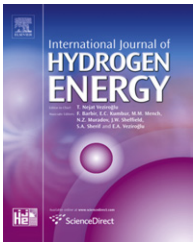
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 4153–4162

Available online at www.sciencedirect.com

SciVerse ScienceDirect

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



# Effect of hydrogen addition to intake air on combustion noise from a diesel engine

*Tuan Anh Nguyen, Masato Mikami*[*]

*Department of Mechanical Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi 755-8611, Japan*

ARTICLE INFO

*Article history:*
Received 18 September 2012
Received in revised form
8 January 2013
Accepted 12 January 2013
Available online 12 February 2013

*Keywords:*
Diesel engine
Combustion noise
Hydrogen
Noise-generation model
Wavelet transformation

ABSTRACT

This study investigates the characteristics of combustion noise from a diesel engine with hydrogen added to intake air. The engine noise with hydrogen addition of 10 vol% to the intake air was lower than that with diesel fuel alone at late diesel-fuel injection timings. A transient combustion-noise-generation model was introduced to discuss noise characteristics based on energy conversion from combustion impact to noise via structure vibration. The results show that the maximum combustion impact energy had a predominant effect on the maximum engine noise power for each cycle. Therefore, the combustion noise largely contributed to the total engine noise in an early stage of the expansion stroke. The dependences of engine noise on the diesel-fuel injection timing for different hydrogen fractions are discussed considering the characteristics of maximum combustion impact energy for each frequency.

## 1. Introduction

Internal combustion engines have become an indispensable and integral part of our daily life. However, diesel engines produce knocking such as impulsive and irregular noises, which are unpleasant [1–3]. From a commercial viewpoint, this may be the main drawback of diesel engines since sound quality has become an important value. Combustion noise may be changed by using another type of fuel. Hydrogen is one of the most promising fuels because it has clean burning characteristics and better performance compared to other fuels. However, hydrogen cannot be used as the only fuel in a compression ignition engine, since the compression temperature is not sufficient to initiate combustion due to its higher self-ignition temperature [4]. Hence an ignition source is required while using it in a compression ignition engine. The simplest method of using hydrogen in a compression ignition engine is to run in the dual fuel mode with diesel fuel that can act as an ignition source for hydrogen. Several investigations have reported on the co-combustion of hydrogen-diesel combustible mixtures [5–7]. Saravanan and Nagarajan investigated hydrogen-diesel co-combustion in a diesel engine [5]. They concluded that knocking occurs only if the hydrogen enrichment equals 50% or more at full load of the engine. Senthil Kumar et al. [6] conducted research on applying hydrogen to improve the combustion of vegetable oil in a diesel engine. They noticed that ignition delay, peak pressure and the maximum rate of pressure rise were increased in the dual-fuel mode operation. Miyamoto et al. [7] researched the performance and emission characteristics of the diesel engine with hydrogen added to the intake air at late diesel-fuel injection timings. They also investigated the effect of diesel-fuel injection timing on the maximum rate of in-cylinder pressure rise for a diesel engine with hydrogen addition to the intake air. The result showed, however, that in the case of a diesel-fuel injection later than TDC with 10 vol%

---

[*] *Corresponding author*. Tel.: +81 836 85 9112.
E-mail address: mmikami@yamaguchi-u.ac.jp (M. Mikami).

0360-3199/$ – see front matter Copyright © 2013, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijhydene.2013.01.082

hydrogen added to the intake air, the maximum rate of in-cylinder pressure rise was lower than that without hydrogen addition at high loads for a naturally aspirated diesel engine. The maximum rate of in-cylinder pressure rise has often been used as an indicator to evaluate the strength of combustion noise source. Therefore, Miyamoto et al. [7] suggests that the hydrogen addition to the intake air could reduce the combustion noise in the case of late diesel-fuel injection. This paper further studies the combustion noise generation with hydrogen addition.

In order to reduce the engine noise effectively, it is necessary to clarify the generation mechanism of vibration and noise in the structure. Haddad et al. [8] estimated the radiation efficiency of several diesel engine components in the reverberation room. Chiatti et al. [9] made the connection between the cylinder pressure signal and the rate of pressure rise by analyzing the cylinder pressure signal. Badaoui et al. [10] and Pruvost et al. [11] separated combustion noise and mechanical noise using spectrofilter. If the in-cylinder signal is known, the combustion and mechanical noises can be separated with a tool known as spectrofilter, which extracts engine noise components which are correlated with in-cylinder pressure, thus providing an estimate of the combustion noise. The generation of noise was studied by engine noise model where the in-cylinder pressure, response of the vibroacoustic transfer function, combustion noise, mechanical noise and engine noise were considered [11]. Kojima et al. [12–15] analyzed combustion noise from a single explosion engine excited by a single combustion impact with a steady-state noise-generation model, in which the combustion-noise power was proportional to the combustion-impact power. Komori et al. [16] experimentally investigated the transient relationship between combustion impact and noise. It was shown that there was a time delay between the combustion-impact power peak and the combustion-noise power peak. In order to investigate the transient characteristics of the combustion noise, Miura et al. [17] proposed a transient noise-generation model for the single combustion impact in a single explosion single-cylinder diesel engine, which can explain the time delay by considering the accumulation process of combustion impact power in the engine structure. Some researches have also applied the transient combustion noise-generation model but mostly for single explosion engines excited by a single combustion impact [17–19]. Sugimoto et al. [18] and Sera et al. [19] investigated noise-generation characteristics in a single explosion four-cylinder engine for different noise-radiation parts and different excited cylinders. The engine noise characteristics of a running engine are different from those of a single explosion engine. A single explosion engine generates only combustion noise, while the noise from a running engine contains combustion noise, combustion-induced mechanical noise and mechanical noise. We recently applied the model to noise analysis of a running engine [20]. The results show that combustion noise largely contributed to the total engine noise in the early stage of the expansion stroke. Maximum combustion impact energy had a predominant effect on maximum combustion noise power and therefore on maximum engine noise power for each cycle. The combustion noise power exponentially decayed with time. The duration of combustion noise depends mainly on the maximum combustion noise power, which is controlled by the maximum combustion impact energy and transmission-radiation rate.

The main objective of this study is to investigate the effect of hydrogen addition to the intake air on combustion noise generation in a diesel engine. We discuss engine noise characteristics based on the transient combustion noise generation model.

## 2. Experimental apparatus and method

The engine used for this experiment is a naturally aspirated single-cylinder water-cooled four-stroke-cycle diesel engine. Diesel fuel is injected directly into the combustion chamber with common-rail fuel-injection equipment. The blowby was re-circulated to the intake port from the engine head cover through an oil catch tank. Table 1 lists the engine specifications. Hydrogen was injected intermittently into the intake air.

Experiments were conducted with an engine speed of 1500 ± 30 rpm, diesel-fuel injection pressure of 150 MPa, and a cooling water temperature of 363 ± 3 K. The start of energizing the injector (SOE) was varied from −6 deg. ATDC to 1 deg. ATDC while the start of diesel-fuel injection (SOI) (hereafter, “diesel-fuel injection timing,” IT) was 4°degrees later than SOE. The in-cylinder pressure was measured by a pressure pick-up (6052B, KISTLER).

Hydrogen was injected intermittently into the intake air by a gas injector (Keihin; KN-3) controlled by a driver unit. The hydrogen supply system apparatus is illustrated in Miyamoto et al. [7]. The start of hydrogen injection was 21 deg. ATDC in the intake stroke. The hydrogen flow rate was controlled by a mass-flow controller (SEC-60, HORIBA STEC). Hydrogen pressure supplied before the hydrogen flow controller was maintained constantly at 400 kPa by using a pressure controller (UR-750, HORIBA STEC). 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 [21]. The hydrogen volume fraction in the intake mixture was 0 and 10 vol%. The available heat produced by diesel fuel and hydrogen per cycle Q was set at 1 ± 0.05 kJ/cycle. When the hydrogen fraction was increased, the diesel-fuel injection duration was decreased manually to maintain Q at the constant value.

The sound pressure was measured by two microphones (RION NA-20) placed 0.1 m away from the engine side on the

**Table 1 – Engine specifications.**

| Engine type | Single cylinder four stroke cycle DI diesel |
|---|---|
| Bore × stroke | 85 mm × 97.1 mm |
| Displacement | 551 $cm^3$ |
| Compression ratio | 16.7 |
| Charged method | Naturally aspirated |
| Piston cavity shape | Re-entrant type |
| Diesel fuel injection system | Common rail |
| Nozzle | Minisac hole nozzle |
| Hole diameter × number of fuel injector | Φ 0.139 mm × 6 |