

The Performance of Multi-Cylinder Hydrogen / Diesel Dual Fuel Engine

Yasumasa Suzuki and Taku Tsujimura
National Institute of AIST

Takuro Mita
Isuzu Advanced Engineering Center, Ltd.

ABSTRACT

Hydrogen can be produced by electrolyzation with renewable electricity and the combustion products of hydrogen mixture include no CO, CO₂ and hydrocarbons. In this study, engine performance with hydrogen / diesel dual fuel (hydrogen DDF) operation in a multi-cylinder diesel engine is investigated due to clarify advantages and disadvantages of hydrogen DDF operation. Hydrogen DDF operation under several brake power conditions are evaluated by changing a rate of hydrogen to total input energy (H₂ rate). As H₂ rate is increased, an amount of diesel fuel is decreased to keep a given torque constant.

When the hydrogen DDF engine is operated with EGR, Exhaust gas components including carbon are improved or suppressed to same level as conventional diesel combustion. In addition, brake thermal efficiency is improved to 40% by increase in H₂ rate that advances combustion phasing under higher power condition. On the other hand, NO_x emission is much higher than one of conventional diesel engine. Additionally, hydrogen DDF engine operation at higher engine load with high H₂ rate is limited by a variability of in-cylinder pressure among each cylinder. Mixing hydrogen and intake air will be encouraged to introduce homogeneous mixture to each cylinder.

Following the result of increase in NO_x emission under hydrogen DDF operation, we evaluate the effects of EGR (Exhaust Gas Recirculation) on the performance. Under 40kW power and H₂ rate 55% condition. When EGR rate is around 20 %, the emission level of hydrogen DDF engine is at the same level as a mass-production diesel engine for heavy duty vehicles. However, there're still problems on soot emission and cylinder-to-cylinder pressure variation.

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INTRODUCTION

Hydrogen as a fuel of next generation vehicles and engines has been focused because hydrogen can be produced with using renewable energy like solar or wind energy. There is possibility that can reduce exhaust gas components derived from carbon atom included in conventional fossil fuels. Fuel cell is considered another power source of vehicle that is fueled with hydrogen. However, hydrogen engines have possibility that achieves the early introduction of hydrogen and renewable energy because it has two advantages over fuel cell. One is lower cost that is derived from availability of existing engine components and technology for combustion control. The other advantage is required purity of hydrogen gas as fuel. Internal combustion engine can use any purity of hydrogen in comparison with a polymer electrolyte fuel cell (PEFC) which needs highly-pure hydrogen. On the other hand, hydrogen has lower energy density in volume and poorer portability than hydrocarbon fuel. However, the utilization of organic chemical hydride such as methylcyclohexane (MCH) and dehydrogenation catalyst that recovery exhaust loss can solve this issue [1].

Many researchers report about the utilization of hydrogen with internal combustion engine [2] [3]. In this study, we focus on the utilization of hydrogen and diesel fuel in a hydrogen diesel dual fuel (DDF) engine. A hydrogen DDF engine is based on diesel engine and has higher compression ratio to be able to achieve better thermal efficiency than gasoline fueled spark ignition engine. Under DDF operation, gas fuel mixture is ignited by a small amount diesel fuel that is injected directly into combustion chamber.

For example, Tomita et al. study the performance of hydrogen DDF operation engine with a single cylinder four-stroke diesel engine under wide range of H₂ rate and diesel fuel injection timing [4]. They reported the performance of exhaust gas emission from hydrogen DDF engine under high H₂ rate condition and the reduction method of smoke and NO_x emissions. They achieved almost zero level of NO_x and soot emissions with significant advancement of diesel fuel injection timing. Miyamoto et al. study about the effects of EGR on performances of hydrogen DDF engine under high load and low hydrogen flow rate conditions with a single cylinder four-stroke diesel engine. They reported that smoke and NO_x emissions are reduced simultaneously [5]. In other words, SAE International is a leading

cylinder diesel engine that has 553 cc displacement and research about the effects of port injection timing and duration under constant hydrogen gas flow rate [6] or pressure [7] condition on performance of hydrogen DDF operation. Additionally, they study the effects of the hydrogen supplying methods including carburetor and positions of a hydrogen injector on intake air path and evaluate the performance [8].

Although many previous studies of hydrogen DDF operation with a single cylinder test engine have been conducted, The previous researches about multi-cylinder hydrogen DDF engine is not so much. McWilliams et al study about the effects of hydrogen concentration and EGR rate on the performance of the 2.0 liter four cylinder hydrogen DDF engine that is equipped with a turbocharger and cooled-EGR (Exhaust Gas Recirculation) system [9]. In their study, the engine was operated in natural aspiration condition to negate the effects of intake gas pressure variation. They reported that advantages of using hydrogen are a reduction in unburned gas component in exhaust gas and increase in thermal efficiency. These tendencies are observed under the condition EGR is introduced. On the other hand, they conclude that the disadvantage of hydrogen DDF operation is the increase of NO_x emissions and the developments of injection and boost strategies are required. We apply hydrogen DDF operation to a commercially available multi-cylinder diesel engine that is equipped variable geometry turbocharger (VGT), intercooler and EGR system. In addition, we consider issues of present multi-cylinder hydrogen DDF engine.

EXPERIMENTAL APPARATUS

Figure 1 shows an overview of the experimental apparatus. We modified 4-cycle water-cooled Inline-4 cylinders diesel engine for hydrogen DDF operation. The specifications of test engine and diesel fuel injector are shown in Table 1. Intake throttle valve, EGR valve and VGT are equipped on this base engine. Overview of Hydrogen supply system is shown in Figure 2. Hydrogen is supplied from compressed gas cylinders. After the pressure reduction and measurement of flow rate, hydrogen is injected into a dedicated gas fuel manifold by gas injectors. We used four injectors to supply enough amount of hydrogen gas for DDF operation. After the injection, hydrogen gas is introduced through an inlet that is located at downstream of the intake throttle valve into fresh air flow. In this study, flow rate of hydrogen is controlled by frequency and period of hydrogen injection valve opening/closing, and injection pressure of hydrogen is adjusted to 0.4 MPa (gage).

Pressure sensors (KISTLER 6056A) are installed to measure each in-cylinder pressure, and amplified signals (KISTLER 5064C) are synchronized with crank angle signal and recorded by a combustion analyzer (ONO SOKKI DS3000). Pressure signals of 100 combustion events acquired in this study, are averaged to analyze combustion performance. Fresh air mass flow is measured by a laminar flow meter (Tsukasa sokken LFE-350B) and a laminar flow calculator (Tsukasa sokken LFC-200). In addition, control and measurement of engine speed and torque are conducted by an electrical dynamometer (HORIBA DYNAS3 ULI340).

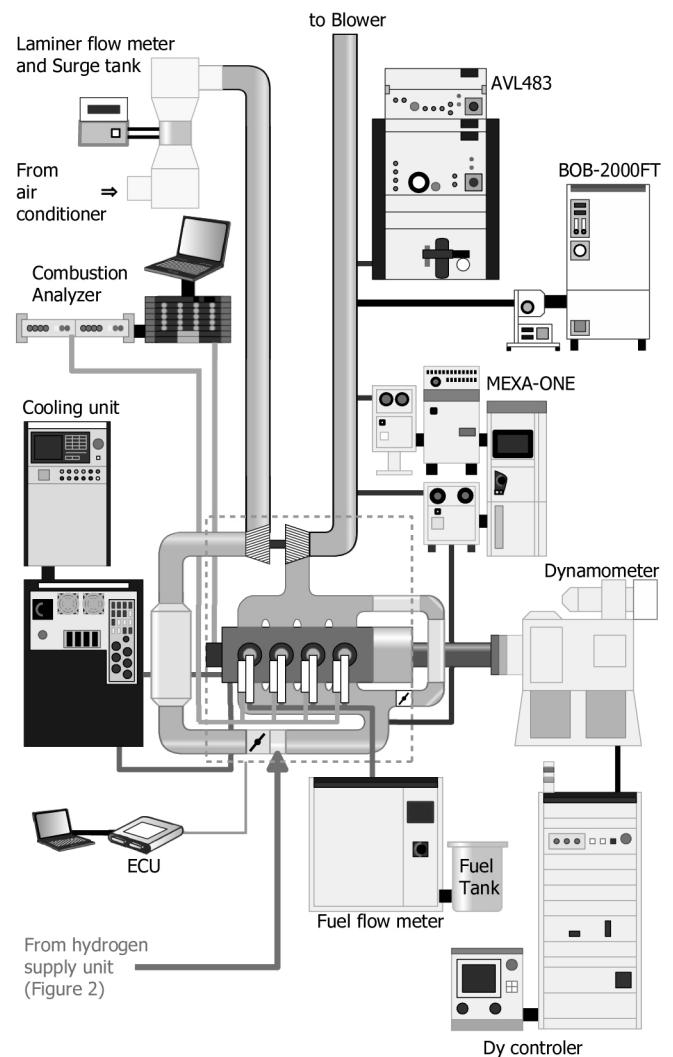


Figure 1. Overview of experimental apparatus

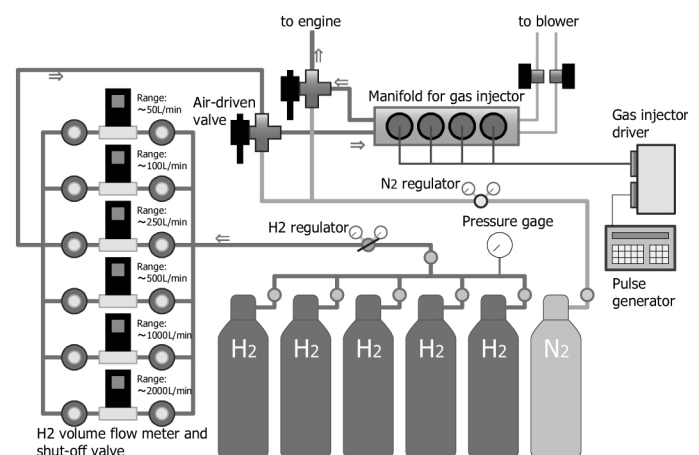


Figure 2. Overview of hydrogen supply unit

We measured components of exhaust gas with three gas analyzers: HORIBA MEXA-ONE, BEST SOKKI BOB-2000FT and AVL micro soot sensor 483. Emission performance is calculated from CO, CO₂, THC and NO_x concentration of exhaust gas and CO₂ concentration

of intake gas measured by MEXA-ONE. A Fourier transform infrared spectroscopy (FTIR) analyzer (BOB-2000FT) is installed to analyze a detailed components of exhaust gas. The FTIR system is coupled with H₂ analyzer to compensate H₂ effect on FTIR measured data, because FTIR signals are enhanced in proportion to hydrogen concentration. Soot concentration is measured by AVL 483 that has measuring unit based on photoacoustic measurement method.

Table 1. Specifications of diesel engine used for this study

Engine type	Inline-4
Displaced volume L	5.2
Bore x Stroke mm	115 x 125
Compression ratio	17.5:1
Fuel	Hydrogen (port injection) Diesel fuel(direct injection)

EXPERIMENTAL RESULTS AND DISCUSSION

Performance of Multi-Cylinder Hydrogen DDF Engine

H₂ rate was changed as experimental parameter and it was conducted to evaluate the performance, advantage and disadvantage of hydrogen DDF operation. In this study, we defined H₂ rate as a ratio of hydrogen to input energy. We choose three power conditions: 20, 40 and 60 kW at a constant engine speed of 1500 rpm. We adjusted diesel fuel injection quantity in proportion to hydrogen flow rate to keep torque and power constant. In addition, diesel fuel injection timing and pressure, position of VGT and intake throttle valve were kept constant with EGR valve closed because we had to observe and understand basic performance and combustion behavior of multi-cylinder hydrogen DDF engine.

20kW Power Condition

It was conducted to compare the performance of hydrogen DDF operation and conventional diesel combustion under 20kW power conditions. Experimental conditions are shown in Table 2. In these experiments, a minimum diesel fuel quantity was the quantity that torque shows about 0 Nm under conventional diesel combustion. Under 20 kW power condition, a maximum H₂ rate was limited by this minimum diesel fuel quantity.

The effects of H₂ rate on combustion behavior under 20 kW power condition are indicated in Figure 3. Rate of heat release (R.H.R.) histories under low H₂ rate condition have two peaks caused by double injection of diesel fuel, and these behaviors are similar to the results of conventional diesel combustion. On the other hand, R.H.R. history under high H₂ rate condition doesn't show such twin peaks, and heat release rate continuously increased toward the time at main injection start. This behavior is assumed to be due to flame propagation through hydrogen mixture. However, diffusive combustion of diesel fuel and hydrogen mixture is dominant under 20 kW power condition because equivalence ratio of hydrogen mixture is low, and R.H.R. in later part of combustion show similar behavior independently of H₂ rate.

The effects of hydrogen rate on thermal efficiency, the maximum in-cylinder pressure rise rate, CA50 (the crank angle when combustion ratio reaches 50%) and COV coefficient of variance (COV) of indicated mean effective pressure (IMEP) is shown in Figure 4. COV of IMEP is calculated by following equation:

$$S_{IMEP} = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100 \quad (1)$$

S_{IMEP} COV of IMEP
 σ_{IMEP} Standard deviation of IMEP
 μ_{IMEP} Exhaust gas (Subscript)

Table 2. Experimental conditions of H₂ DDF operation: 1500rpm, 20kW (parameter: H₂ rate)

Operation		Base diesel only	H ₂ DDF
Engine speed rpm		1500	
Power		20	
IMEP MPa		0.42	
EGR rate %		18	0
H ₂ rate %		0	0 – 69
H ₂ volume flow rate NL/min		0	0 - 290
Intake O ₂ concentration %		19.6	20.8 – 19.2
Equivalence ratio	H ₂	0	0 – 0.19
	Diesel	0.28	0.28 – 0.10
	Overall	0.28	0.28 – 0.29
Diesel fuel injection	Pressure MPa	90	
	Pattern	Double injection (pre + main)	
	Timing deg.ATDC	pre: 0 main: 12	
	Quantity mm ³ /st	pre: 3 main: 41	pre: 3 main: 30– 13

Under high H₂ rate condition, combustion phase and CA50 is advanced by flame propagation through hydrogen mixture. However, thermal efficiency of hydrogen DDF operation gets worse than that of conventional diesel combustion.

The effects of H₂ rate on intake oxygen mass flow rate, exhaust gas emission, the proportion of unburned components on injected fuel and total combustion efficiency under each H₂ rate condition are indicated in Figure 5 and Figure 6. In this study, it is believed that CO, THC, and soot is formed from diesel fuel and the ratio of each unburned component is calculated by following equations:

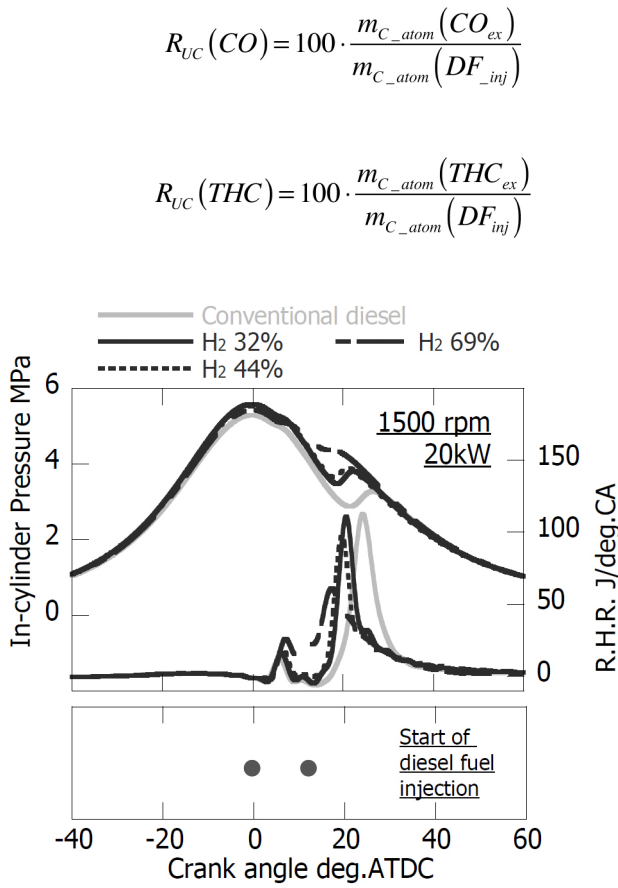


Figure 3. Combustion behavior under hydrogen DDF operation and conventional diesel combustion (Engine speed: 1500rpm, Power: 20kW, parameter: H2 rate

$$R_{UC}(Soot) = 100 \cdot \frac{m_{C_atom}(Soot_{ex})}{m_{C_atom}(DF_{inj})} \quad (4)$$

Similarly, Unburned hydrogen ratio is calculated by following equation:

$$R_{UC}(H_2) = 100 \cdot \frac{m_{H_atom}(H_{2_ex})}{m_{H_atom}(H_{2_im})} \quad (5)$$

$R_{UC}(i)$ Proportion of unburned component i on injected fuel

i : CO, THC, Soot or H₂

$m_{j_atom}(k)$ Mass of atom j contained in species k

j : C or H

k : CO, THC, Diesel Fuel (DF) or H₂

ex Exhaust gas (Subscript)

inj Injected fuel (Subscript)

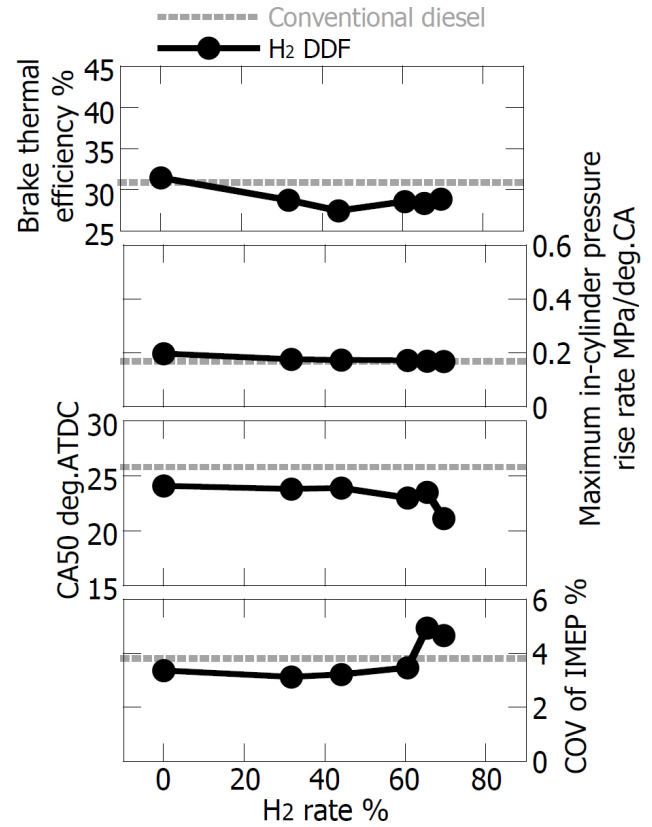


Figure 4. Effects of H2 rate on brake thermal efficiency, maximum in-cylinder pressure rising rate, CA50 and COV of multi-cylinder hydrogen DDF engine (Engine speed: 1500 rpm, Power: 20 kW)

im Intake manifold (Subscript)

On the other hand, total combustion efficiency is defined in the following equation:

$$\eta_{comb} = \frac{1}{\dot{Q}_{diesel} + \dot{Q}_{H_2}} \times \left[\dot{Q}_{diesel} \{100 - R_{UC}(CO) - R_{UC}(THC) - R_{UC}(Soot)\} + \dot{Q}_{H_2} \{100 - R_{UC}(H_2)\} \right] \quad (6)$$

An increase in H₂ rate, which is decrease of diesel fuel injection quantity, improves CO₂, CO and THC emissions. On the other hand, H₂ emission and the proportion of unburned hydrogen on fuel introduced into engine are very high and it is suggested that the decrease of brake thermal efficiency and total combustion efficiency under 20kW power and hydrogen DDF operation condition is due to the incomplete combustion of hydrogen mixture.