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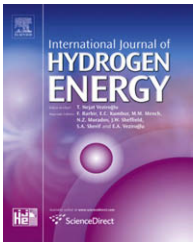

Hydrogen combustion in a compression ignition diesel engine

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ARTICLE INFO

Article history:
Received 28 January 2009
Received in revised form
12 March 2009
Accepted 13 March 2009
Available online 17 April 2009

Keywords:
Hydrogen
HCCI
Diesel
Dual-fuel

ABSTRACT

The investigation presented in this paper concerns both pure hydrogen combustion under HCCI (homogeneous charge compression ignition) conditions and hydrogen–diesel co-combustion in a compression ignition (CI) engine.

The investigation on the simultaneous combustion of hydrogen and diesel fuel was conducted with various hydrogen doses in the range from 0% to 17% with respect to energy percentage. With hydrogen of 17% the hydrogen–diesel–air mixture was stoichiometric and provided favorable conditions for generating combustion knock. Small amounts of hydrogen (about 5%) when added to a diesel engine shorten the diesel ignition lag and, in this way, decrease the rate of pressure rise. It provides better conditions for soft run of the engine and can increase engine durability. The final conclusions concerning hydrogen impact on combustion knock intensity, mass fraction burned (MFB) and heat release rate of the engine are detailed.

1. Introduction

There are several reasons for applying hydrogen as an additional fuel to accompany diesel fuel in the internal combustion (IC) compression ignition (CI) 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 [1]. Better homogeneity of the combustible mixture would provide better conditions for the complete combustion process. Additionally, faster combustion becomes closer to constant volume causing an increase of the indicated efficiency.

Thus, the presented strategy is proposed for improving engine combustion and thermodynamics. There are however drawbacks which can reduce the positive impact of in-cylinder air–diesel enrichment by hydrogen. First, hydrogen, applied as a fuel in the IC engine, provides favorable conditions for generating combustion knock [1–3]. This is especially observed under a high compression ratio (CR) as is typical for a diesel engine. Combustion knock results from the spontaneous ignition of a portion of the end gas mixture in the combustion chamber ahead of the propagating flame. When this abnormal combustion occurs, there is a rapid release of chemical energy in the remaining unburned mixture, causing high local pressures and generating propagating pressure waves with amplitude of several bars across the combustion chamber. These pressure waves are transmitted through the engine structure resulting in the combustion ping heard by observers in close proximity to the engine. The large amplitude pressure waves of the hot combusted gases in the cylinder are the primary reason for mechanical engine failure through increased thermal and mechanical stress.

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doi:10.1016/j.ijhydene.2009.03.020

Nomenclature

γ	Polytropic index
CA	Crank angle
CA ign	Crank angle of ignition
CI	Compression ignition
CNG	Compressed natural gas
COV	Coefficient of variation
CR	Compression ratio
EGR	Exhaust gas recirculation
ER	Equivalence ratio
HCCI	Homogeneous charge compression ignition
HFCP	In-high frequency component of in-cylinder pressure
IC	Internal combustion
IMEP	Indicated mean effective pressure
Lambda	Excess air factor
LHV	Lower heating value
MFB	Mass fraction burned
M_F	Mass of fuel dose burned as function of a crank angle
M_T	Total mass of the fuel dose burned
NTP	Normal temperature and pressure
p	Pressure
PP	Peak pressure
Q_{ch}	Energy released by combustion
SI	Spark ignited
TDC	Top dead center
ATDC	After TDC
BTDC	Before TDC
V	Volume

Furthermore, faster combustion caused by the addition of high amounts of hydrogen, leads to both higher in-cylinder peak pressures and temperatures. Thus, higher amounts of NOx are expected in exhaust gases as a result [3].

Several investigations have been reported on pure hydrogen combustion in CI engines and also on the co-combustion of hydrogen–diesel combustible mixtures. Among other things Saravanan and Nagarajan investigated hydrogen–diesel co-combustion in a diesel engine [4]. They worked with hydrogen doses as enrichment to the diesel fuel. Hydrogen was changed in the range from 10% to 90% by volume. They focused on emission and performance characteristics of the engine as functions of brake load at various hydrogen doses. They concluded that knock can occur if only the hydrogen enrichment equals 50% or more at full load of the engine. Additionally they found lower hydrocarbons (HC), NOx emission as far as exhaust emission was concerned. Summing up they concluded that the optimal hydrogen enrichment with diesel was 30%. Nagalingam et al. conducted research on applying hydrogen to improve combustion of vegetable oil in a diesel engine [14]. In their work, experiments were conducted to evaluate the engine performance while using small quantities of hydrogen in a compression ignition engine primarily fueled with a vegetable oil, namely Jatropha oil. Results indicated an increase in the brake thermal efficiency from 27.3% to a maximum of 29.3% at 7% of hydrogen mass share at the maximum power output. He also noticed significant smoke reduction by 20%. There was also a reduction in HC and CO emissions from 130 to 100 ppm and 0.26%–0.17% (by volume), respectively, at maximum power output. The optimum hydrogen mass share was found to be 7%. With diesel, the brake thermal efficiency was increased from 30.3% to 32% at 5% hydrogen mass share. With hydrogen induction, due to high combustion rates, the NO level was increased from 735 to 875 ppm at full output. He also noticed that ignition delay, peak pressure and the maximum rate of pressure rise were increased in the dual-fuel mode of operation. Combustion duration was reduced due to higher flame speed of hydrogen. Additionally, a higher premixed combustion rate was observed with hydrogen induction. However, in several issues, authors came to contrary conclusions when considering combustion duration, combustion start and the rate of pressure rise. Thus, the problem is investigated and discussed as presented in this paper.

Among others, the study presented by Tsujimura et al. [8] describes the characteristics of the auto-ignition of hydrogen jets in a constant volume vessel. Tsujimura concentrated on the thermodynamic states of the ambient gas, which influenced on auto-ignition delays of hydrogen jets. He concluded that the ambient gas temperature has a significant effect on the auto-ignition delay of the hydrogen jet. At ambient gas temperatures below about 1100 K, the auto-ignition delay linearly depends on the temperature in the Arrhenius coordinates. For temperatures greater than about 1100 K, the temperature dependence of the auto-ignition delay is weak, and the auto-ignition delay reaches a limited value.

Welch and Wallace [5] conducted investigations on hydrogen combustion by its auto-ignition with glow plug assist in a reciprocating engine at a compression ratio of 17. Results indicate that the hydrogen fueled diesel engine can produce higher power than an ordinary diesel engine due to the absence of smoke emissions. Another positive feature is reduced NOx emissions compared to the ordinary diesel engine.

Naber and Siebers successfully investigated the hydrogen auto-ignition process under diesel conditions [12]. The auto-ignition of hydrogen was investigated in a constant volume combustion vessel. The varied parameters were as follows: the injection pressure and temperature, the orifice diameter, and the ambient gas pressure, temperature and composition. They obtained a strong Arrhenius correlation between ignition delay and temperature, so did Tsujimura [8]. The influence of other parameters was not significant. For gas densities typical of top dead center (TDC) in diesel engines, ignition delays of less than 1.0 ms were obtained for gas temperatures greater than 1120 K. They confirmed that compression ignition of hydrogen is possible in a diesel engine at reasonable TDC conditions.

It should be also mentioned, that recently ITM Power signed a contract with Bi-Fuels Limited to accelerate the testing of hydrogen–diesel bi-fuel technology. The contract is the first step in establishing further test data on this technology, and exploring the impact of hydrogen injection into