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Combustion and Emission of a Compression Ignition Engine Fueled with Diesel and Hydrogen-Methane Mixture

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***Abstract*—**The present study conducted experimental investigation on combustion and emission characteristics of compression ignition engine using diesel as pilot fuel and methane, hydrogen and methane/hydrogen mixture as gaseous fuels at 1800 rev min^{-1}. The effect of gaseous fuel on peak cylinder pressure and heat release is modest at low to medium loads. At high load, the high combustion temperature and high quantity of pilot fuel contribute to better combustion efficiency for all kinds of gaseous fuels and increases the peak cylinder pressure. Enrichment of hydrogen in methane gradually increases the peak cylinder pressure. The brake thermal efficiency increases with higher hydrogen fraction at lower loads. Hydrogen addition in methane contributed to a proportional reduction of CO/CO_2/HC emission without penalty of NO_x. For particulate emission, methane and hydrogen, could both suppress the particle emission. 30% hydrogen fraction in methane is observed to be best in reducing the particulate emission.

***Keywords*—**Combustion characteristics, diesel engine, emissions, methane/hydrogen mixture.

I. Introduction

WITH the development of industrialization and motorization of modern world, considerable demand of fossil fuel becomes a worldwide concern since its non-renewability and also its impact on environmental deterioration. On-road and off-road diesel engine or compression ignition (C.I.) engine is wildly employed for its high fuel efficiency and low hydrocarbon (HC) and carbon dioxide (CO) emission, but its inherent characteristic makes itself become the major contributor of nitric oxides (NO_x) and particulate matter (PM) emissions. Various technical solutions are proposed for removing NO_x and PM, such as selective catalytic reduction (SCR) and diesel particulate filter (DPF), in order to meet the increasing stringent emission legislations. But the heavy dependent of catalysts on precious metals and the higher cost for retrofitting the after-treatment devices make it hard to be popularized. Accordingly, various compromising strategies are raised and one among them is "dual-fuel diesel engine" concept [1].

The principle of the dual-fuel diesel engine is the cooperation of diesel fuel and "free-soot" gaseous fuel, such as natural gas (mainly methane), liquid petroleum gas (LPG), hydrogen and syngas, et al. The gaseous fuel involved combustion in C.I. engine can behave differently: firstly, non-combustible premixed gaseous-fuel/air mixture is ignited by the diesel premixed combustion at specific temperature and pressure; secondly, rich gaseous fuel/air mixture supports the diesel flame propagation and consecutively combusted independently; thirdly, the gaseous fuel is well premixed with the injected diesel plume and intake air within the combustion chamber and simultaneously combust. Although the combustion modes for gaseous fuels are similar, different gaseous fuel behaves diverse effect on engine performance and emission characteristics. For dual-fuel engine, various methods were applied to induct gaseous fuel into diesel engine to achieve the mentioned combustion modes, such as carburetion, continuous manifold induction, timing-controlled manifold/port hydrogen injection, direct hydrogen injection [2].

Natural gas (NG) has been widely used in modern vehicles and its application in diesel engine is normally in diesel-NG dual-fuel mode. Papagiannakis et al. [3]-[5] conducted experiments on a diesel and natural gas fueled dual-fuel single-cylinder diesel engine. The results indicated that the ignition delay of diesel-NG dual-fuel operation was extended than normal diesel operation. The peak heat release rate and cylinder pressure decreased with the increase of NG addition at low to medium load but increased at higher load due to the fast burning rate of diesel-NG cooperated combustion. Drastically increase of CO/HC as well as decrease of particulate became the trade-off effect for diesel-NG dual-fuel engine. The control of CO emission can be fulfilled by intake air pre-heating and increasing of pilot diesel [6]. A slight decrease of NO emission was also observed. Poompipatpong and Cheenkachorn [7] focused on the effect of engine compression ratio and speed on the emissions of a four-cylinder diesel-NG dual-fuel engine. They found that higher compression ratio and higher engine speed can achieve higher thermal efficiency and lower CO emission. But lower thermal efficiency was still observed at lower engine load. For diesel-natural gas fueled dual-fuel engine, lower thermal efficiency, extremely higher CO/HC emission at low to medium load will be the main limitation for ULSD-Methane dual-fuel engine without modification.

Hydrogen is another promising alternative fuel for internal combustion engine targeting at improving the engine efficiency, reducing emissions and improving fuel economy. Diesel-hydrogen dual-fuel engine attracted more attention

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recently. The diesel-hydrogen dual-fuel combustion process in a heavy-duty diesel engine was investigated by Liew et al. [8]. It was revealed that the peak cylinder pressure would dramatically increase at 70% of full engine load or above and this effect should be limited for safety and engine mechanical durability issues. Meanwhile, the combustion efficiency of hydrogen was relative low when small amount of hydrogen was inducted. Gatts et al. [9] further studied the combustion efficiency of hydrogen by measuring the unburned hydrogen exhaust. They suggested that the combustion efficiency of hydrogen was engine load dependent and the hydrogen should be supplemented at higher load to achieve higher hydrogen energy conversion efficiency and better diesel fuel efficiency. In terms of emissions characteristics, the experimental results were consistent. As indicated by [10]-[12], the HC/CO/CO_2/PM gradually reduced with the increase of hydrogen addition. NO_x emission decreased at low to medium load with small amount of hydrogen input but increased at higher load due to the high combustion temperature of hydrogen which enhanced the NO_x formation. The thermal efficiency was engine load, speed and hydrogen amount dependent as reported by Miyamoto et al. [13].

Hydrogen as a peculiar fuel has many special properties, such as wide flammability, fast burning velocity, low ignition energy and non-carbon, which can combined with other gaseous fuel so as to improve the overall energy utilization efficiency. Lata et al. [2], [14], [15] conducted theoretical and experimental study on diesel engine using LPG and hydrogen mixture as gaseous fuel. The major finding indicated that the low efficiency at lower load for diesel-LPG dual-fuel engine was removed by inducing hydrogen into LPG fuel when engine was operated at higher than 10% of full load.

II. Special Objectives

Methane has a low flame propagation speed, narrow flammability while hydrogen has the opposite properties which can enhance the methane fuel and make it more suitable for engine. Hydrogen has a fast burning rate, diffusivity and low ignition energy which make the combustion unstable while methane can make the combustion smoother. The mixture of methane and hydrogen has already been investigated in S.I. engine [16], [17]. However, from the mentioned literature review, there is scarce of study of diesel-methane dual-fuel engine with addition of hydrogen as combustion enhancer. The effect of hydrogen addition in diesel-methane dual-fuel engine will be experimentally investigated in this study.

III. Experimental Methodology

In the present study, the engine was operated under dual-fuel mode at five steady engine loads at 1800 rev min^{-1} with BMEP of 0.08, 0.24, 0.41, 0.57 and 0.71MPa, which was roughly 10%, 30%, 50%, 70% and 90% of the full load. The energy substitution ratio of the gaseous fuel, including methane (99.5%), hydrogen (99.9%) and hydrogen-methane mixture, was controlled at 40±1%. The hydrogen-methane mixture had a proportion of 30:70, 50:50 and 70:30 at volume basis and named H30-M70, H50-M50 and H70-M30, respectively. The hydrogen energy fraction of the gaseous fuel can be calculated as 11.67%, 23.56% and 41.30%, correspondingly, where the lower heating value of hydrogen and methane are 119.93 and 50.02 MJ/kg; the density under 1atm are 0.0837 and 0.6512 g/cm^3, respectively.

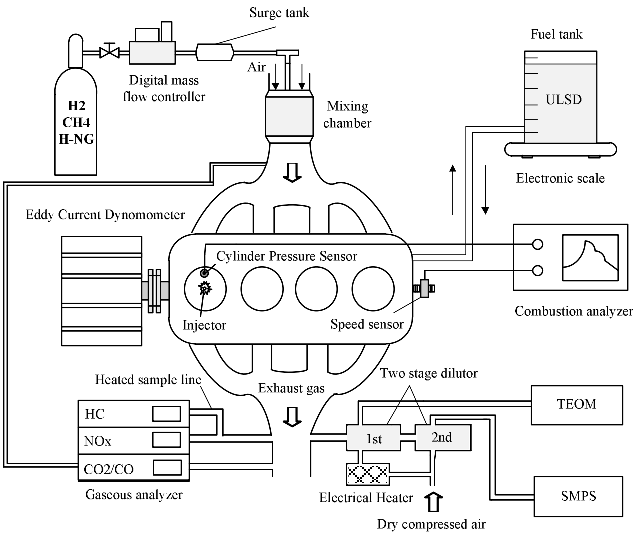

Fig. 1 Experimental diagram

The experimental setup is shown in Fig. 1. The diesel engine was mounted on an eddy-current dynamometer where the engine torque and speed were controlled by the Ono Sokki testing management system. The in-cylinder pressure was measured by a piezoelectric sensor (type 6056A, Kistler Co., Inc.) and the pressure signal was amplified with a charge amplifier (type 5011B, Kistler Co., Inc.). A crank-angle encoder was employed for crank-angle signal acquisition at a revolution of 0.5 °CA. The intake and exhaust gas temperatures were measured by K-type thermocouples. For gaseous emissions, total HC was measured with a heated flame ionization detector (HFID, CAI Inc.); NO/NO_x was measured with a heated chemiluminescent analyzer (HCLA, CAI Inc.). CO and CO_2 were measured with non-dispersive infrared analyzers (NDIR, CAI Inc.). O_2 was measured with a portable gas analyzer (Anapol AG). All the gas analyzers were warmed up for at least 1 hour and calibrated with span and zero gases before each experimental condition. For particulate emissions, a two stage Dekati mini-diluter was employed for diluting the exhaust gas for particle sampling. The dilution ratio calculation method can be found in [18]. The first-stage diluted exhaust gas was delivered to a tapered element oscillating microbalance (TEOM 1105, Rupprecht & Patashnick Co., Inc.) for measuring particulate mass concentration, and the second-stage one was connected with a scanning mobility particle sizer (SMPS, TSI Inc.) for measuring the particle size distribution and number concentration. The SMPS consists of a TSI 3071A differential mobility analyzer (DMA) and a TSI 3022 condensation particle counter (CPC).

The gaseous fuel energy substitution ratio can be calculated using (1). Where, the $\dot{m}_{ULSD}$, $\dot{m}_{H2}$ and $\dot{m}_{CH4}$ refers to the mass flow rate of ULSD, hydrogen and methane in kg/hr, respectively. LHV_{ULSD}, LHV_{H2} and LHV_{CH4} refers to the lower heating value of ULSD, hydrogen and methane in MJ/kg, correspondingly.

$$Substitution\,ratio = \frac{\dot{m}_{H2} \cdot LHV_{H2} + \dot{m}_{CH4} \cdot LHV_{CH4}}{\dot{m}_{ULSD} \cdot LHV_{ULSD} + \dot{m}_{H2} \cdot LHV_{H2} + \dot{m}_{CH4} \cdot LHV_{CH4}} \quad (1)$$

IV. Results and Discussions

A. Combustion Characteristics

At low to medium loads, it is observed that the peak cylinder pressure decreases with the increase of all kinds of the gaseous fuel input, but the effect is relative modest. For ULSD-Methane and ULSD-Hydrogen cooperated combustion, the peak cylinder pressure will decrease at low to medium loads. At high engine load, due to the high combustion temperature and high quantity of injected pilot fuel, the combustion efficiency of the gaseous fuel is high and the fast burning rate of gaseous will contribute to a higher cylinder pressure. It is noticed that ULSD-Hydrogen combustion becomes unstable and hard to control at high load. With the addition of hydrogen into methane, the peak cylinder pressure will gradually increase relative to ULSD-Methane operation and this effect become apparent at 90% load.

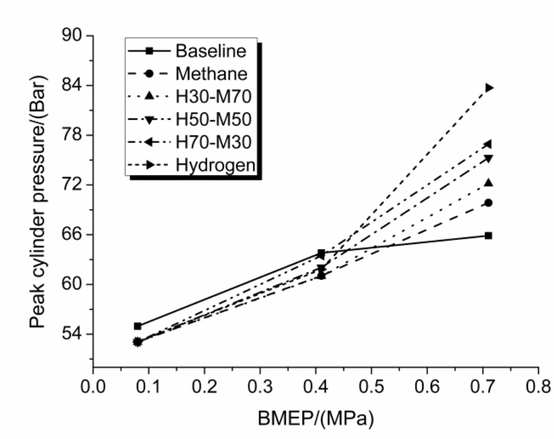

Fig. 2 Effect of hydrogen-methane mixture on peak cylinder pressure

Fig. 5 shows the effect of hydrogen-methane mixture on engine heat release rate at BMEP of 0.71MPa. For ULSD-Methane dual-fuel engine, the peat heat release rate increased apparently compared with the baseline with ULSD operation. The heat release rate profile for ULSD-Hydrogen reveals that, hydrogen auto-combustion occurred and the main combustion phase occurred at premixed combustion phase and the heat released during diffusion combustion phase reduces a lot relative to other cases. When hydrogen is inducted into methane, the peak heat release rate increases gradually.

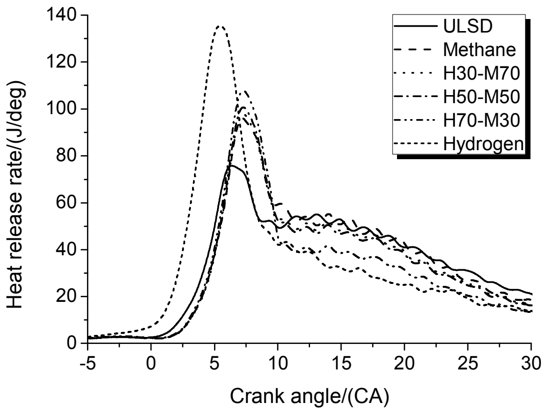

Fig. 3 Effect of hydrogen-methane mixture on heat release rate

B. Engine Performance

The overall brake thermal efficiency (BTE) can be calculated using (2). *T*refers to the engine torque in Nm, *n* refers to the engine speed in rev min^{-1}.

$$BTE = \frac{T \cdot 2\pi n}{\dot{m}_{ULSD} \cdot LHV_{ULSD} + \dot{m}_{H2} \cdot LHV_{H2} + \dot{m}_{CH4} \cdot LHV_{CH4}} \quad (2)$$

For ULSD-Methane dual-fuel combustion, the overall BTE is always lower than the baseline. This effect is more obvious at lower loads and the average decreasing rate of BTE is 12.57%. For ULSD-Hydrogen dual-fuel combustion, the BTE is engine load dependent and it will decrease at medium load or below and increase at higher loads. BTE will deteriorate at low to medium load due to the low combustion efficiency of the gaseous fuel. One of the major finding here is that when hydrogen is enriched in the methane, the BTE will gradually increase at all loads. At low to medium loads with BMEP of 0.08 and 0.24MPa, the deterioration of BTE is alleviated and higher than both ULSD-Methane and ULSD-Hydrogen operations.

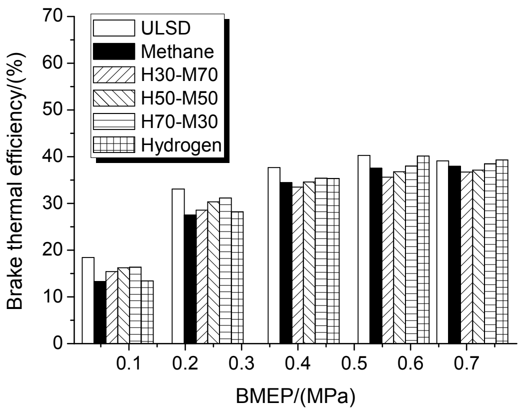

Fig. 4 Effect of hydrogen-methane mixture on brake thermal efficiency

Fig. 5 shows the effect of hydrogen-methane mixture on CO emission. For ULSD-Methane dual-fuel combustion, CO is one of the incomplete combustion by-products of methane and it is found that the CO emission increases sharply throughout the five loads. The increasing rate of CO is compared with the baseline, respectively. Gatts [19] et al. conducted experiment investigation on incomplete combustion of methane under diesel-methane dual-fuel operation condition. They pointed out that the combustion efficiency of methane as gaseous fuel was depending on engine load, the gaseous fuel amount and engine speed. In the present study, although the combustion efficiency of methane improved at higher load, CO emission remains stay at unacceptable level. On the contrary, for ULSD-Hydrogen dual-fuel combustion, the CO emission decreases at all load sowing to the direct replacement of the carbon content from hydrogen to diesel fuel. The addition of hydrogen into the methane can extend the flammability of methane as reported by Akansu [20] and the incomplete combustion of methane will be alleviated. This effect is validated in this study: with the increase of hydrogen fraction in methane, the CO emission decreases gradually. When the engine was operated at 90% of the full load, CO emission can nearly recover to the baseline level. The CO emission is 4.58, 3.92, 3.50, 2.94 and 0.74 times on average of five loads than baseline for Methane, H30-M70, H50, M50, H70-M30 and Hydrogen, respectively.

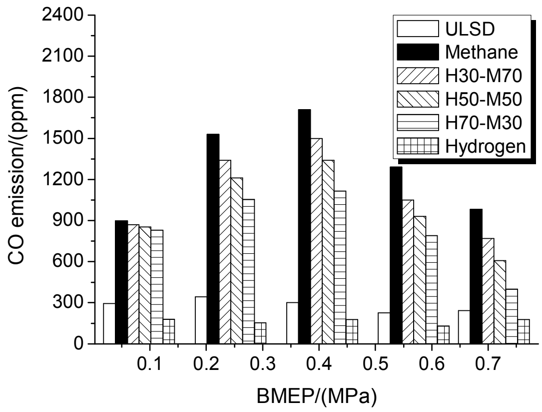

Fig. 5 Effect of hydrogen-methane mixture on CO emission

Fig. 6 shows the effect of hydrogen-methane mixture on total HC emission. For ULSD-Methane dual-fuel combustion, the result is similar with that of CO emission. The total HC inevitably contains the escaped unburned methane [19] and the improvement of methane combustion efficiency will be the key factor for reducing the total HC emission. Moreover, the formation of HC is always affected by the combustion process, flame propagation mechanism and the local equivalence ratio [21] and these factors are influenced by the dual-fuel combustion process especially at low to medium load [22]. For ULSD-Hydrogen dual-fuel combustion, it is observed that the total HC emission uniformly decreases at five loads. The total HC emission is 12.01, 10.26, 9.03, 7.69 and 0.78 times on average of former three loads at BMEP 0f of 0.08, 0.24 and 0.41MPa than baseline for Methane, H30-M70, H50, M50, H70-M30 and Hydrogen, respectively. It's 6.67, 4.77, 2.61, 1.55 and 0.80 times on average for the higher loads at BMEP of 0.57 and 0.71MPa, correspondingly.

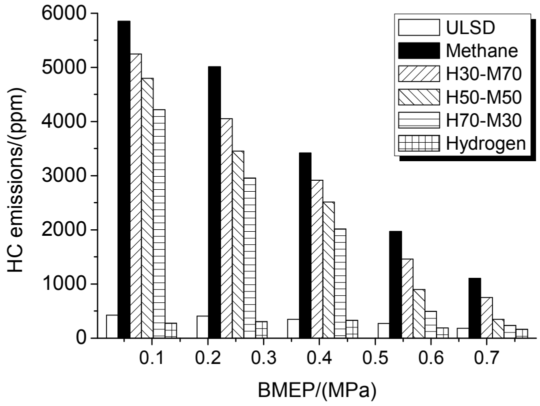

Fig. 6 Effect of hydrogen-methane mixture on total HC emission

Fig. 7 shows the effect of hydrogen-methane mixture on NO_x emission. For ULSD-Methane and ULSD-Hydrogen dual-fuel combustion, similar trend is observed that NO_x emission will decrease slightly at lower load and increase at medium to high loads. Due to the higher combustion temperature and faster burning rate of hydrogen than methane, ULSD-Hydrogen combustion will enhance the NO_x formation. When hydrogen is mixed with methane, an interesting phenomena is found, small amount of hydrogen addition will reduce the NO_x emission and with the increase of hydrogen fraction in methane, NO_x emission will increase. For H50-M50 case, the NO_x is basically the same with ULSD-Methane operation.

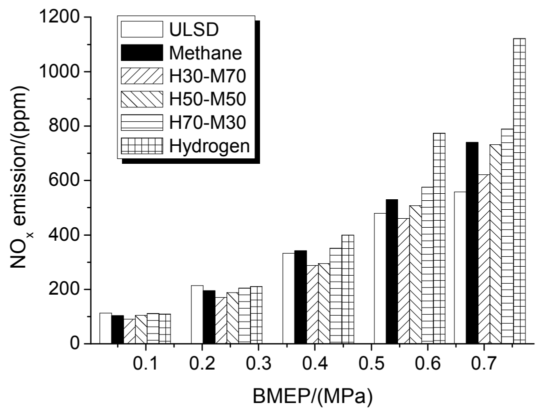

Fig. 7 Effect of hydrogen-methane mixture on NO_x emission

Fig. 8 shows the effect of hydrogen-methane mixture on NO_2 emission. For both ULSD-Methane and ULSD-Hydrogen dual-fuel combustion, enhancement of NO_2 formation is observed, this result is consistent with the finding of [23]. NO_2 emission is considered to be even more toxic than NO emission and can initiate healthy and environmental problems more profoundly. But when it's connect with after treatment devices, the NO_2 emission play as an effective oxidizer for particulate. The best percentage of NO_2 in NO_x is 50% to achieve best efficiency for SCR and DPF. For ULSD-Methane and ULSD-Hydrogen combustion, the NO_2 percentage at five loads is 71.63%, 59.44%, 32.46%, 8.49%, 4.05% and 78.90%, 63.84%, 34.75%, 10.34%, 6.87%, correspondingly. It can be found that with the increase of load, the NO_2 reduced gradually and the enhancement of after treatment device depending on the shifted NO_2 will only works at 50% load and below. When hydrogen is added into methane, the NO_2 fraction reduces with the increased of hydrogen fraction. This maybe one of the reasons for the reduction of NO_x emission for hydrogen/methane mixture compared with hydrogen/methane alone.

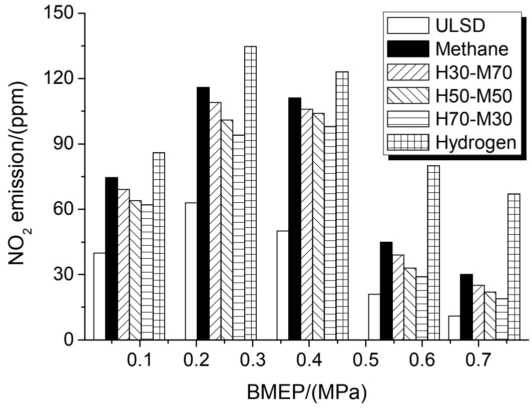

Fig. 8 Effect of hydrogen-methane mixture on NO_2 emission

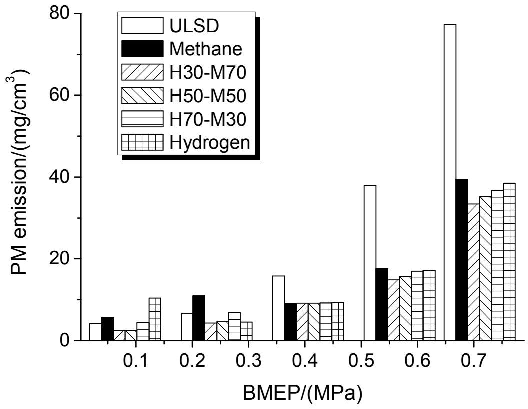

Fig. 9 Effect of hydrogen-methane mixture on particulate emission

C. Particulate Emission

Hydrogen and methane are two typical non-sooting gaseous fuels, thus the replacement of the diesel fuel by them will directly contribute to the reduction of the soot precursor formation in order to proportionally suppress the generation of diesel particulate. As can be clearly seen in Fig. 9, for ULSD-Hydrogen and ULSD-Methane dual-fuel combustion at BMEP of 0.41, 0.57 and 0.71MPa, the average decreasing rate of diesel particulate is 48.55% and 48.72%, respectively. Under lower loads with BMEP of 0.08 and 0.21MPa, an increase of particulate emission is noticed mainly due to the cooling effect of the charge dilution of hydrogen and methane that will retard the diesel oxidation. It is observed that the addition of hydrogen in methane can further reduce the particulate and it's depending on the concentration of the hydrogen. Small proportion (H30-M70) is found to be best in reducing particulate emission.

V. Conclusions

In this study, the effect of hydrogen enrichment on combustion and emission characteristics of a diesel-methane dual-fuel engine was experimentally investigated at five typical loads at 1800 rev min^{-1}. The major findings are listed as following:

The effect of gaseous fuel on cylinder pressure is load dependent. At high load, ULSD-Hydrogen (40% energy substitution) will become unstable sue to the fast burning rate of hydrogen. Hydrogen addition in methane will increase the peak heat release rate and heat release rate at all loads.

Both ULSD-Methane and ULSD-Hydrogen will apparently reduce the thermal efficiency at lower loads and increase the efficiency at high load. Hydrogen enrichment will enhance the methane combustion efficiency so as to recover the low efficiency for dual-fuel mode at lower loads close to normal diesel operation.

Methane and hydrogen almost have the same effect on reducing the particulate emission. However, ULSD-Methane operation is limited for ultra-high CO and HC emissions and ULSD-Methane operation is limited for high NO_x emission at high load. The addition of hydrogen in methane will gradually reduce the CO and HC emission and can also reduce the NO_x in particular hydrogen fraction.

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