Fuel 87 (2008) 3591–3599

Contents lists available at ScienceDirect

Fuel

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

Combustion analysis on a DI diesel engine with hydrogen in dual fuel mode

N. Saravanan *, G. Nagarajan, G. Sanjay, C. Dhanasekaran, K.M. Kalaiselvan

Department of Mechanical Engineering, Internal Combustion Engineering Division, College of Engineering, Guindy, Anna University, Chennai 600 025, India

A R T I C L E I N F O

Article history:
Received 25 January 2008
Received in revised form 4 July 2008
Accepted 8 July 2008
Available online 3 August 2008

Keywords:
Hydrogen
Port injection
Diethyl ether
Dual fuel
Emission

A B S T R A C T

Hydrogen is expected to be one of the most important fuels in the near future to meet the stringent emission norms. In this experimental investigation, the combustion analysis was done on a direct injection (DI) diesel engine using hydrogen with diesel and hydrogen with diethyl ether (DEE) as ignition source. The hydrogen was injected through intake port and diethyl ether was injected through intake manifold and diesel was injected directly inside the combustion chamber. Injection timings for hydrogen and DEE were optimized based on the performance, combustion and emission characteristics of the engine. The optimized timing for the injection of hydrogen was 5° CA before gas exchange top dead center (BGTDC) and 40° CA after gas exchange top dead center (AGTDC) for DEE. From the study it was observed that hydrogen with diesel results in increased brake thermal efficiency by 20% and oxides of nitrogen (NO_x) showed an increase of 13% compared to diesel. Hydrogen-DEE operation showed a higher brake thermal efficiency of 30%, with a significant reduction in NO_x compared to diesel.

1. Introduction

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 [1]. Increase in stringent environment regulations on exhaust emissions and anticipation of the future depletion of world wide petroleum reserves provide strong encouragement for research on alternate fuels [2]. Hydrogen is one of the most promising alternate fuels. It's clean burning characteristics and better performance drives more interest in hydrogen fuel [3]. Many researchers have used hydrogen as a fuel in spark ignition (SI) engine [4]. A significant reduction in power output was observed while using hydrogen in SI engine In addition pre ignition, backfire and knocking problems were observed at high load. These problems have resulted in using hydrogen in SI engine within a limited operation range [5,6]. However hydrogen cannot be used as a sole fuel in a compression ignition (CI) engine, since the compression temperature is not enough to initiate the combustion due to its higher self-ignition temperature [7]. Hence an ignition source is required while using it in a CI engine. The simplest method of using hydrogen in a CI engine is to run in the dual fuel mode with diesel as the main fuel or Diethyl Ether can be used that can act as an ignition source for hydrogen. In a dual fuel engine the main fuel is either inducted/carburated or injected into the intake air stream with combustion initiated by diesel. The major energy is obtained from diesel while the rest of the energy is supplied by hydrogen.

The hydrogen operated dual fuel engine has the property to operate with lean mixtures at part load and no load, which results in NO_x reduction, with an increase in thermal efficiency thereby reducing the fuel consumption. It was also observed that hydrogen could be substituted for diesel up to 38% on volume basis without loss in thermal efficiency, however with a nominal power loss.

Hydrogen used in the dual fuel mode with diesel by Masood et al. [8] showed the highest brake thermal efficiency of 30% at a compression ratio of 24.5. Lee et al. [9] studied the performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection technique. An increase in thermal efficiency by about 22% was noted for dual injection at low loads and 5% at high loads compared to direct injection. Lee et al. [10] suggested that in dual injection, the stability and maximum power could be obtained by direct injection of hydrogen. However the maximum efficiency could be obtained by the external mixture formation in hydrogen engine. Das et al. [11] have carried out experiments on continuous carburation, continuous manifold injection, timed manifold injection and low pressure direct cylinder injection. The maximum brake thermal efficiency of 31.32% was obtained at 2200 rpm with 13 Nm torque. Hashimoto et al. [12] have done extensive experimental investigation with DEE and diesel used as ignition source for igniting hydrogen fuel. Table 1 shows the properties of hydrogen in comparison with diesel and DEE. Fig. 1 shows the photograph of hydrogen and DEE flow arrangements.

Electronic injectors for hydrogen can have a greater control over the injection timing and injection duration with quicker response to operate under high-speed conditions [13]. The advantage of hydrogen injection over carburated system is problems like

* Corresponding author. Tel.: +91 9881128166.
E-mail address: sarav_2003@yahoo.co.in (N. Saravanan).

0016-2361/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2008.07.011

Nomenclature

J/°	Joules per degree	CI	compression ignition
kg/h	kilograms per hour	SI	spark ignition
kW	kilowatts	ECU	electronic control unit
mm	millimeter	DFC	digital mass flow controller
cm^3	cubic centimeter	IR	infra red
		NRV	non-return valve
Abbreviations		DSO	digital storage oscilloscope
PPM	parts per million	LPM	liters per minute
DEE	diethyl ether	UBHC	unburned hydro carbons
BSN	Bosch smoke number	NO_x	nitrogen oxides
TDC	top dead center	CO	carbon monoxide
BGTDC	before gas exchange top dead center	BTDC	before top dead center
CAD	crank angle duration	CA	crank angle
DI	direct injection	HHR	heat release rate

Table 1
Properties of hydrogen in comparison with diesel and DEE

Sl. No.	Properties	Diesel	Hydrogen	DEE
	Formula	$C_nH_{1.8n}C_8–C_{20}$	H_2	$C_2H_5OC_2H_5$
1	Auto ignition temperature (K)	530	858	433
2	Minimum ignition energy (mJ)	–	0.02	–
3	Flammability limits (volume % in air)	0.7–5	4–75	1.9–36.0
4	Stoichiometric air fuel ratio on mass basis	14.5	34.3	11.1
5	Molecular weight (g mol)	170	2.016	74
6	Limits of flammability (equivalence ratio)	–	0.1–7.1	–
7	Density at 160 C and 1.01 bar (kg/m^3)	833–881	0.0838	713
8	Net heating valve MJ/kg	42.5	119.93	33.9
9	Flame velocity (cm/s)	30	265–325	–
10	Quenching gap in NTP air (cm)	–	0.064	–
11	Diffusivity in air (cm^2/s	–	0.63	–
12	Octane number			
	Research	30	130	–
	Motor	–	–	–
13	Cetane number	40–55	–	>125
14	Boiling point (K)	436–672	20.27	307.4
15	Viscosity at 15.5 °C, centipoise	2.6–4.1	–	0.023
16	Vapour pressure at 38 °C kPa	Negligible	–	110.3
17	Specific gravity	0.83	0.091	–

backfire and pre ignition can be eliminated with proper injection timing [14]. The photographic view of the hydrogen injector position on the cylinder head is shown in Fig. 2 and the photographic view of the hydrogen and DEE injector position on the intake manifold is shown in Fig. 3. Fig. 4 shows the cross sectional view of the hydrogen injector.

The distinguished feature of hydrogen-operated engine is that it does not produce major pollutants such as hydrocarbon (HC), carbonmonoxide (CO), sulphur dioxide (SO_2), lead, smoke, particulate matter, ozone and other carcinogenic compounds. This is due to the absence of carbon and sulphur in hydrogen. However hydrogen-operated engines suffer from the drawback of higher NO_x emissions that has an adverse effect on the environment. The formation of NO_x could be due to the presence of nitrogen in the fuel and air and also the availability of oxygen in the air. In the case of hydrogen it is obvious that NO_x is due to the nitrogen present in air [15]. When the combustion temperature is high some portion of nitrogen present in the air reacts with oxygen to form NO_x. One of the ways of reducing NO_x is to operate the hydrogen engine with lean mixtures. Lean mixture results in lower temperature that would slower the chemical reaction, which weakens the kinetics of NO_x formation [16,17]. NO_x emissions increase with increase in equivalence ratio and peaks at an equivalence ratio of 0.9.

The objective of the present work is to use hydrogen (by injection in the intake port) in the following ways and study the performance, combustion and emission characteristics and compare with baseline diesel:

1. Hydrogen in the dual fuel mode with diesel.
2. Hydrogen with diethyl ether as an ignition source.

2. Experimental setup and procedure

The test engine used was a single cylinder water-cooled DI diesel engine, having a rated power of 3.7 kW that runs at a constant speed of 1500 rpm which was modified to work with hydrogen in the dual fuel mode. The specifications of the test engine are given in Table 2. Fig. 5 shows the schematic view of the experimental setup. The flow diagram for hydrogen and DEE is shown in Fig. 6. The fuel injector was controlled by means of an electronic control unit (ECU). An Infrared detector was used to give signals to the ECU for injector opening based on the preset timing and also to control the duration of injection. The injection timing and injection duration can be varied with the help of ECU. Hydrogen flow was taking place based on the preset value. A pressure regulator as well as a digital mass flow controller controlled the flow. Table 3 shows the technical specifications of the hydrogen injector.

In the experimental investigation first the injection timing and injection duration for hydrogen were optimized. For this injection timing from 5° CA before ignition top dead center (BITDC) to 25° CA after ignition top dead center (AITDC) in steps of 5° CA was taken with hydrogen injection duration of 30° CA. 60° CA and 90° CA at a constant hydrogen flow rate of 5.5 liters per minute. The next step in the investigation was optimizing the hydrogen flow. For this hydrogen was varied from 1.5 liters per minute to 9 liters per minute insteps of 1.5 liters per minute for the entire load conditions. The optimized conditions for hydrogen based on the performance, emission and combustion characteristics are as follows.

- Hydrogen injection timing 5° BGTDC.
- Hydrogen injection duration 30° CA.
- Hydrogen flow rate 7.5 liters per minute.

3. Instrumentation

An electrical dynamometer with 10 kW capacity with a current rating of 43.5 A was used as a loading device. A non-dispersive infra red (NDIR) type exhaust gas analyzer (Qrotech make) was used