diesel injection pressure and diesel injection patterns.

At low load conditions, engine operation with an H_2 energy share ratio of up to 98% was achieved without any engine operation implications. This condition provided a simultaneous reduction of carbon and NOx emission of over 90% while soot emissions were dropped by 85% compared to the conventional diesel-only operation. At medium load, the increased NOx emission due to the high energy content of hydrogen fuel was found to be the primary challenge.

Introduction

Hydrogen has attracted wide attention as a fuel of the future because it is abundant, clean and highly efficient. It can be electrochemically converted into electricity using fuel cells or combusted in internal combustion engines. Although fuel cells are a promising technology for the future, the use of hydrogen in internal combustion engines remains of high importance mainly for energy generation purposes or heavy-duty applications. In this direction, several research studies have been performed on the suitability and merits of hydrogen as a fuel for internal combustion engines.

The implementation of the fuel in spark-ignited (SI) engines has demonstrated excellent prospects to achieve satisfactory performance with extremely low harmful emissions [1–4]. On the other hand, due to the high auto-ignition temperature of hydrogen, its implementation in compression-ignition (CI) engines is challenging and can only be achieved over a wide engine operation range with the addition of a lower auto-ignition fuel such as diesel or biodiesel [5,6]. Hydrogen can be used in small energy share ratios for improving the engine's performance and as proved in Refs. [7–9] provide reductions in carbon, smoke and NOx emissions. Besides, hydrogen can be used in higher energy share ratios with the (bio)diesel fuel injected close to the

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https://doi.org/10.1016/j.ijhydene.2018.05.062
0360-3199/

engine's top dead centre (TDC) working as a combustion trigger [7,10,11]. An expansive overview of the research studies in the implementation of hydrogen fuel in a dual-fuel operation of compression-ignition engines can be found in Ref. [12]. Although most of the research studies highlight the significant reduction of carbon emissions with the implementation of hydrogen fuel, the main challenge was found to be the increased NOx emissions at medium to high loads operation (when high energy share ratios are implemented). This is a result of the combustion of a high energy-content fuel [5,9]. Hydrogen has an apparent effect on diesel combustion process and is depicted as a sharp increase in peak in-cylinder pressure and peak heat release rate [13,14]. This often leads to an increase in the brake thermal efficiency compared to the neat diesel operation. In contrast, at low loads, H_2 fuel can contribute to great NOx reductions by more than 50% as reported by Karagoz et al. [15]. According to Talibi et al. [8], the NOx reduction is due to the decrease of diesel fuel combusted near the spray fringe where the diesel fuel-air equivalence ratio is at an approximately stoichiometric ratio.

Exhaust gas recirculation (EGR) is a well-known technique applied mainly (but not only) in compression-ignition engines for the reduction of NOx emission [16]. The implementation of EGR in hydrogen-diesel dual-fuel engines can provide significant reductions in NOx emissions. However, high EGR rates lead to the reduction of oxygen availability in the cylinders, poor soot oxidation and hence increase of the exhaust soot emissions. Despite the soot emission penalty, research studies have demonstrated a simultaneous reduction of NOx and soot emission under optimum parameters compared to the neat diesel operation. Wu and Wu [17] reported a simultaneous reduction of NOx and smoke emissions compared with using neat diesel fuel by applying 20% hydrogen-energy-share ratio and 40% EGR in a single cylinder DI engine. Suzuki and Tsujimura [18] achieved a simultaneous reduction of NOx and smoke emissions in operating a dual-fuel engine with high hydrogen rates over 70% and EGR.

Implementing advanced injection and combustion strategies is an alternative way of controlling the harmful NOx emissions of compression-ignition engines. As demonstrated in the literature [19,20], optimum injection timing and multiple injection strategies can provide significant reductions in the exhaust emissions. An early diesel fuel injection can lead to high in-cylinder pressure rise and increased NOx formation while late injections can deteriorate engine's performance and fuel efficiency. Tomita et al. [21] confirmed the increase of NOx formation in a hydrogen-dual fuel engine when an early diesel injection was applied. However, when the diesel injection was shifted to 33° before TDC, a reduction of NOx emissions was reported. This pre-mixed charge compression ignition (PCCI)-alike combustion strategy provided enough available time for the diesel fuel to mix with the air and hydrogen before the ignition, leading to a lean mixture with diesel fuel becoming the ignitor source for a wide range of the cylinder. Therefore, very slow combustion with smooth heat release was achieved. However, so early diesel fuel injections can only be applied for low equivalence ratios with an unstable combustion performance to be quite likely. Also, diesel injection pressure has a significant effect on the performance and emissions generation of compression-ignition engines. Although in dual-fuel operation part of the diesel fuel is substituted with H_2 fuel, it is expected that diesel pressure still plays a significant role in the control of engine's performance and emissions.

In this paper, a heavy-duty multi-cylinder compression-ignition engine is operated in a dual-fuel mode with hydrogen and diesel. The experimental analysis presented focuses on two engine operating conditions of 20 kW and 40 kW representing low and medium engine loads respectively at a fixed speed of 1,500 rpm. The target of this experimental study was to achieve the maximum H_2 energy share ratios for each engine load enabling smooth operation and minimum carbon emissions while controlling NOx and soot emissions by means of exhaust gas recirculation and advanced injection strategies.

Experimental apparatus

A 5.2L four-cylinder heavy-duty compression-ignition engine was used as the platform for testing and measuring the performance and emissions output of hydrogen-diesel dual-fuel operation. The conventional engine, running on diesel fuel only, is equipped with an intake throttle valve, a high-pressure Exhaust Gas Recirculation (EGR) system and a Variable Geometry Turbocharger (VGT) boosting system.

The engine was coupled to a 346 kW transient AC dynamometer (HORIBA DYNAS3 ULI340) and the four cylinders were instrumented with pressure sensors (KISTLER 6056A) for measuring the instantaneous in-cylinder pressure and calculating the heat release rate of the engine. For the engine-out emissions, three exhaust gas analysers (HORIBA MEXA-ONE, BEST SOKKI BOB-2000FT and AVL micro soot sensor 483) were implemented for recording the CO, CO_2, THC, NOx, soot and unburned hydrogen emissions.

The detailed engine layout and specifications are given in Fig. 1 and Table 1.

Four injectors were used to supply the engine with hydrogen fuel into a dedicated gas fuel chamber prior the intake manifold of the engine. Hydrogen fuel was homogeneously delivered to the four cylinders of the engine after passing an air-hydrogen mixer. The hydrogen supply system consisted of compressed gas cylinders, pressure regulators and flow rate measurement devices as shown in Fig. 2. The hydrogen injection pressure was set to 4 bar (gauge) for all experiments in this paper while the injection quantity was controlled by the frequency and period of the hydrogen injectors' valves opening times. Compressed nitrogen (N2) gas was used to purge the hydrogen gas out of the engine system after the end of the experimental procedure for safety reasons.

Results and discussion

All the experimental testing for both conventional and dual-fuel operation presented in this paper was performed at a