INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–11

Available online at www.sciencedirect.com

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

An investigation of the combustion process of a heavy-duty dual fuel engine supplemented with natural gas or hydrogen

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ARTICLE INFO

Article history:
Received 24 July 2016
Received in revised form
18 December 2016
Accepted 24 December 2016
Available online xxx

Keywords:
Dual fuel engine
Hydrogen
Natural gas
Combustion process
Peak heat release rate

ABSTRACT

This paper compares the effects of the addition of hydrogen (H_2) or natural gas (NG) on the combustion of a heavy-duty diesel engine converted to operate under gaseous fuel-diesel dual fuel combustion mode. The parameters examined include the start of combustion (SOC), heat release process, peak heat release rate (PHRR), and combustion duration. Significant positive effects on the combustion process were only observed with the addition of a relatively large amount of H_2 or NG. When operated at low load, the addition of a large amount of H_2 or NG reduced the heat release rate (HRR) of the premixed combustion. By comparison, the addition of a relatively large amount of H_2 or NG at high load significantly increased the PHRR of the diffusion combustion. The addition of H_2 has more significant impact on the PHRR than NG. The addition of NG retarded the SOC while the impact of the addition of H_2 on SOC was relatively mild. The significant variation in HRR and its phasing make it necessary to further optimize the combustion of a dual fuel engine. The impact of the addition of gaseous fuel on the brake thermal efficiency was also examined and discussed. The increased thermal efficiency was only observed with the addition of relatively large amount of H_2 or NG at medium to high load. The improved thermal efficiency was due to the decrease in combustion duration and the shifting of the combustion phasing toward the optimal one. The decreased thermal efficiency observed at low load was due to the low combustion efficiency of the gaseous fuel supplemented.

Introduction

The application of alternative gaseous fuels has been recognized as an effective approach to reduce our dependence on imported oil and enhance national energy security. These include traditional natural gas (NG) containing mainly methane (CH_4) [1–5], liquefied petroleum gas (LPG) [6–9], low BTU gases such as landfill gas and digester gas containing CH_4 with the presence of a significant amount of diluents [10,11], synthesis gas [12] produced through gas reforming of solid

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http://dx.doi.org/10.1016/j.ijhydene.2016.12.115
0360-3199/

Please cite this article in press as: Li H, et al., An investigation of the combustion process of a heavy-duty dual fuel engine supplemented with natural gas or hydrogen, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2016.12.115

Nomenclature

CA	Crank angle
CI	Compression Ignition
H_2	Hydrogen
HRR	Heat release rate
MFB	Mass fraction burned
NG	Natural gas
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
PHRR	Peak heat release rate
PM	Particulate matter
PME	Palm methyl ester
SI	Spark ignition
SOC	Start of combustion
TWC	Three-way catalyst converter

fuels such as coal and bio-mass, and hydrogen (H_2) recognized as the most promising onsite carbon-free energy carrier [13–16]. These gaseous fuels can be used in spark ignition (SI) engines [4,17–19] to take advantage of the excellent knock resisting properties of CH_4-containing gaseous fuels [20–22], the fast flame propagation features of H_2-containing gaseous fuels [23–25], and the formation of a homogeneous air-fuel mixture without utilizing a complex fuel injection system. However, the thermal efficiency of SI engines is usually lower than compression ignition (CI) engines due to the lower compression ratio limited by the onset of knock [21,22] and energy loss associated with the throttling of the intake mixture when operated at low load [26]. The operation of SI engines with a lean mixture was reported to significantly improve the thermal efficiency of SI engines operated with gaseous fuels [24,27–29]. However, the ever increasingly stringent emissions regulations make it impractical for lean burn SI gaseous fuel engines to meet oxide of nitrogen (NO_x) emissions standards without utilizing after-treatment systems [30,31]. The integration of spark ignition stoichiometric combustion with a three-way catalyst (TWC) converter and hybridization technologies has been recognized as one feasible path to approach zero emissions [32].

Natural gas and H_2 can be burned as supplemental fuel in CI diesel engines by dual fuel mode with H_2 and NG added into the intake air. The combustion of the pilot diesel directly injected into the cylinder provides the energy source for the ignition of the premixed air-fuel mixture and the control of start of combustion (SOC) [33–37]. Such a dual fuel combustion mode has been highlighted for the following attractive features: (1) higher thermal efficiency than SI engines; (2) flexible fuel capability including the diesel only operation when gaseous fuel is not available; (3) reduced emissions of particulate matter (PM) due to the improved premixed combustion, better mixing of gaseous fuel with air, and the relatively low carbon/hydrogen ratio of the gaseous fuel; and (4) stable combustion as indicated by less cycle-to-cycle variation under normal operating conditions compared to lean burn SI engines.

In past decades, extensive research has been conducted to explore the detailed impact of the addition of H_2 or NG to diesel engines on engine performance (brake power and thermal efficiency), cylinder pressure, combustion process, regulated emissions including PM, NO_x, unburned gaseous fuel added to intake mixture [38], and their combustion efficiency [39,40]. The diesel engines examined included small single cylinder diesel engines [33,41,42], light-duty, multi-cylinder diesel engines [43–45], and heavy-duty diesel engines [39,40,46,47]. For example, the recent research on NO_x emissions from dual fuel engines reported a significant impact of the addition of H_2 or NG in increasing the emissions of NO_2 [44,45,48] especially with the addition of a small amount of H_2 or NG at low load [49,50]. There is increasing interest in comparing the impact of the pilot and supplemental fuels on the combustion and emissions characterization of dual fuel engines [45,51]. The pilot diesel explored included ultra-low sulfur diesel (ULSD), biodiesel noted as palm methyl ester (PME), and B50, a mixture of 50% ULSD and 50% PME. For example, Polk et al. [52,53], investigated the impact of the addition of NG and propane on the combustion characteristics of a 1.9 L Volkswagen turbocharged direct injection diesel engine. The impact of the addition of propane and NG on the fuel conversion efficiency, heat release process, ignition delay, and combustion duration were examined under constant load and constant pilot quantity, respectively. Imran et al. [54], compared the impact of pilot diesel fuel quantity and fuel type on the combustion characteristics (ignition delay, in-cylinder pressure, and rate of energy release) and emissions (specific NOx and hydrocarbons). Dual fuel operation was shown to have longer ignition delay than diesel fuel only operation observed at similar operating conditions.

This research addressed the effects of the addition of H_2 or NG on the combustion process of a heavy-duty diesel engine converted to operate under gaseous fuel-diesel dual fuel combustion mode. The effect of H_2 addition on the combustion of a H_2-diesel dual fuel engine was investigated at 10–70% load with the addition of up to 6.5% vol. H_2 into the intake air. The impact of the addition of up to 5% vol. NG on the combustion process was explored at 15–100% load. The combustion parameters examined included the SOC, peak heat release rate (PHRR), combustion duration, and brake thermal efficiency.

Experimental set-up and combustion analysis

Test engine and dynamometer

The engine used was a 1999 Cummins ISM370 diesel engine with a rating of 370 horsepower (hp). This turbocharged, 6-cylinder diesel engine model was widely used to power Class-8 heavy-duty trucks. Detailed specifications for this engine can be found in Table 1. The test engine was coupled to a 550 hp General Electric (GE) Direct Current (DC) dynamometer used to absorb the engine load and control engine speed. Torque was controlled by supplying an electronic throttle signal to the engine and controlling the amount of diesel fuel injected.

This engine was converted to operate under NG-diesel and H_2-diesel dual fuel combustion modes, respectively, with the gaseous fuel mixed into the intake air. No experiment was conducted for the simultaneous addition of H_2 and NG. With

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