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The combustion characteristics of diesel engine burned with auxiliary gaseous fuels

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Abstract. Diesel engines becomes more and more popular for automobile applications nowadays. The fuel economy of diesel vehicles is better than most gasoline vehicles. However, the exhaust emissions, especially NOx and PM, are always a problem to be solved for diesel engines. Diesel fuel blended with gaseous fuels is a promising way to ease up this problem. This paper presents the experimental work conducted to investigate the effect of auxiliary gaseous fuel, including hydrogen, natural gas, and biogas, on the combustion characteristics of a heavy-duty diesel engine. Results of experiments showed that nitrogen oxides decreased compared to diesel fuel only. The opacity of the exhaust gas also decreased. The BSFC increased and the thermal efficiency decreased slightly compared to diesel fuel only. The pressure in the engine cylinder was also measured and the associated heat release rate was obtained in this work. According to the result of the cylinder pressure analysis, different characteristic of the combustion rate and timing were observed.

1. Introduction

The thermal efficiency of diesel engine is generally higher than gasoline engine, and diesel fuel is also cheaper than gasoline. However, the nitrogen oxides (NOx) and particulate matter (PM) emission of diesel engine is higher than gasoline engine. With the tougher and tougher standard of emission in these years, the emission control technology has become the focus of every automobile company. Exhaust gas recirculation (EGR) system has been used to decrease the formation of NOx during combustion stage inside engine cylinder, but has some negative impacts on thermal efficiency. Selective catalytic reduction (SCR) system has been widely used in recent years to remove NOx in the exhaust gas, but the consumption of urea becomes additional cost, and driver should refill urea from time to time. Diesel particle filter (DPF) system is used to remove PM in the exhaust gas. The filter in the system can be clogged with particles and cause high back pressure after being used for a while. It has to be cleaned by regeneration, or replaced to turn the filter back to the good condition for the engine. The work of cleaning the filter, and the hardware of regeneration system built in the DPF system increase the cost to maintain the engine.

Addition of gas fuel into the intake system of the engine can change the combustion process directly and affect the formation of pollutants. Adding gas fuel to diesel engine may decrease exhaust emission, and is an alternative way for emission control. In this study, we use hydrogen, natural gas, and biogas as an auxiliary fuel for diesel engine to investigate their effects on engine performance as well as emission reduction.

Maki and Prabhakaran have conducted a hydrogen addition test in a diesel engine running on a dynamometer[1], and found some beneficial results. Both BSFC and NOx emission have 20% improvement by adding hydrogen. On the contrary, Masood et al found that adding hydrogen into diesel engine may cause negative effect on fuel consumption and NOx emission. But they found substantial decrease in PM[2]. Lyford-Pike took natural gas powered and diesel powered vehicle to the chassis dynamometer to do experiment[3]. The results showed that the natural gas vehicle releases much less NOx than diesel vehicle. Besides, there's 26%~45% difference of NOx emission between the natural gas vehicle and the diesel vehicle. According to the review of Ashok et al, natural gas addition may decrease 27.6% of NOx for diesel engine and also lower the opacity[4]. Lata and Misra observed that when hydrogen addition reached 50% or natural gas addition reached 70%, the diesel engine started to knock[5]. The knocking phenomenon was also reported by Wannatong's research[6].

Previous research gave contradictory results. Some people found beneficial effects by adding gaseous fuel. However, some other people found contrary effects. In this paper, we added hydrogen , natural gas, and biogas into the diesel engine and look for the effects in engine performance and emission reduction. The maximum blend ratio of gas fuel was set as 20% based on total energy of the fuel supply to avoid knocking of the engine.

2. Experiment system

The experiments were carried out on a HINO W06E engine. Figure 1 shows the whole set of engine and dynamometer. Details of the engine specification were given in Table 1.

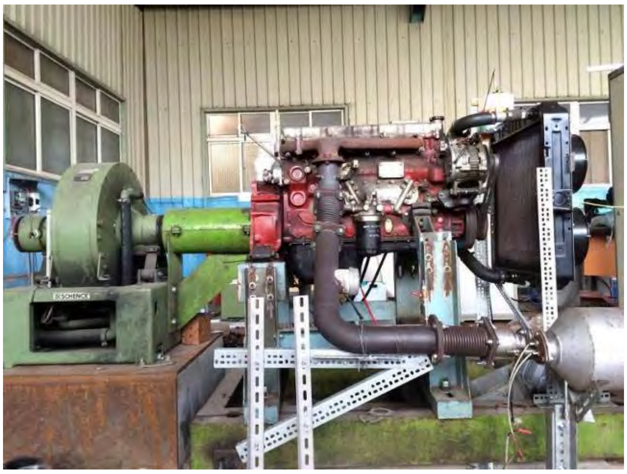

Figure 1. The engine and the dynamometer for the experiment

Table 1. Specification of the engine

Item	Spec.
Brand	Hino
Model	W06E
Cylinder arrangement	Inline 6 cylinders
Aspiration type	Naturally aspirated
Displacement	6,000 c.c.
Max rated power	165 Ps@3,000 rpm
Max rated torque	42 kg-m@1800 rpm
Injection timing	14 °CA BTDC

In order to apply loading on the engine, we use SCHENICK W230 engine dynamometer to do it. The specification of the dynamometer was shown as Table 2.

Table 2. Specification of the dynamometer

Item	Spec.
Power	230 kW
Rated torque	750 Nm
Minimal speed for rated torque	620 rpm
Minimal speed for maximal power	2928 rpm
Maximal speed	7500 rpm
Moment of inertia	0.53 kg-m^2

The intake system was modified to adopt auxiliary gaseous fuel, as shown in Figure 2. The air went through the air filter, the laminar flow meter, and then went into the intake manifold. The gas fuel was supplied from the compressed gas bottles. Each bottle is equipped with a flow meter such that the flow rate of gas fuel was indicated and can be adjusted with a valve. There is a water tank specially designed for hydrogen to avoid back fire of hydrogen.

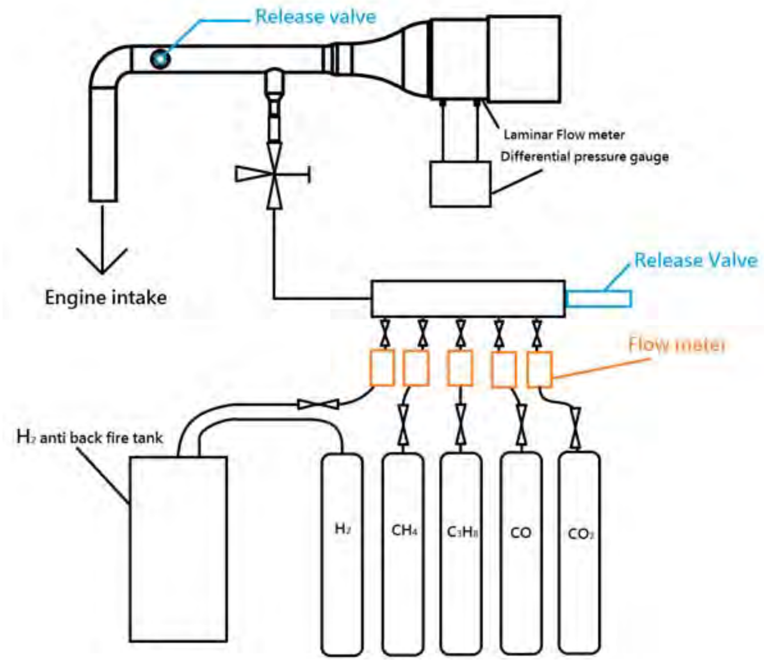

Figure 2. The intake system was modified to adopt auxiliary gaseous fuel

A high accuracy electronic scale was used to measure the weight of the fuel tank for the fuel consumption measurement. An NGK NOx sensor and the MA200A Opacity Meter was used to measure the engine emission. The brake efficiency can be obtained by Eq.(1)-Eq.(3).

$$\eta_B = \frac{W}{Q} \tag{1}$$

$$Q = \dot{m}_d Q_d + \rho_f V Q_f \tag{2}$$

$$W = 2\pi T_q \Omega \tag{3}$$

where

Q : Power delivered by fuel (J/min)

$\dot{m}_d$: Fuel consumption (g/min)

Q_d : Heating value of diesel(kJ/kg)
ρ_f : Density of gas fuel (g/L)
V : Flow rate of gas fuel (L/min)
Q_f : Heating value of gas fuel
W : Brake power of the engine (J/min)
Ω : Engine speed (rad/sec)
T_q : Torque output of the engine (Nm)

3. Test Procedure

Steady engine tests were carried out in this study. The test procedure followed the European Stationary Cycle 13 Modes as shown in Figure 3. We picked Mode 6 and Mode 11 for the experiment. The engine was operated at high load(270Nm) and low speed(1650rpm) with Mode 6, and low load(190Nm), high speed(1950rpm) with Mode 11. In each test point, only diesel fuel was supplied into the engine in the beginning. Engine speed was locked by the dynamometer. Fuel was increased gradually until the target torque was reached. This is the reference condition of pure diesel fuel. Then gaseous fuel was introduced into the intake manifold according to the preset ratio. Engine torque would increase as more fuel was supplied. The diesel fuel was then reduced gradually until engine torque returned to the same value as that of reference condition. Since engine output power remained the same, the efficiency and the emission characteristics can be compared on the same power basis.

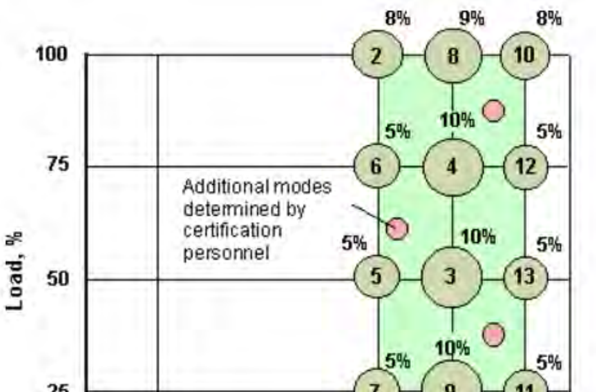

Figure 3. European Stationary Cycle 13 modes

Four different gaseous fuels were considered in this paper, namely, pure hydrogen, pure methane, mixture of 90% methane and 10% carbon dioxide, and mixture of 70% methane and 30% carbon dioxide. Pure hydrogen was to simulate synthesized gas produced by gasification or carbonization of biomass. Pure methane was to simulate imported natural gas which will become dominant fuel in Taiwan in the near future. Since imported natural gas is in the form of LNG, pure methane is the major component. Mixture of 90% methane and 10% carbon dioxide was to simulate domestic natural gas which is extracted in middle Taiwan. Mixture of 70% methane and 30% carbon dioxide was to

simulate bio gas which can be converted from pig effluent and will become an important byproduct of pig farm in southern Taiwan.
The blend ratio of gas fuel addition was based on total energy supplied to engine. Two ratios were set in this study, 10% and 20%. The total energy supplied to engine was calculated from the fuel consumption of reference condition, i.e., the pure diesel test. The flow rate of the gas fuel of each experiment setting was shown as Table 3.

Table 3. Flow rate of gas fuel addition (LPM)

	Hydrogen		Methane	
Energy ratio	Mode 6	Mode 11	Mode 6	Mode 11
10%	71.5	41.0	23.5	13.5
20%	143.0	81.9	47.0	26.9
	Domestic NG		Biogas	
Energy ratio	Mode 6	Mode 11	Mode 6	Mode 11
10%	2.61	1.49	10.06	5.76
20%	5.21	2.99	20.11	11.53

4. Result of the study

4.1. Basic performance of the engine

Figure 4 shows the results of thermal efficiency for engine running with hydrogen addition. The left bars represent thermal efficiency at low load condition, while the right bars represent thermal efficiency at high load condition. We can see that thermal efficiency is about 25% at low load , and 35% at high load. The thermal efficiency decreased as hydrogen was added. The more hydrogen added, the more efficiency loss could be found. The thermal efficiency of the engine with imported natural gas addition was shown in Figure 5. The thermal efficiency decreased a little less compared to pure diesel test at low load, but not so much as hydrogen addition. The thermal efficiency keep the same at high load compared to pure diesel test. The thermal efficiency of the engine with domestic natural gas addition was shown in Figure 6. The thermal efficiency of the engine with biogas addition was shown in Figure 7. Both domestic natural gas and biogas affected thermal efficiency a little. Generally speaking, addition of gas fuel may decrease the thermal efficiency slightly. More the blend of gas fuel, lower the thermal efficiency.

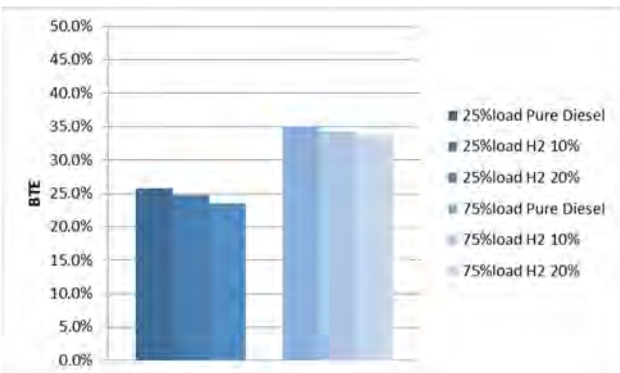

Figure 4. Thermal efficiency of the engine with hydrogen addition

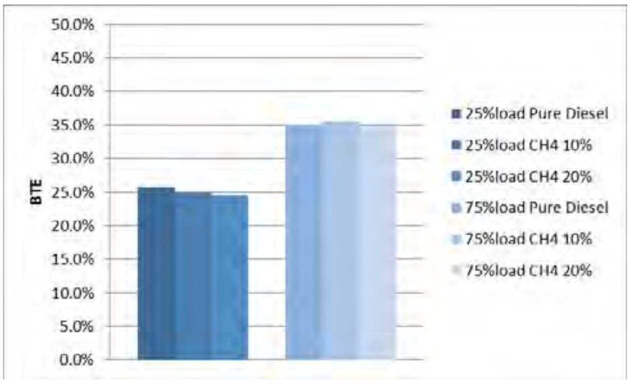

Figure 5. Thermal efficiency of the engine with natural gas addition

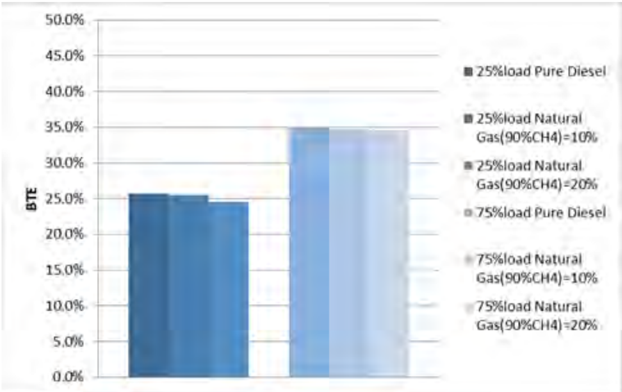

Figure 6. Thermal efficiency of the engine withdomestic natural gas addition

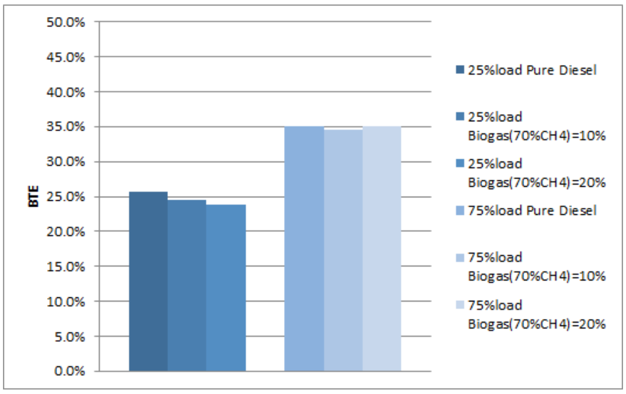

Figure 7. Thermal efficiency of the engine with biogas addition

4.2. Emission analysis

The unit of engine emission measurement is volume concentration(% or ppm). We convert the volumetric measurement to mass of the pollutant emitted per unit output work. If the displacement of the engine, engine speed, and the volume concentration of the pollutant are known, the pollutant emitted per unit output work can be calculated as the following equation.

$$\dot{m}_a = \text{Displacement(L)} \times \text{Speed(RPM)} \times \frac{1}{2} \times 10^{-3} (\frac{m^3}{L}) \tag{4}$$

$$\dot{m}_{am} = \dot{m}_a \times 1183.9(\frac{g}{m^3})/28.97(\frac{g}{mole}) \times 60 \tag{5}$$

In Equ. (5), the constant 1183.9 is the density of air at NTP, the constant 28.97 is the average molecular weight of air. Because the volume percentage is same as mole percentage for ideal gas, the volume percentage of the measured pollutant is its mole percentage. The concentration of the pollutant can be multiplied by the flow rate of exhaust gas to calculate the mole flow rate of each pollutant. Take NOx for the example. The measured value is NOx(ppm). The way to transfer NOx(ppm) to mole flow rate is shown in Equ. (6).

$$\dot{m}_{NO_x m} = \dot{m}_{am} \times NO_x(ppm) \tag{6}$$

The way to transfer measured value to mass flow rate was shown in Equ. (7).

$$\dot{m}_{NO_x} = 2451.98 \times \dot{m}_a \times NO_x(ppm) \times 46(g / mole) \tag{7}$$

The mass flow rate divided by the measured power output(hp) is the amount of emission per unit output work(g/bhp-hr).

$$m(g / bhp - hr) = \frac{\dot{m}(g / hr)}{\dot{W}(hp)} \tag{8}$$

The NOx emission result with hydrogen addition is shown at Figure 8. The NOx emission factor decreased with hydrogen addition. It is 5.9 g/bhp-hr with pure diesel fuel at low load. Adding hydrogen would reduce NOx by 20%. However, the reduction of NOx is not noticed at high load.

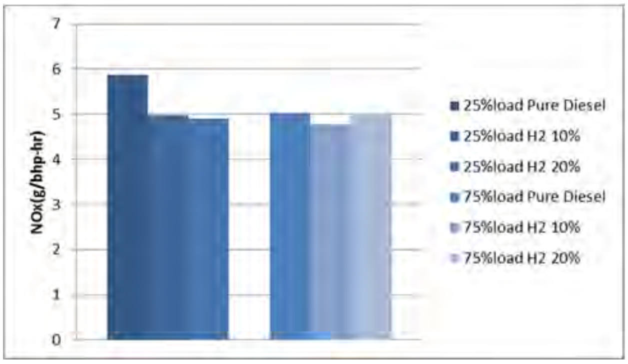

Figure 8. NOx emission with hydrogen addition

The NOx emission factor with natural gas addition is shown at Figure 9. NOx decreasing is good at low load as well as high load. There is 19% decrease of NOx at low load, 10% at high load.

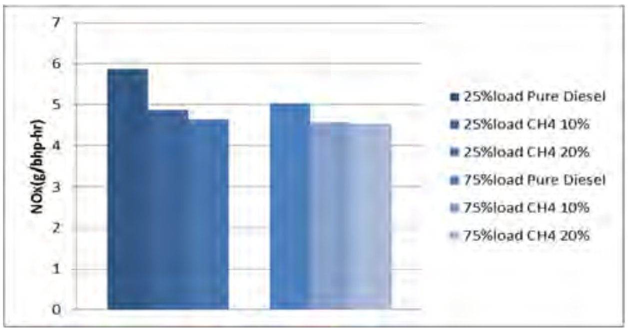

Figure 9. NOx emission with natural gas addition

The NOx emission factor with domestic natural gas addition is shown at Figure 10. The decrease of NOx is even more than natural gas. There is 24% decrease at low load, and 12% at high load. The domestic natural gas contains CO_2. CO_2 cannot be burned and have high specific heat, so it has the effect like EGR to decrease the formation of NOx during combustion.

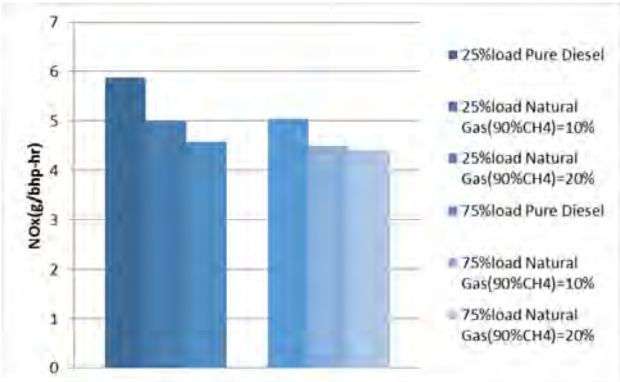

Figure 10. NOx emission with domestic natural gas addition

The NOx emission factor with bio gas addition is shown at Figure 11. The biogas has the best effect on NOx reduction compared to the other gas fuel addition. There is 30% decrease at low load, and 22% at high load. There is higher CO_2 blend in biogas than domestic natural gas.

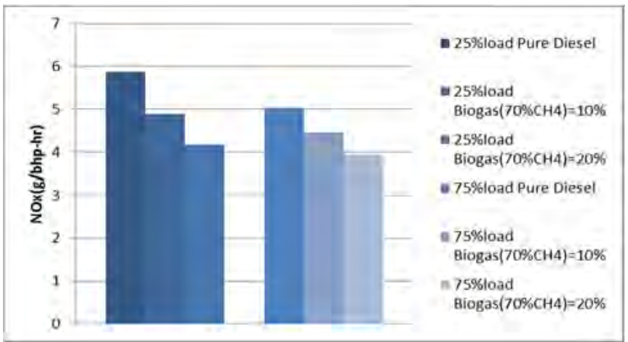

Figure 11. NOx emission with biogas addition

The opacity of the exhaust gas with hydrogen addition is shown at Figure 12. The opacity of the exhaust gas decreased with hydrogen addition. It is $0.75m^{-1}$ opacity with pure diesel fuel at high load, and 36% of opacity decrease can be reached. The effect of decreasing opacity by hydrogen addition is better at high load on the engine than low load.

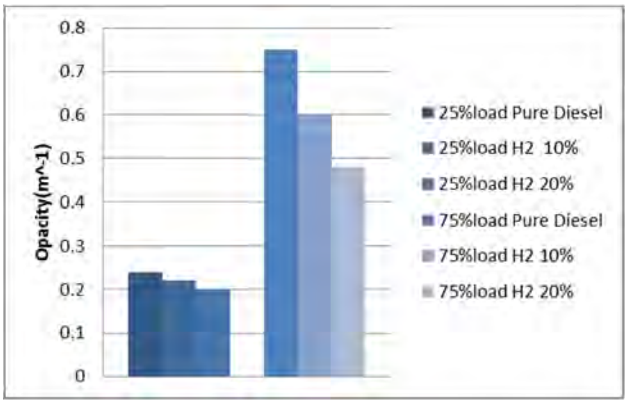

Figure 12. Opacity of exhaust gas with Hydrogen addition

The opacity of the exhaust gas with natural gas addition is shown at Figure 13. The reduction of opacity with natural gas addition is even better than hydrogen addition. The more natural gas addition, the lower the opacity would be. There is 75% decrease of opacity at low load. At high load, the reduction of opacity is 48%.

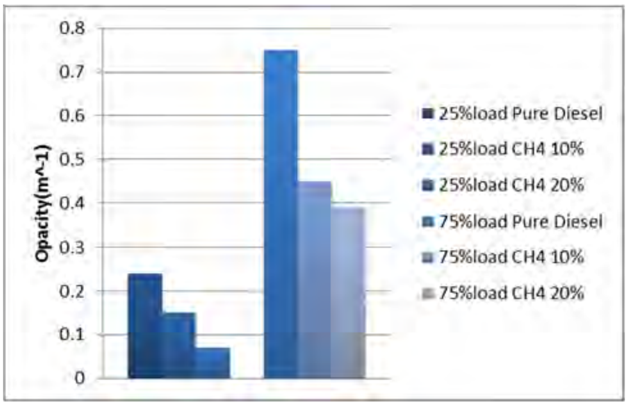

Figure 13. Opacity of exhaust gas with natural gas addition

The opacity of the exhaust gas with domestic natural gas addition is shown at Figure 14. The reduction of opacity is also good, but not as good as natural gas. There is 42% reduction of opacity at low load, and 44% reduction at high load.

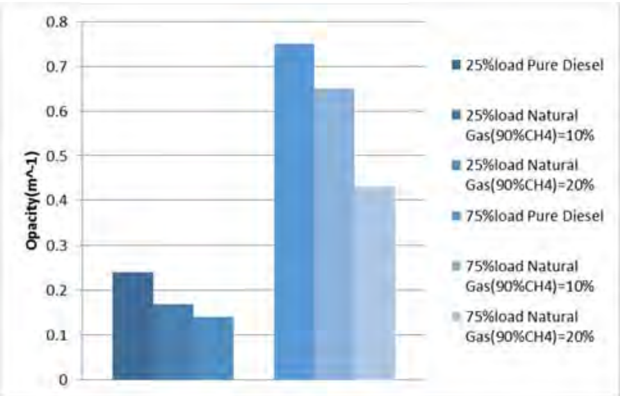

Figure 14. Opacity of exhaust gas with domestic natural gas addition

The opacity of the exhaust gas with biogas addition is shown at Figure 15. The reduction of opacity is better than domestic natural gas but lower than natural gas. There is 66% reduction of opacity at low load, and 47% reduction at high load.

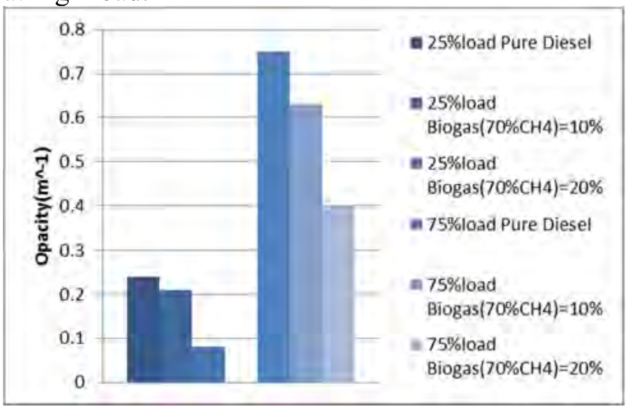

Figure 15. Opacity of exhaust gas with biogas addition

Opacity measurement is just a qualitative way for the emission of particle matter. The actual PM amount cannot be evaluated by opacity measurement, but the concentration of particular pollutant is higher when the opacity is higher. The data of the opacity in this research showed that the gas fuel can decrease the concentration of the particular pollutant well.

4.3. Combustion analysis

The injection timing is 14°CA before TDC, controlled by the automatic timing device. The Figure 16 shows the combustion was delayed to 7° CA after TDC and revealed the period from injection to start of the combustion is about 21° CA.

Different fuel conditions have different features of combustion. The difference of the combustion between different fuel condition can be observed by measuring real time cylinder pressure. Figure 16 shows the cylinder pressure with different gas fuel addition with 10% at high load. Hydrogen addition can speed up the combustion. Natural gas and bios gas delayed the combustion.

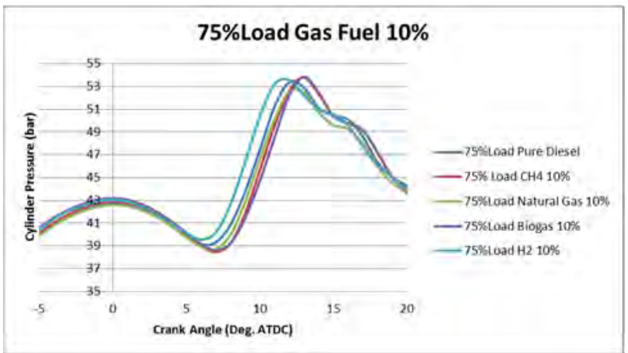

Figure 16. Cylinder pressure with different gas fuel addition at high loading test

The heat release rate can be calculated by the following equation.

$$Q_{hr} = \left(\frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta} \right) d\theta \quad (12)$$

where

Q_{hr} is the heat release rate(J/deg)

P is pressure(Pa)

V is the volume of the cylinder(m^3)
$\gamma = c_p / c_v$, Cp is the constant pressure specific heat, and Cv is the constant volume specific heat.

The heat release rate with different gas fuel addition with 10% at high load is shown in Figure 17. The first combustion peak went faster with hydrogen addition than other fuel condition. The first combustion peak is higher with natural gas addition than biogas addition. The cylinder pressure of combustion is higher with natural gas addition than biogas addition. These feature of combustion can be the reason of the thermal efficiency of natural gas addition be higher than pure diesel test.

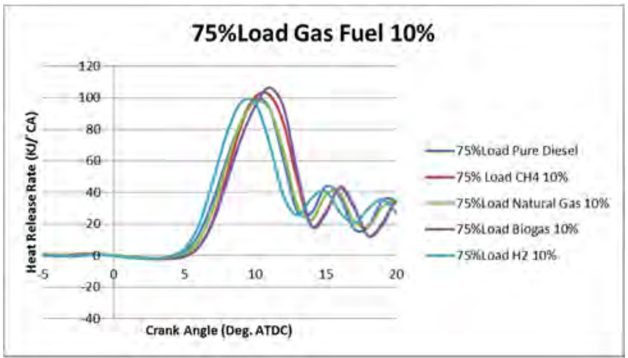

Figure 17. The heat release rate with different gas fuel addition at high loading test

5. Conclusion

(1). The results of experiment showed that the thermal efficiency decreased with hydrogen addition. The thermal efficiency also decreased with natural gas and biogas addition, but not that much as hydrogen addition.
(2). The effect of NOx reduction is better with hydrogen addition at low load than high load. The effect of NOx reduction is much better with natural gas and biogas. The blend of CO_2 affects the NOx formation a lot. Higher the blend of CO_2, better the effect. It's caused by the EGR effect of CO_2 during combustion.
(3). The reduction of opacity of the exhaust gas is good with all kind of gas fuel addition. The gas fuel can decrease the particle matter formed from the combustion.
(4). The result of cylinder pressure and the heat release rate show that hydrogen addition can speed up the combustion. Although methane and biogas can delay the combustion, it can increase the heat release rate and the peak of combustion pressure to increase the thermal efficiency.

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