Fuel 199 (2017) 162–168

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Influence of hydrogen addition on combustion characteristics and particle number and size distribution emissions of a TDI diesel engine

Carmen C. Barrios [a,*], Aida Domínguez-Sáez [a], Dévora Hormigo [b]

[a] Environmental Department, Research Centre for Energy, Environment and Technology (CIEMAT), Avda. Complutense, 40, 28040 Madrid, Spain
[b] Department of Mechanical Engineering, Polytechnic University of Madrid (UPM), C. José Gutierrez Abascal, 2, 28006 Madrid, Spain

HIGHLIGHTS

- With hydrogen injection, the number of nucleation mode particles decreases in direct proportion to the total particle number.
- With hydrogen injection, decrease the NOx emission.
- THC emissions decrease when the engine operates with a 25% of fuel energy substituted by hydrogen.
- CO_2 emissions decrease when hydrogen is injected.

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 15 December 2016
Accepted 23 February 2017

Keywords:
Hydrogen
Exhaust emissions
Engine performance
Particle emissions

ABSTRACT

The aim of the study is to evaluate the influence of hydrogen addition on the combustion process, the specific fuel consumption, brake thermal efficiency and emissions, especially particle emissions in the range 5.6–560 nm in size distribution and number of a diesel engine. The tests were performed on a 2.0 TDI diesel engine VW Euro 4, in nine stable conditions (2000, 2500, and 3000 min^{-1} at 15%, 30% and 45% engine load) with 0% of H_2 and substituted 25% of energy from diesel fuel by H_2. Experimental result shows that if we substitute 25% of the energy released in the combustion process with energy from hydrogen, the rate of decrease in the emission of CO_2 reaches up 22% for a load of 15% and 2500 min^{-1}, the expected 25% reduction is not achieved due to a slight decrease in brake thermal efficiency in many of the conditions experienced. No significant increase of NOx is observed in any condition. The number of particles decreased up to 63% when engine works at 3000 min^{-1} and 15% of maximum engine torque with hydrogen injection, in relation to the engine operating with commercial diesel. Moreover, the 25% of diesel fuel substitution by hydrogen causes a reduction in the maximum in-cylinder pressure, decreasing up to 16% at most demanding load condition (3000 min^{-1} with 45% of maximum engine torque). This is due to the water generated during hydrogen oxidation, which absorbs heat to evaporate and cause a temperature and in-cylinder pressure decrease in the combustion process, that ensures the physical motor integrity.

1. Introduction

The activities carried out in large modern cities generate many environmental problems, being the poor air quality in metropolitan areas one of the most serious due to its impact on public health [1,2]. Except in very specific situations in nearby towns to industrial areas, the most important source of atmospheric pollutant in modern cities is the vehicle traffic on its roads. Being conscious of this environmental problem and taking into account the high energy demand, the use and development of renewable energy source, and unconventional and cleaner fuels is absolutely justified. Strategies to improve emissions from diesel engines, based on clean combustion studies, has focused on alternative fuels both liquid and gaseous such as second-generation biodiesel, ethanol, compressed natural gas (CNG), the liquefied petroleum gas (LPG), liquefied natural gas (LNG) and hydrogen (H_2). All these alternative fuels have been considered as viable substitutes for conventional

Abbreviations: CD, commercial diesel; CO, carbon oxide; CO_2, carbon dioxide; GMD, geometric mean diameter; LHV, lower heating value; LNT, lean NOx trap; NEDC, new European driving cycle; NOx, nitrogen oxides; η_{ef}, thermal efficiency; EGR, exhaust gas recirculation; Esub, energy of substitution; SFC, specific fuel consumption; THC, total hydrocarbons; UDC, urban driving cycle.

* Corresponding author.
E-mail address: carmen.barrios@ciemat.es (C.C. Barrios).

http://dx.doi.org/10.1016/j.fuel.2017.02.089

fuels without extensive modifications to the engine [3–5]. Use these fuels helps to reduce the impact of combustion engine emissions on the environment although will continue presenting difficult challenges to solve. In the case of biofuels that contribute to a better balance of the carbon cycle, keep local emission of CO and CO_2 and the supply of raw materials needed to manufacture it without affecting soil and food crops is not solved yet. On the other hand, several alternatives as CNG, LPG and LNG improve particle number emission, but affect engine autonomy and do not solve the problem of pollutant emissions associated with carbon content so fossil fuels dependency continues. Hydrogen is a fuel whose combustion does not produce particles, carbon monoxide (CO), carbon dioxide (CO_2) or hydrocarbons (THC) since it do not contain any carbon atom [6,7] and that can be derived from biological sources [8] or waste sources [9]. In theory, hydrogen oxidation needs more air per mass unit with respect to diesel combustion. Besides, hydrogen requires an ignition source due to its low cetane number and a flash point higher than diesel fuel, does not ignite by compression in a modern diesel engine. However, once the reaction begins, hydrogen is highly reactive causing a faster reaction rate in a wide range of air-fuel ratios than hydrocarbon fuels such as gasoline and diesel, even in lean mixture. Fast and thermally neutral branching chain reactions of hydrogen cause high flame speeds, especially when compared this with relative slower endothermic and thermally significant chain reactions that happen in combustion of a hydrocarbon fuel [10]. In a diesel engine, the hydrogen can be introduced into the inlet manifold mixed with air in a mixture that resist the auto-ignition before the pilot fuel injection, while the diesel is injected directly into the combustion chamber through the conventional fuel injection system, so that self-ignition of the diesel fuel sprayed may act as pilot to ignite hydrogen [11–13]. This was the technique used in this experimental work.

The aim of this study is to evaluate the influence of using hydrogen as a partial fuel, in the gaseous emissions and ultrafine particle number and size distribution emissions, and in the combustion process of a 2.0 TDI diesel engine VW Euro 4. The work focuses on whether the energy substitution of a constant percentage (25%) in the diesel-air mixture with energy from hydrogen in different operating conditions of the engine (2000, 2500, and 3000 min^{-1} at 15%, 30% and 45% of maximum engine torque), results in a reduction of gaseous emissions and particle emissions and if this reduction is also associated with a reduction for a given particle size.

2. Materials and methods

2.1. Engine and sampling

The dynamometer engine test bench used was composed of a diesel engine and dynamometer (SCHENK W150) controlled by a HORIBA's SPARC system. The diesel engine tested was a 2.0 TDI 140 hp @ 4000 rev^{-1}, Euro 4, four stroke and direct injection (Table 1). This engine is widely studied by the authors in other scientific papers [3,14]. The exhaust gas after-treatment system consisted of a diesel oxidation catalyst (DOC) and no particle filter. In order to make a correct characterization of emissions were measured emissions of particle in number and size distribution, exhaust gas pollutant (CO, CO_2, THC and NOx) and all engine operating parameters were recorded (speed, torque, throttle position, intake air temperature, temperature of the exhaust gas, flow of exhaust gas, the percentage of exhaust gas recirculation, fuel temperature, specific fuel consumption and brake thermal efficiency). Particle size distribution were measured with an Engine Exhaust Particle Sizer 3090 (EEPS, commercially available from TSI Inc.) and a Rotating Disc Raw Gas Diluter MD19-2E, a first hot dilution (150 °C and dilution factor of 1:1695) and a second cold dilution (1:2 dilution factor) [15]. An OBS 2200 (HORIBA Inc.) was used to measure the concentrations of the exhaust gas sample pollutants. The particle sampling and dilution system has previously been proven and tested in author's previous publications [15–17]. The engine in-cylinder gas pressure was measured with a piezoelectric pressure transducer (type 6046A60 Kistler Co., Inc. with a pressure range of 0–250 bar), installed via a glow plug adaptor in conjunction with a Kistler 5015 charge amplifier. The amplified signals were correlated with the signal from crank angle encoder (type 420, Heidenhain). These pressure readings were logged by PCs utilizing National Instruments (NI) data acquisition systems.

Table 1
Test engine specifications.

	2.0 TDI Volkswagen
Year	2005 (Euro 4)
Configuration	In-line 4-cylinder
Air intake	Turbocharged
Fuel injection	Direct Injection
Displacement	2.0 L
Max torque	320 N m @1750–2500 rev^{-1}
Max power	103 kW @4000 rev^{-1}
Compression ratio	18
EGR	Yes
DPF	No

2.2. Hydrogen intake injection

Hydrogen was introduced through a nozzle to the intake manifold before entering the combustion chamber. It was supplied from a high-pressure cylinder (150 bar) and then reduced to a pressure of 1–3 bar using a pressure regulator. The hydrogen passes through a shutoff valve, which closed if any backfire results in the sample line. After, hydrogen passes through a digital mass flow controller (Red-y GSM-D, Vögtlin Instrument) specially calibrated to measure hydrogen, to an accuracy of ±0.3% of full scale + ±0.5% of reading (approx. ±1 L/min depending on each condition) and finally, hydrogen was injected into the engine inlet manifold upstream of the inlet valves (before the turbo input and after the air flow meter).

2.3. Experimental procedure

Regulated emissions and particle emissions in number and size distribution were measured in nine stable conditions (2000, 2500, and 3000 min^{-1} at 15%, 30% and 45% engine load) with 0% of H_2 and substituted up to 25% of energy from diesel fuel by H_2 (with a hydrogen purity grade >99.9999 vol.%). Engine load percentage is calculated with respect to the maximum engine torque at each speed, using Commercial Diesel (diesel fuel with 7% v/v Fatty Acid Methyl Ester – FAME according to current fuel standards of European Union). The amount of hydrogen required to replace 25% of energy was calculated using the formula (1). To achieve DC/H ratio needed to replace 25% of the energy of the diesel fuel with hydrogen, the injection was gradually increased by 5 L/min until reaching the stationary condition, so as to avoid any uncontrolled change during engine operation with Hydrogen. Operating conditions and amount of H_2 used are shown in Table 2. Each operating condition was held for one minute and monitored at 1 Hz. Only 30 data were used for the analysis, deleting the first 25 and the last 5 data, thus ensuring that the engine and emissions were stabilized. Tests were performed, randomly and automatically controlled, in order to ensure repeatability of measurements, all outliers are neglected.