Energy 63 (2013) 375–386

Contents lists available at ScienceDirect

Energy

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

# Multi objective optimization of performance parameters of a single cylinder diesel engine running with hydrogen using a Taguchi-fuzzy based approach

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ARTICLE INFO

*Article history:*
Received 13 April 2013
Received in revised form
11 September 2013
Accepted 18 October 2013
Available online 15 November 2013

*Keywords:*
Hydrogen
Performance
Combustion
Fuzzy
Taguchi
MPCI (multi performance characteristics index)

ABSTRACT

Environmental issues and rapid exhaustion of fossil fuels are the major concerns over the past two decades to search for alternative fuels. Among various alternatives hydrogen is a long-term renewable and least polluting fuel. Its clean burning capability helps to meet the stern emission norms. Full substitution of diesel with hydrogen may not be convenient for the time being but employing of hydrogen in a diesel engine in dual fuel mode is possible. In this experimental investigation a TMI (timed manifold injection) system has been developed using ECU (electronic control unit) with varying injection strategy to deliver hydrogen on to the intake manifold. Through adopting this technique in the existing diesel engine a momentous improvement in performance and combustion parameters has been observed. The study also attempts to explain the application of the fuzzy logic based Taguchi analysis to optimize the performance parameters i.e. BSEC (Brake specific energy consumption), Vol. Eff. (Volumetric efficiency) and BTHE (brake thermal efficiency) for the different hydrogen injection strategies.



## 1. Introduction

As an alternative fuel hydrogen is being paid considerable attention to reinstate the rapidly depleting petroleum-based fuels. The current world's energy consumption relies primarily on the fossil fuels like petroleum. While fossil fuel is being depleted, there is an urgent need to carry out research and develop viable alternative fuels as a substitute for petroleum based fuels to meet the increasing energy demand with the minimum environmental and economical impact, thereby reducing the reliance on crude oil derived fuels. The internal combustion engines have already become an indispensable and integral part of our present day life. In recent days the importance of environment and energy are emphasized in various energy schemes provide strong encouragement for research on alternate fuels [1]. Hydrogen is one of the most promising alternate fuels. It's clean burning characteristics helps to meet the stringent emission norms. Maximum usage of hydrogen as a fuel was adopted in spark ignition engine, however, in this experimental investigation efforts were taken to utilize in compression ignition engine. Due to the high self-ignition temperature of hydrogen, it needs some ignition source to start the combustion. Hence in dual fuel mode diesel is used as an ignition source. Since knocking does not permit large proportion of hydrogen, only up to 30% of energy is supplied by hydrogen [2–4]. There are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in the IC (internal combustion) CI (compression ignition) engine. Firstly, it increases the H/C ratio of the entire fuel. Secondly, injecting small amounts of hydrogen to a diesel engine could decrease heterogeneity of a diesel fuel spray due to the high diffusivity of hydrogen which makes the combustible mixture better premixed with air and more uniform. It could also reduce the combustion duration due to hydrogen's high speed of flame propagation in relation to other fuels. The laminar flame speed for hydrogen is 1.9 m/s at normal pressure and temperature, and it is almost five times higher when compared to 0.4 m/s for most hydrocarbon fuels [5]. The flammability limits of hydrogen vary from an equivalence ratio of 0.1–7.1, and the engine is hence operated with a wide range of air/fuel ratio. The lower heating value of hydrogen is 120 MJ/kg which is higher than that of diesel fuel (42 MJ/kg). The auto-ignition temperature of hydrogen (858 K) is also higher than that of diesel (530 K) [6]. Hydrogen

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http://dx.doi.org/10.1016/j.energy.2013.10.045

**Nomenclature**

| | |
|---|---|
| TMI | timed manifold injection |
| ECU | electronic control unit |
| NHR | net heat release, kJ |
| MGT | mean gas temperature, K |
| BP | brake power, kW |
| BSEC | brake specific energy consumption, kJ/kW-h |
| $m_f$ | mass flow rate of fuel, kg/h |
| Vol. Eff. | volumetric efficiency, % |
| BTHE | brake thermal efficiency, % |
| $E_{H_2}$ | lower heating value of hydrogen, MJ/kg |
| $E_{diesel}$ | lower heating value of diesel, kJ/kg |
| $H_2$ | hydrogen |
| MPCI | multi performance characteristics index |
| IC | internal combustion |
| CI | compression ignition |
| S/N | signal-to-noise, dB |
| ATDC | after top- dead-centre |
| DAQ | data acquisition |
| DI | direct injection |
| D | degree |
| kg | kilogram |
| DISL | diesel |
| 10D2KGDISL | 10° injection timing at 2 kg load without $H_2$ |
| 10D6KGDISL | 10° injection timing at 6 kg load without $H_2$ |
| 10D10KGDISL | 10° injection timing at 10 kg load without $H_2$ |
| H1 | first injection strategy of hydrogen (@9000 μs) |
| μs | microseconds |
| 10D2KGH1 | 10° injection timing at 2 kg load with H1 |
| 10D6KGH1 | 10° injection timing at 6 kg load with H1 |
| 10D10KGH1 | 10° injection timing at 10 kg load with H1 |
| H2 | second injection strategy of hydrogen (@15,000 μs) |
| 10D2KGH2 | 10° injection timing at 2 kg load with H2 |
| 10D6KGH2 | 10° injection timing at 6 kg load with H2 |
| 10D10KGH2 | 10° injection timing at 10 kg load with H2 |
| H3 | third injection strategy of hydrogen (@21,000 μs) |
| 10D2KGH3 | 10° injection timing at 2 kg load with H3 |
| 10D6KGH3 | 10° injection timing at 6 kg load with H3 |
| 10D10KGH3 | 10° injection timing at 10 kg load with H3 |
| $D_i$ | inlet manifold diameter (INNER), m |
| $Q$ | heat source, J |
| $\theta$ | Crank angle, degrees |
| $V$ | volume, $m^3$ |
| $p$ | pressure, bar |
| $k$ | specific heat capacity, J $kg^{-1}$ $K^{-1}$ |
| $\dot{m}$ | mass flow rate, kg $h^{-1}$ |
| $E$ | energy, J |
| CA | crank angle, degrees |
| $y_i$ | value of quality characteristics measured from the trial |
| $n$ | number of the test in a trial |
| $X_i$ | S/N ratio value measured from the trial |
| $X_{Max}$ | maximum S/N ratio value |
| $X_{Min}$ | minimum S/N ratio value |
| $X_{Normalized}$ | normalized S/N ratio value |
| S | small |
| M | medium |
| L | large |
| VS | very small |
| VVS | very VERY small |
| VL | very LARGE |
| VVL | very very large |

replacement of air in real conditions is based on volume. As a result, there will be good amount of replacement of air [7–9]. Better homogeneity of the combustible mixture would provide better conditions for the complete combustion process. Hydrogen can be used in a CI engine in the dual fuel mode with diesel acting as an ignition source for the hydrogen fuel in addition to being the main fuel. In this method a large quantity of hydrogen cannot be used, since the hydrogen will replace the air, thereby reducing the air available for diesel combustion [10]. Table 1 shows the properties of hydrogen in comparison with diesel. In the present work, hydrogen was injected into the intake manifold and ignited with diesel injected in the conventional manner.

**Table 1**
Properties of hydrogen in comparison with diesel.

| Sl. No. | Properties | Diesel | Hydrogen |
|---|---|---|---|
| 1. | Formula | $C_nH_{1.8}nC_8$–$C_{20}$ | $H_2$ |
| 2. | Auto ignition temperature (K) | 530 | 858 |
| 3. | Minimum ignition energy (MJ) | – | 0.02 |
| 4. | Flammability limits (volume % in air) | 0.7–5 | 4–75 |
| 5. | Stoichiometric air fuel ratio on mass basis | 14.5 | 34.3 |
| 6. | Molecular weight (g/mol) | 170 | 2.016 |
| 7. | Limits of flammability (equivalence ratio) | – | 0.1–7.1 |
| 8. | Density at 16 °C and 1.01 bar (kg/$m^3$) | 833–881 | 0.0838 |
| 9. | Net heating value (lower) MJ/kg | 42.5 | 119.93 |
| 10. | Flame velocity (cm/s) | 30 | 265–325 |
| 11. | Quenching gap in NTP air (cm) | – | 0.064 |
| 12. | Diffusivity in air ($cm^2$/s) | – | 0.63 |
| 13. | Octane number | 30 | 130 |
| 14. | Cetane number | 40–55 | – |
| 15. | Boiling point (K) | 436–672 | 20–27 |
| 16. | Viscosity at 15.5 °C, (centipoise) | 2.6–4.1 | – |
| 17. | Specific gravity | 0.83 | 0.091 |

## 2. The hydrogen–diesel dual-fuel concept

In dual-fuel engines the primary gaseous fuel like hydrogen of high octane index (>130) is premixed with air in the inlet manifold and compressed and then fired by a small liquid fuel injection which ignites spontaneously at the end of compression phase. The advantage of this type of engine resides in the fact that it is an attempt for the combination of the best of the two combustion processes using the difference of flammability of two fuels at different stages of the combustion process. A conventional diesel engine can be easily modified to operate in this mode. This engine can accept a wide range of liquid and gaseous fuels as the primary energy source. Natural gas and liquefied petroleum gas and hydrogen are important alternative fuels that are readily available for immediate use. However, because their cetane numbers are very low, approaching zero, they are not directly suited to CI (compression ignition) engines. The hydrogen–diesel dual-fuel concept method combines the advantages of the high part load efficiency, inferior specific fuel consumption of a diesel engine and the clean combustion characteristics of hydrogen and oxygen. Hydrogen has an auto-ignition temperature of about 858 K and, as such, it is not possible to attain ignition of hydrogen by compression alone at the compression ratio of 17.5 at the existing engine configuration in the present work. Some source of ignition has to be created inside the combustion chamber to ensure ignition [11–15]. A small quantity of liquid diesel fuel is injected as pilot fuel by means of the existing fuel injection equipment near the end of the