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Cylinder Pressure Variations of the Fumigated Hydrogen-Diesel Dual Fuel Combustion

[1]Boonthum Wongchai, [1]Porranat Visuwan and [2]Sathaporn Chuepeng

[1]Department of Mechanical Engineering, Faculty of Engineering,
Kasetsart University, 50 Ngamwongwan Road, Bangkok 10900, Thailand
[2]Department of Mechanical Engineering, Faculty of Engineering at Si Racha,
Kasetsart University, 199 Sukhumvit Road, Chonburi, 20230, Thailand

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ABSTRACT

Cylinder pressure is one of the main parameters of diesel engine combustion affecting several changes in exhaust gas emission composition and amount as well as engine useful power, specifically when alternative fuels are used. One among other alternative fuels for diesel engine is hydrogen that can be used as fumigated reagent with air prior to intake to engine in order to substitute the main fossil diesel. In this study, experimental investigation was accomplished using a single cylinder diesel engine for agriculture running on different ratios of hydrogen-to-diesel. Cylinder pressure traces corresponding to the crank angle positions were indicated and analyzed for maximum cylinder pressure and their coefficient of variation. The regression analysis is used to find the correlations between hydrogen percentage and the maximum cylinder pressure as well as its coefficient of variation. When higher hydrogen percentages were added, the combustion shifted toward later crank angles with the maximum cylinder pressure decreased and eminent effects at higher load and speed. The plots of hydrogen percentage against the coefficient of variation of the maximum cylinder pressure (COV_{Pmax}) show the increase in variation of maximum cylinder pressure when the hydrogen percentage increased for all conditions tested. Gaseous hydrogen fumigated prior to intake to the engine reduced maximum cylinder pressure from the combustion while increasing the values of COV_{Pmax}. The maximum pressure-hydrogen percentage correlations and the COV_{Pmax}-hydrogen percentage correlations show better curve fittings by second order (n = 2) correlation compared to the first order (n = 1) correlation for all the test conditions.

Keywords: Cylinder Pressure, Hydrogen, Maximum Pressure, Hydrogen-Diesel Dual Fuel, Diesel Engine

1. INTRODUCTION

Today's energy consumption is a major global problem especially fossil fuel e.g., coal, natural gas, gasoline oil and diesel oil, used in our everyday life. Alternative fuels have being used to substitute or even replaced them as fossil fuels are mostly nonrenewable energy. Diesel is one of the important fuels in transportation, industry, power plants and so on. Some alternative fuels are used to mix with diesel as the dual fuel for decreasing diesel consumption (Banapurmatha *et al*., 2008; Soberanis and Fernandez, 2010; Lata *et al*., 2011; Selim, 2011).

Among other alternative fuel, hydrogen is a promising fuel which can be produced from various sources such as water (Korakianitis *et al*., 2010; Miyamoto *et al*., 2011; Shin *et al*., 2011; Wu and Wu, 2012). However, hydrogen addition in diesel engine affects engine performance and emissions (Jarungthammachote *et al*., 2012) as hydrogen-diesel dual fuel exhibits different combustion characteristics. Cylinder pressure in the combustion chamber is a main

Corresponding Author: Boonthum Wongchai, Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, 50 Ngamwongwan Road, Bangkok 10900, Thailand

parameter affecting other combustion related consequences such as the engine performance that effect by hydrogen quantity (Sena *et al*., 2008; Lujan *et al*., 2010; Perez and Boehman, 2010; Asad *et al*., 2011; Antonopoulos and Hountalas, 2012).

From the aforementioned point of view, there are yet some aspects of using fumigated hydrogen as dual fuel with fossil diesel in terms of cylinder pressure variation. Therefore, the main aim of this study is to analyze the combustion generated pressure of hydrogen-diesel duel fuel mode.

2. MATERIALS AND METHODS

2.1. Test Engine

In the present study, a single cylinder Kubota RT100 direct injection diesel engine with specification listed in **Table 1** is used. **Figure 1** shows its setup on the engine test bed.

2.2. Measuring System Layout

The schematic diagram of the experiment is shown in **Fig. 2**.

Table 1. Test engine specification

Maker	Kubota
Model	RT100 DI
Number of cylinder	1
Bore × Stroke	88×90 mm
Displaced volume	547 cm^3
Compression ratio	18:1
Maximum power	7.4 kW @ 2,400 rpm
Maximum torque	3.4 kg·m @ 1,600 rpm

Fig. 1. The setup of the engine test bed

2.3. Combustion Analysis System

Cylinder pressure traces were acquired by Kistler 6052C piezo pressure transducers which are suited to applications where the bore is smaller than 5 mm (this case). Key technical data of the transducer are listed in **Table 2**. An amplifier Dewetron DEWE-30-4 3066A03 was employed for conditioning the charge signals from piezo-electric transducers.

Crankshaft position was determined by an incremental shaft encoder model BDK 16.05A.0360-5-4 from Baumer Electric which was mounted in alignment with the engine crank shaft at the front of the engine. The conditioned cylinder pressure signals from both channels of the charge amplifier corresponding to the engine crank shaft position signal from the shaft encoder signal were simultaneously collected using DEWESoft software.

The Crank Angle (CA) at Top Dead Center (TDC) is detected before measuring the cylinder pressure and the pressure is measured every 1 degree of CA for the time duration of 100 revolutions of the engine.

2.4. Hydrogen Dosing Module

Hydrogen gas pressure is controlled at 1 bar by the valve and hydrogen flow across the flow meter before flow into the cylinder. Hydrogen flow rates are 0, 5, 10, 15 and 20 lpm.

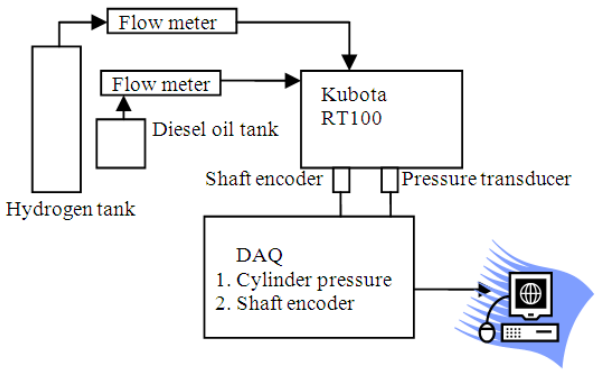

Fig. 2. Schematic diagram of the experimental setup

Table 2. Cylinder pressure transducer specification

Measuring range (FSO)	0-250 bar
Sensitivity	19.90 pC/bar
Linearity	±0.4% FSO
Natural frequency	160 kHz

Table 3. Test conditions

Test condition	Engine revolution (rpm)	Engine torque (%)
Exp. 1	2,000	25
Exp. 2	2,000	50
Exp. 3	1,600	15
Exp. 4	1,600	25

Hydrogen percentage ($\%H_2$) is percentage of mass fraction between hydrogen consumption and diesel consumption using Eq. 1:

$$\%H_2 = \frac{m_H}{m_f} \times 100 \quad (1)$$

Where:

m_H = Hydrogen mass flow rate ($kg \cdot s^{-1}$)
m_f = Diesel oil mass flow rate ($kg \cdot s^{-1}$)

2.5. The Calculation of Coefficient of Variation

The coefficient of variation of the maximum pressure ($COV_{P_{max}}$) is defined as in Eq. 2:

$$COV_{P_{max}} = \frac{S.D._{P_{max}}}{\overline{X}_{P_{max}}} \quad (2)$$

where, $S.D._{Pmax}$ is the standard deviation of the maximum pressure at each test conditions listed in **Table 3**. The $\overline{X}_{P_{max}}$ denotes the average of the maximum cylinder pressure at each test condition.

3. RESULTS

3.1. Maximum Cylinder Pressure

Cylinder pressure characteristics corresponding to the Crank Angle in Degree (CAD) at around the end of compression stroke and the beginning of the expansion stroke are show in **Fig. 3** for different hydrogen percentages at 2,000 rpm speed and 25% torque (Exp. 1). **Fig. 4** shows the magnification of the maximum pressure illustrated in **Fig. 3** and numerated in **Table 4**.

3.2. The Correlation of Maximum Cylinder Pressure and Hydrogen-To-Diesel Ratio

The hydrogen percentage is plotted against the maximum cylinder pressure for all the test conditions. The first order and second order correlations between maximum cylinder pressure (P_{max}) and hydrogen-to-diesel ratio are shown in **Fig. 5 and 6**, respectively.

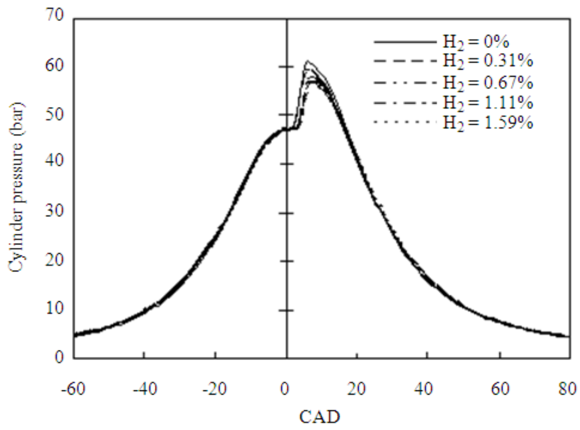

Fig. 3. Average cylinder pressure at various hydrogen-to-diesel ratios for the test condition Exp. 1

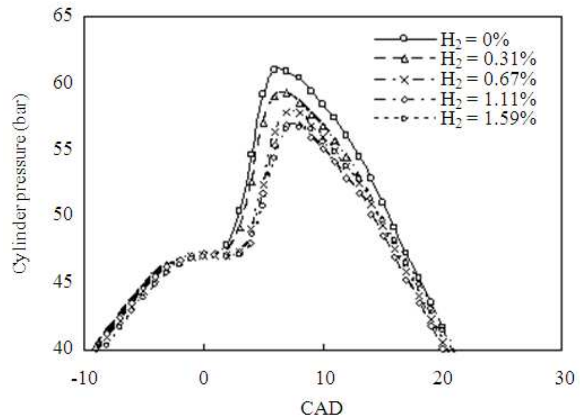

Fig. 4. The magnification of maximum cylinder pressure for the test condition Exp. 1

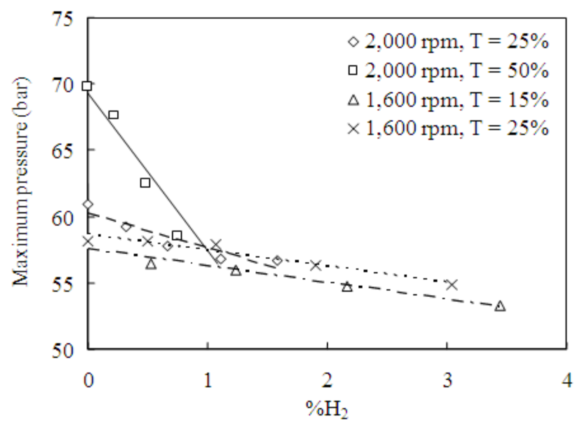

Fig. 5. The first order correlation between maximum cylinder pressure (P_{max}) and hydrogen-to-diesel ratio

Table 4. Maximum cylinder pressure (P_{max})

	Exp. 1		Exp. 2		Exp. 3		Exp. 4	
H_2 lpm	$\%H_2$	P_{max} bar	$\%H_2$	P_{max} bar	$\%H_2$	P_{max} bar	$\%H_2$	P_{max} bar
0	0.00	60.94	0.00	69.79	0.00	57.99	0.00	58.14
5	0.31	59.22	0.22	67.54	0.52	56.43	0.49	58.12
10	0.67	57.82	0.48	62.54	1.24	55.97	1.06	57.83
15	1.11	56.79	0.75	58.47	2.17	54.73	1.90	56.32
20	1.59	56.71	1.08	58.01	3.45	53.25	3.04	54.80

Table 5. Correlation constants for the maximum cylinder pressure in Eq. 3 and 4

Order	Condition	a	b	c	R^2
1	Exp.1	-2.6515	60.2480		0.8712
	Exp.2	-11.9040	69.3100		0.9242
	Exp.3	-1.2816	57.5650		0.9690
	Exp.4	-1.1787	58.5700		0.9401
2	Exp.1	2.2068	-6.1711	60.940	1.0000
	Exp.2	8.0564	-20.6670	70.511	0.9689
	Exp.3	0.1138	-1.6770	57.730	0.9767
	Exp.4	-0.2641	-0.3660	58.272	0.9776

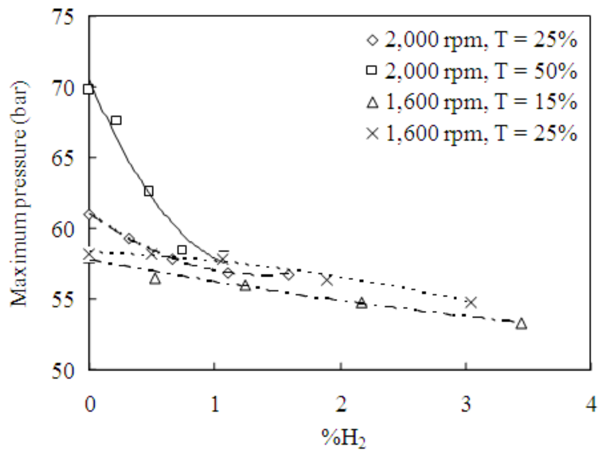

Fig. 6. The second order correlation between maximum cylinder pressure (P_{max}) and hydrogen-to-diesel ratio

The relationships between maximum cylinder pressure (P_{max}) and hydrogen percentage in first (n = 1) and second (n = 2) orders generate the correlation constants for regression analysis numerated in **Table 5** with R^2 in the form of Eq. 3:

$$(n = 1)\ P_{max} = a(\%H_2) + b \quad (3)$$

and in the form of Eq. 4:

$$(n = 2)\ P_{max} = a(\%H_2)^2 + b(\%H_2) + c \quad (4)$$

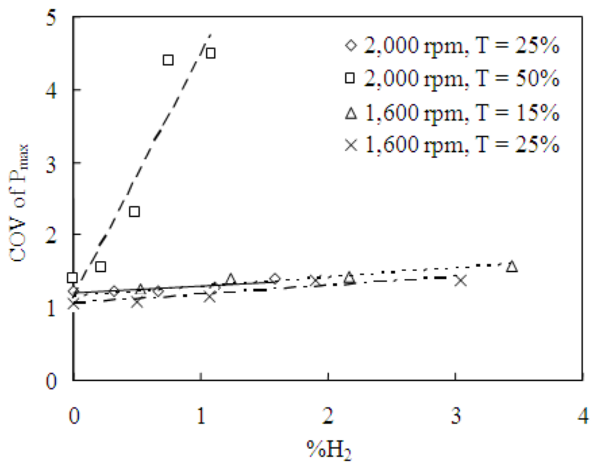

Fig. 7. The first order correlation between coefficient of variation of maximum cylinder pressure ($COV_{P_{max}}$) and hydrogen-diesel ratio

3.3. Coefficient of Variation of the Maximum Cylinder Pressure

The hydrogen percentage is also plotted against the coefficient of variation of the maximum cylinder pressure for all the test conditions. The first order and second order correlations between the coefficient of variation of the maximum cylinder pressure ($COV_{P_{max}}$) and hydrogen-to-diesel ratio are shown in **Fig. 7 and 8**, respectively.

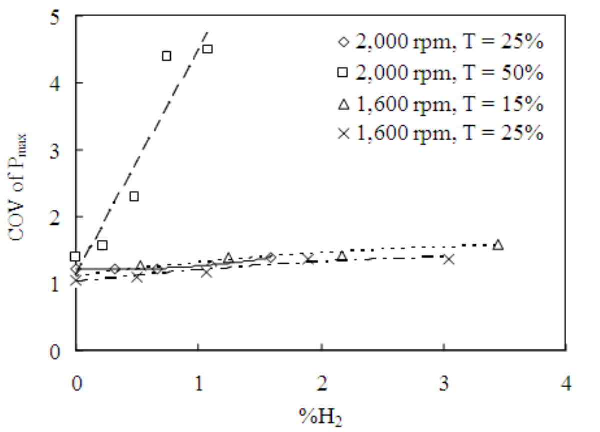

Fig. 8. The second order correlation between coefficient of variation of maximum cylinder pressure ($COV_{P_{max}}$) and hydrogen-diesel ratio

Table 6. Correlation constants for the coefficient of variation of the maximum cylinder pressure in Eq. 5 and 6

Order	Condition	a	b	c	R^2
1	Exp.1	0.1023	1.1907		0.7964
	Exp.2	3.3334	1.1320		0.8893
	Exp.3	0.1311	1.1484		0.8951
	Exp.4	0.1195	1.0525		0.8809
2	Exp.1	0.1091	-0.0718	1.2250	0.9899
	Exp.2	-0.0106	3.3450	1.1304	0.8893
	Exp.3	-0.0287	0.2308	1.1069	0.9387
	Exp.4	-0.0275	0.2040	1.0207	0.9179

The relationships between maximum cylinder pressure (P_{max}) and hydrogen-to-diesel ratio in first (n = 1) and second (n = 2) orders generate the correlation constants numerated in **Table 6** with R^2 in the form of Eq. 5:

$$(n = 1)COV_{P_{max}} = a(\%H_2) + b \quad (5)$$

and in the form of Eq. 6:

$$(n = 2)COV_{P_{max}} = a(\%H_2)^2 + b(\%H_2) + c \quad (6)$$

4. DISCUSSION

The experimental results in **Fig. 3** have shown that the maximum cylinder pressure obtained from this engine occurred after the engine top dead center for all the test conditions. It has seen from **Fig. 4** that when higher hydrogen percentages were added, the combustion shifted toward later crank angles while maintaining the same area under the pressure-crank angle thus, the same output as set in **Table 3**. It is obvious in the **Fig. 4** that the maximum cylinder pressure decreased as the hydrogen percentages were added.

The reducing maximum cylinder pressure traces were confirmedly plotted against the hydrogen-to-diesel ratio in term of hydrogen percentage, shown in **Fig. 5 and 6** with the first and second order correlations, respectively. It is found that the lower engine loads gave lower maximum cylinder pressures. The added hydrogen percentages show eminent effects at higher load and speed; this can be observed by the sharp slope in maximum cylinder pressure reduction both in **Fig. 5 and 6**.

The results of the maximum pressure-hydrogen percentage correlations in **Table 5** show better curve fittings by second order correlation ($R^2 \rightarrow 1$) compared to the first order correlation for all the test conditions. The averaged values of R^2 are 0.9261 and 0.9808 for linear (first order) equation and parabola (second order) polynomial equations, respectively. All curves are the decreasing function and P_{max} can decrease by increasing hydrogen percentage.

In **Fig. 7 and 8**, the plots of hydrogen percentage against the coefficient of variation of the maximum cylinder pressure ($COV_{P_{max}}$), respectively for the first and second order correlations show the increase in variation of maximum cylinder pressure when the hydrogen-to-diesel increased for all conditions tested. The values of $COV_{P_{max}}$ are in the level of less than 1.2 in majority. Acceptingly, the test condition Exp. 2 which is at high speed and high load is found to give a prominent increase in $COV_{P_{max}}$ even when only subtle amount of hydrogen percentages were added. This can be observed by the sharp slope of $COV_{P_{max}}$ increase both in **Fig. 7 and 8**.

The results of the $COV_{P_{max}}$ - hydrogen percentage correlations in **Table 6** show better curve fittings by second order correlation ($R^2 \rightarrow 1$) compared to the first order correlation for all the test conditions. The averaged values of R^2 are 0.8654 and 0.9340 for linear (first order) equation and parabola (second order) polynomial equations, respectively. All curves are the increasing function and $COV_{P_{max}}$ increased by increasing hydrogen percentage.

5. CONCLUSION

The experimental investigation of maximum cylinder pressure and its variations of the fumigated hydrogen-diesel dual fuel combustion can draw the conclusions as the followings:

- The maximum cylinder pressure obtained from this engine occurred after the engine top dead center. When higher hydrogen percentages were added, the combustion shifted toward later crank angles. The maximum cylinder pressure decreased as the hydrogen percentages were added
- The added hydrogen percentages show eminent effects at higher load and speed that can be observed by the sharp slope in maximum cylinder pressure reduction
- The maximum pressure-hydrogen percentage correlations show better curve fittings by second order correlation compared to the first order correlation for all the test conditions
- The plots of hydrogen percentage against the coefficient of variation of the maximum cylinder pressure show the increase in variation of maximum cylinder pressure when the hydrogen-to-diesel increased for all conditions tested. The values of $COV_{P_{max}}$ are in the level of less than 1.2 in majority, accept the test condition at high speed and high load which is prominent increase in $COV_{P_{max}}$
- The $COV_{P_{max}}$-hydrogen percentage correlations show better curve fittings by second order correlation compared to the first order correlation for all the test conditions

6. ACKNOWLEDGMENT

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