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Effect of Injection Timing on the Engine Performance and Exhaust Emissions of a Dual-Fuel Compression Ignition Engine

Pomprab Sriumpunpuk[1,3] Sak Sittichompoo[2,3] Mongkol Dangsoontornchai[2]
Sarapon Thitipatanapong[2] Nattapol Pongrasri[1,3] Chiewcharn Haoharn[2,3]
and Kampanart Theinnoi[2,3*]

Abstract

The investigation of available alternative fuel to meet high efficiency and more stringent emission controls for compression ignition engine is very challenge. Di-Methyl Ether (DME) is a very interesting fuel of choice in the evolution of alternative fuel due to the physical and chemical properties that matches with conventional diesel fuel. DME combustion also emits overall low emissions especially, particulate matter (PM). The aims of this study was to demonstrate and evaluate the feasibility of the engine performance improvement with lower fuel consumption by optimising the injection timing. The experimentation was conducted on different injection timing (e.g. 15.5°, 13.5° and 17.5° BTDC (before top dead center)). The retard injection timing (13.5° CAD) at high engine load with EGR addition was able to improve engine performances and reduced the level of NO_X emissions however this can be effect on higher black smoke. Therefore, the optimisation of injection timing for dual fuel (DME additions together with diesel engine) engine is required for different operating conditions.

Keywords : Alternative fuel , Di-methyl ether, Injection timing, Engine performance, Compression ignition engine dual fuel

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[1] Department of Mechanical and Automotive Engineering Technology (MAet), Faculty of Engineering and Technology, King Mongkut's University of Technology North Bangkok (Rayong Campus), Nonglalok, Bankhai, Rayong 21120, Thailand

[2] Department of Power Engineering Technology, College of industrial Technology, King Mongkut's University of Technology North Bangkok, 1518 Pracharat 1 Rd., Wongsawang, Bangsue, Bangkok 10800, Thailand

[3] Research Centre for Combustion Technology and Alternative Energy (CTAE), Science and Technology Research Institute, King Mongkut's University of Technology North Bangkok, 1518 Pracharat 1 Rd., Wongsawang, Bangsue, Bangkok 10800, Thailand

[*] Corresponding author, E-mail: ktn@kmutnb.ac.th, kampanart.t@cit.kmutnb.ac.th Received 18 January 2016, Accepted 24 March 2016

1. Introduction

Nowadays, the growing concern regarding to the emission registration from diesel engine and the fossil fuel resource, the demand of diesel engine has gradually increased due to the higher performance, durability and better fuel economy compared to spark ignition (SI) engine [1-2].

The alternative fuel becomes more available, such as DME, biodiesel, gas to liquid-GTL which can be used in diesel engine, however, standard diesel engines are required to be modified engine before using with alternative fuel in the engine.

DME should be considered as a “future fuel” for diesel engine because it can be used in different types of engines and technologies. DME has been used as an alternative fuel in compression ignition engines, as it has majority of the properties similar to conventional diesel fuel. DME is an oxygenated fuel with a chemical formula of CH_3OCH_3 [3]. DME is in gas phase under standard temperature and pressure (STP). The Physical properties of DME are identical to liquefied petroleum gases (LPG) [4] which can be used in compression ignition engine in dual fuel mode. The advantage of DME is that it has higher cetane number than diesel fuel, low noise combustion and smoke free combustion could be obtained [5] due to oxygen content in the molecule. However, the main disadvantage of DME is lower heating value than diesel which leads to higher fuel consumption. This causes drop in engine performance in term of thermal efficiency.

The unmodified engine operation with DME combustion fuel simultaneously reduced the combustion efficiency and emission. In order to the high compression ratio of diesel engine and high cetane number and low auto ignition temperature in DME [6]. Advance combustion will occur, when DME injected in to the cylinder [7]. An adjustment of injection timing should be optimized.

The work presented here is part of an on-going research study with the overall aim of understanding the influence of DME as dual fuel for diesel engine. The first aspect of the study looks at the influence of DME combustion with unmodified engine (15.5° CAD, BTDC) and modified by advanced and retarded injection timing by 2° degree (CAD, BTDC)

2. Experimental Apparatus

The experiments were performed on a Yanmar L100V engine, which is a 435 cm^3, naturally aspirated, single cylinder, direct injection diesel engine. The engine specifications are given in table 1. An Eddy-current dynamometer was coupled to the engine and used to load the engine. The test rig includes other standard engine instrumentation such as thermocouples to monitor oil, air intake and exhaust temperatures. A gas supply system was used for the DME, with an injector just in the intake manifold to provide DME with the inlet charge. The DME flow rate was controlled by gas flow meter. The full engine test rig is shown in Fig.1.

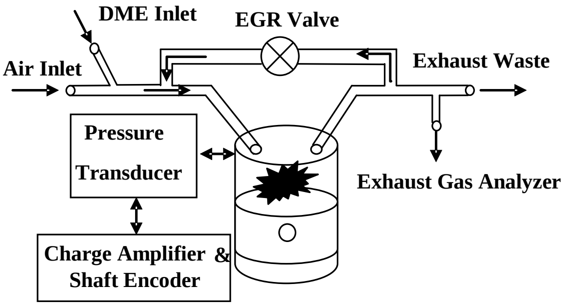

Fig. 1 Schematic diagram

Table 1 Engine specification

Model	YANMAR L100V
Type	4 Stroke Diesel engine
Number of cylinder	1
Bore/Stroke	86mm/75mm
Displacement volume	435 cm^3
Compression ratio	21.2:1
Combustion system	Direct Injection
Max. Output (kW)	6.8 kW @ 3600 RPM
Injection timing	15.5° CAD BTDC

The EGR flow was manually controlled by a valve and the EGR level was determined volumetrically as the percentage reduction in volume flow rate of air at a fixed engine operating point. A Kistler 6056A pressure transducer (1% measurement accuracy), mounted flush at the cylinder head and connected via a Kistler 5081 charge amplifier to a data recorder board which was used to record the cylinder pressure. The crankshaft position was measured using a digital shaft encoder.

Horiba MEXA-584L exhausts gas analysis was employed to measure carbon dioxide (CO_2), carbon monoxide (CO), oxide of nitrogen (NO_X) and total unburned hydrocarbons (HC). Engine black smoke was measured using a Bosch Smoke Meter. All the emissions analyzers were calibrated with certified gases. TSI Nanoscan SMPS 3910 was used to measure mass and number distribution of particle in engine exhaust gas.

2.1 Testing conditions and fuels

The Experimental under different engine speed of 1,200, 1,500 and 1,800 RPM with an engine load of 25, 50 and 75% of maximum engine load and different ratio of EGR 0, 10 and 20% of air in combustion. The injection timing was examined at standard injection timing (15.5° CAD BTDC), retard injection timing 2° (13.5° CAD BTDC) and advance injection timing 2° (17.5° CAD BTDC).

2.2 Fuel

The experiment engine was primarily tested using conventional diesel fuel which the initial result was used as a reference for comparison test with engine fueled using DME injection. The DME injected in the intake manifold to enrich the inlet charge in order to examine the effect of DME addition on the engine performance and emissions. In this case, the engine was fuelled with diesel and diesel fuels with an addition of 10% DME. The main physical and chemical properties of DME and diesel fuel are presented in Table 2.

Table 2 Physical and chemical properties of DME and diesel fuel

Properties	DME	Diesel
Formula	CH_3OCH_3	$C_{14}H_{30}$
Density (g/cm^3)	0.00197(gas)	0.856
HHV (kJ/kg)	31,681	46,800
LHV (kJ/kg)	28,430	43,200
Cetane number	55-60	40-55
Boiling point (°C)	-24.9	125-400
Wt.% Oxygen	34.8	0
Wt.% Carbon	52.2	86
Wt.% Hydrogen	13	14

3. Results and discussion

3.1 Effect of fuel

The experiment compared the performance with emission between conventional diesel and 10% DME addition by mass of diesel at engine speed 1,500 RPM, 50% load and standard injection timing (15.5° CAD BTDC).

In-cylinder pressures profile is shown in Figure 2 for the engine with and without DME addition. The maximum combustion pressure when using DME was slightly lower than combustion pressure of diesel fuel, though the pressure profile has slightly higher dP/dt due to the high cetane number, low auto ignition temperature and short ignition delay [8] which enable early combustion. Therefore the advance combustion would take place [9].

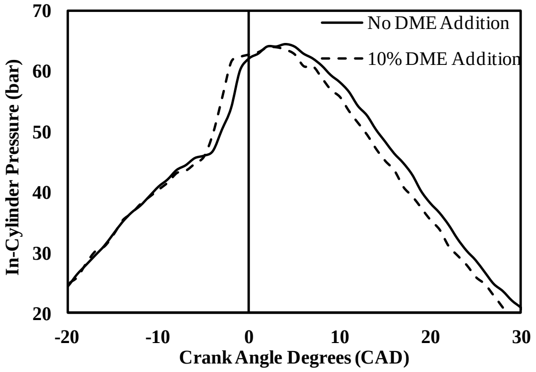

Fig. 2. Effect of DME addition on in-cylinder pressure

The results of 10% DME addition was compared with neat diesel fuel in terms of combustion efficiency. It can be observed in figure 3 that 10% DME fuelling slightly decreased the brake thermal efficiency due to the lower heating value of DME compared with diesel. On the other hand specific energy consumption (SEC) of DME addition is higher than diesel because of the low engine performance when using DME, hence the engine must be increase fuel injection rate to keep the same engine output and stability.

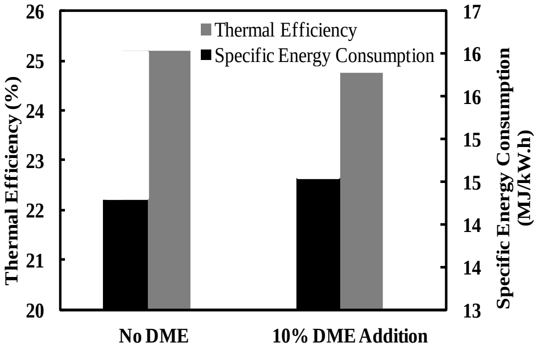

Fig.3. Effect of DME addition on thermal efficiency and specific energy consumption

The oxygenated fuel and non C-C bonds in a molecule frequently reduced to the soot formation as show in Fig.4. In this case, DME was responsible for soot free combustion. [7, 10-11]

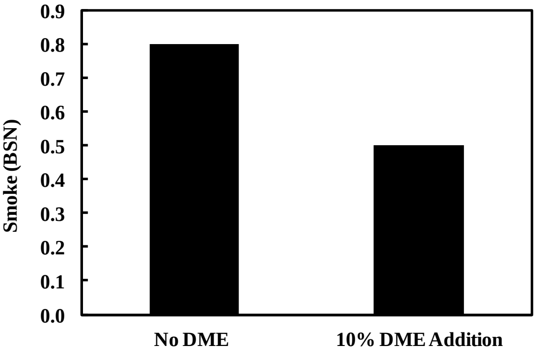

Fig.4. Effect of DME addition on smoke

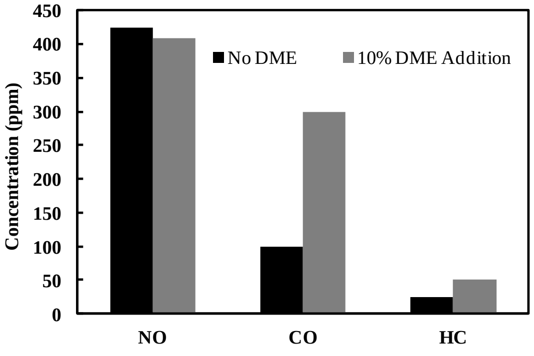

Fig.5 Effect of DME addition on exhaust gas emission

The DME addition in the intake manifold resulted in further NOx reductions. The reduction in the combustion temperature because of the low heating value of DME is the most likely reason to explain this trend. In addition, the lower local combustion temperature as a consequence of the more homogeneous combustion process when DME is added in the admission charge could contribute to this NO_X-decreasing trend [12]. However the carbon monoxide (CO) and total hydrocarbons (THC) level emitted from engine using DME were increased with DME addition compared with emission from diesel fuel. [7] This occurred as effect of incomplete combustion when injected DME and auto ignition before injection timing. (Fig.5)

3.2 Effect of injection timing

This experiment compare performance with emission of 10% DME addition in engine with various injection timing at standard injection timing (15.5° CAD BTDC), advance injection timing (17.5° CAD BTDC) and retard injection timing (13.5° CAD BTDC). All conditions tested under the same engine conditions, 1500 RPM, 50% load and 0% EGR.

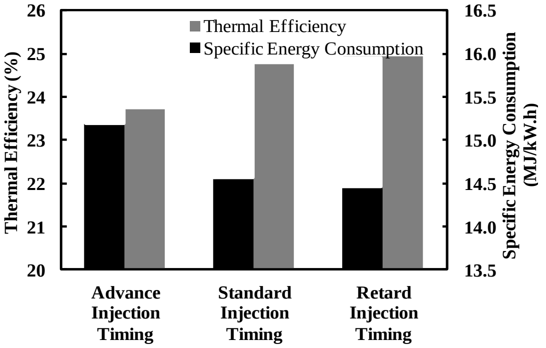

Fig.6. Effect of injection timing on thermal efficiency and specific energy consumption.

The advanced injection timing has no significant effect on smoke number which was slightly lower than retard injection timing as can been seen in Fig.7. The high level of soot formation with retardation of the injection timing has been found due to less time to complete combustion.

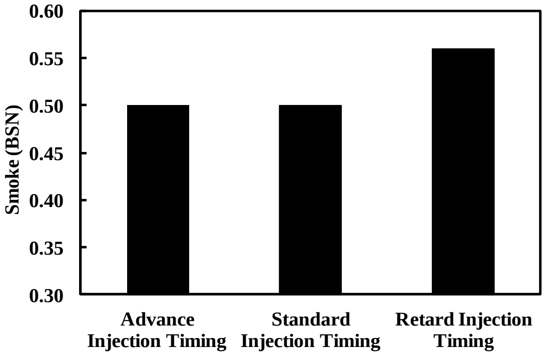

Fig.7. Effect of injection timing on smoke

The main NOx formation from diesel engine is thermal NOx. The retarded injection timing produced lower thermal NOx formation than standard and advance injection timing (Fig.8) in order to the lower adiabatic flame temperatures. On the other hand, injection timing demonstrated insignificant effect on total hydrocarbon.

As the result, the advantage of retard injection timing with DME dual fuel engine produced lower emission and better fuel economy. Therefore, the retard injection timing will be used for parametric study (e.g. engine load, engine speed and EGR) in the next section.

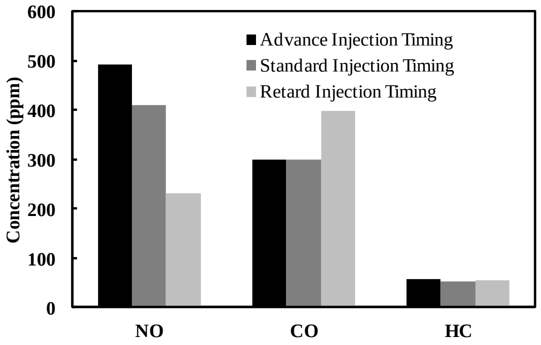

Fig.8. Effect of injection timing on exhaust gas emission

3.3 Effect of retard injection timing and engine speed on performance and emission

This experiment used 10% DME by port-injection and adjusted for retard injection timing for 2 CAD from standard injection timing and tested at 50% engine load without EGR addition.

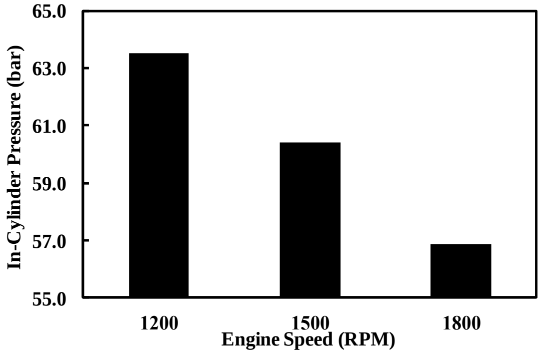

Fig.9. Effect of engine speed on in-cylinder pressure under retard injection timing

In Fig. 9 shows the maximum combustion pressure at each engine speed. The result shows that the engine speed of 1,200 rpm has the highest combustion pressure because retard injection timing caused shortened combustion period which led to higher peak of combustion pressure in given duration. Combustion duration at high engine speed was shorter than that of in low engine speed which combusted hot gas expansion process was incomplete and led to lowered peak pressure. However, thermal efficiency and SEC at the medium engine speed (1,500 RPM) shown the higher thermal efficiency and better fuel economy were indicated as shown in Fig. 10.

In the case of black smoke level (Fig.11). Black smoke concentration at 1,500 RPM was lower than that of 1,200 and 1,800 RPM about 63 % and 17%, respectively. In order to when added 10% DME in duel fuel engine, the engine was able to operate with higher efficiency at 1,500 RPM and affected soot oxidation.

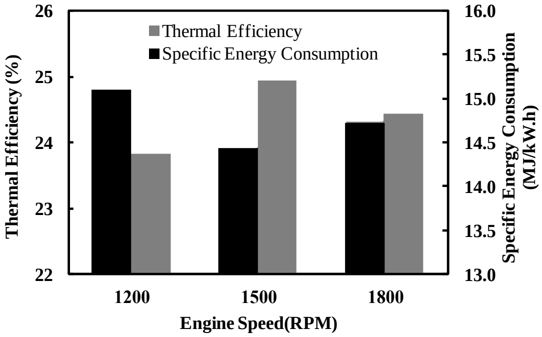

Fig.10. Effect of engine speed on thermal efficiency and specific energy consumption under retard injection timing

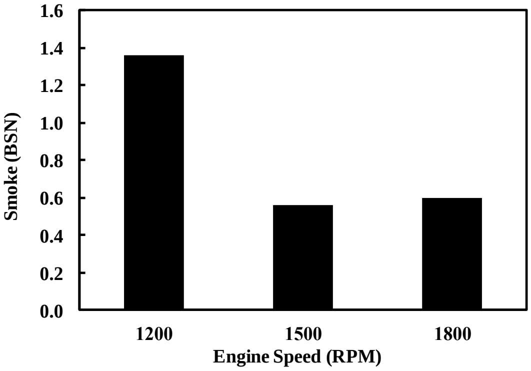

Fig.11. Effect of engine speed on smoke under retard injection timing

Testing at high engine speed (1800 RPM) produced lower NO_X emission level compares with low and middle speeds (Fig.12) due to the lower peak combustion pressure of high engine speed was able to decrease NO_X level. On the other hand, CO and total HC concentrations emitted from all engine speeds condition were about at the same level.

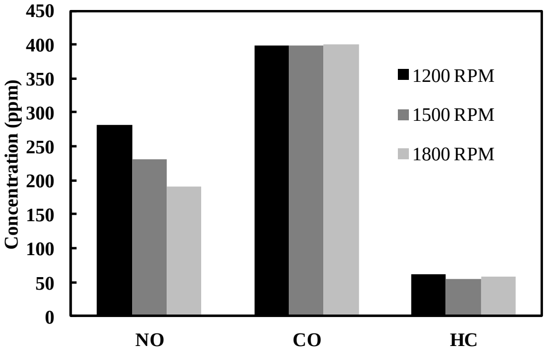

Fig.12. Effect of engine speed on emissions under retard injection timing

3.4 Effect of retard injection timing and engine load on performance and emission

This engine test condition in low, medium and high engine load (25, 50 and 75% respectively) and using 10% DME addition at 1,500 RPM and 0% EGR. Fig. 13 showed in-cylinder at each engine load. Average in-cylinder pressure increased as engine load increased. In addition at 75% engine load produced higher thermal efficiency with lower SEC (Fig 14) compared with other conditions due to more complete combustion process.

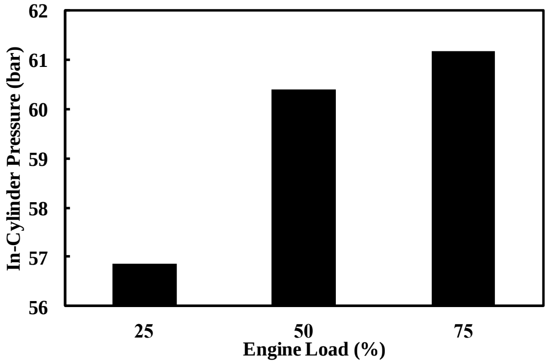

Fig.13. Effect of engine load on in-cylinder pressure under retard injection timing

Fig. 15 illustrated high amount of soot was indicated at high engine load which was significant higher than medium and low load by 80% and 84%, respectively. Furthermore, highest NO and CO concentrations were observed at 75% engine load as shown in Fig.16. NO was significant increased due to the relationship of pressure-temperature according to thermodynamic properties of gas. Meanwhile, CO was noticeable increased due to high amount of diesel was injection to overcome high engine load which caused fuel-rich region. This led to poor oxygen entrainment from intake air to fuel drops and caused incomplete combustion. In addition, port-injected DME also displaced partial air intake which led to local-insufficient air to promote CO oxidation in late combustion process.

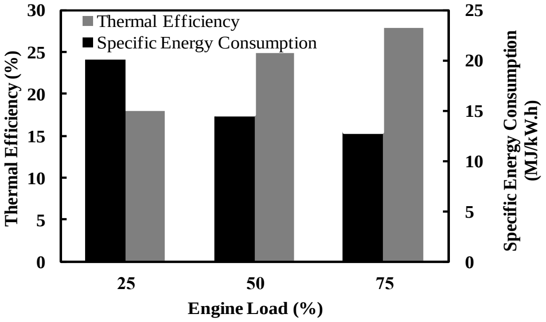

Fig.14. Effect of engine load on thermal efficiency and specific energy consumption under retard injection timing.

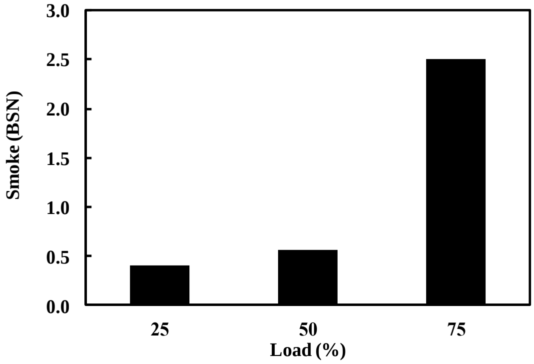

Fig.15. Effect of engine load on smoke number under retard injection timing

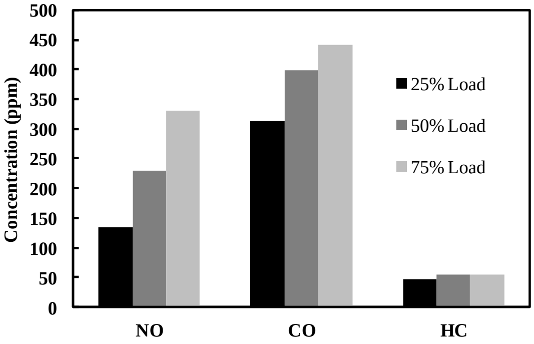

Fig.16. Effect of engine load on emissions under retard injection timing

3.5 Effect of retard injection timing and EGR on performance and emission

In this study, engine-out performance and emission from DME dual fuel engine was performed at engine speed 1,500 RPM and 50% engine load which used EGR system at 0, 10 and 20% of intake air. (By volume)

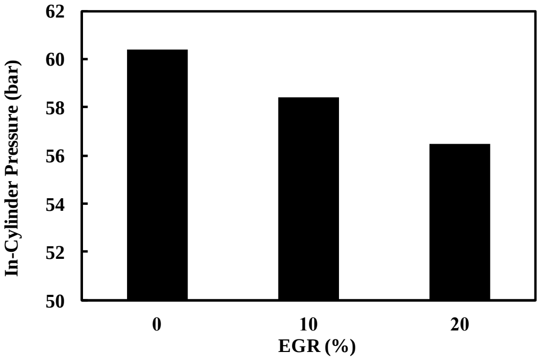

Fig.17. Effect of retard injection timing and EGR on In-Cylinder pressure

The higher EGR addition to combustion chamber lead to incomplete combustion caused the lower pressure in-cylinder. No EGR addition found the highest in-cylinder pressure (60.2 Bar), which higher than of 10% and 20% EGR addition for 4% and 10%, respectively. (Fig.17)

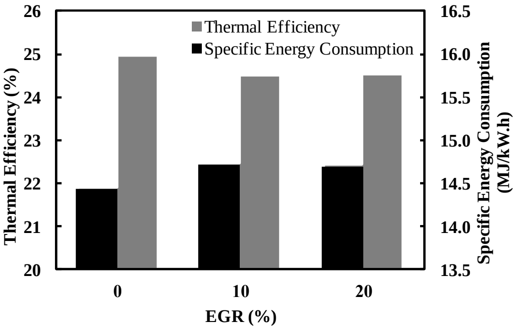

Fig.18. Effect of EGR on thermal efficiency and specific energy consumption under retard injection timing

Thermal efficiency (Fig. 18) without EGR was higher than of conditions using EGR due to introduction exhaust gas that consist moisture and other incombustible gases into cylinder caused poor combustion process and yielded noticeable effect on SEC. Under 0% EGR condition was the best energy consumption and complete combustion.

The engine with DME addition with retard injection timing and without EGR system produced lower smoke compare with EGR condition due to EGR system was an effectively reduce combustion temperature and led to NOx reduction. Increasing EGR flow rate led to increased smoke number as the results as shown in Fig.19.

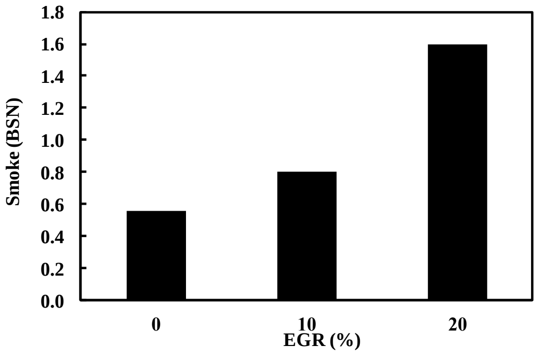

Fig.19. Effect of EGR on smoke under retard injection timing

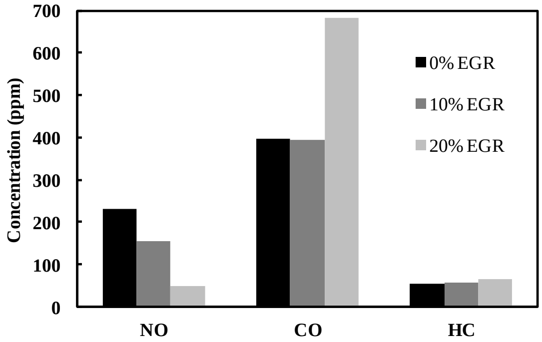

Fig.20. Effect of EGR on emission under retard injection timing

EGR system was able to effectively reduced NO_X concentration emitted from engine due to its chemical effects on combustion process which led to the lower combustion temperature. Nitrogen oxides from thermal NO_X were reduced when EGR (10% and 20% by Vol) was introduced. As expected from EGR introduction, CO concentration was significant increased due to poor combustion process as shown in Fig.20. In this case, the situation of oxygen presence in the cylinder was close to critical. As intake air was replaced by both DME port-injection and EGR introduction which resulted in insufficient oxygen to oxidise CO into CO_2.

3.5 Particle size distributions

Particle mass distributions with port-injected DME 10%-50% by volume compared with conventional diesel combustion is shown in Fig.21.

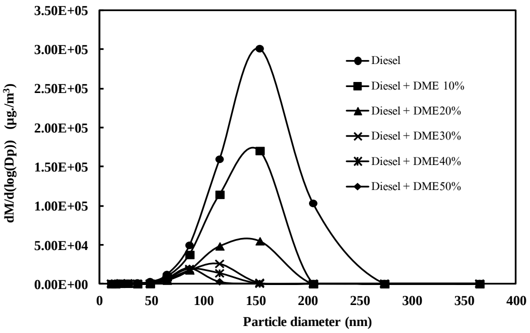

Fig.21. Effect of DME addition on Particle size distributions

PM in accumulation mode was found to reduce toward smaller diameter when DME was introduced. Furthermore, increasing amount of DME injection was able to further reduce particle size. PM size was effectively reduced by outstanding oxygenate-fuel characteristic of DME which enhanced PM oxidation during and after combustion process.

4. Conclusion

Introduction of DME-diesel dual fuels in compression ignition engine led to the start of combustion occurred before the injection of convention diesel fuel, which reduced overall thermal efficiency. In addition, the engine also produced higher overall emissions. After modified the engine which injection timing was adjustable (Advance 2° CAD) revealed the decrease of thermal efficiency while the energy consumption and emission (NO_X and THC) increased and BSN reduced. On the other hand, the retard injection timing led to improved thermal efficiency and thus, energy consumption, reduction of NO_X and THC. Overall, retard fuel injection timing of engine was needed to find the optimization point to further improve the efficiency and emission of DME dual fuel engine. The result of retard injection timing when increase engine speed the combustion pressure was reduce. Considering all engine speed revealed that medium engine speed (1,500 RPM) at high engine load and 20% EGR addition was the most optimal condition in term of fuel economy and decrease NO_X emission.

According to the test results at high engine load (75% load) indicated the highest thermal efficiency and excellent fuel economy. On the other hand, black smoke, NO_X and CO at high load was higher than low and medium engine load.

NO_X reduction strategy, EGR led to overall reduction of engine performances while demonstrated excellent NOx reduction performance. NOx-PM trade-off is necessary to obtain satisfied engine performances. From the result effect of EGR show the decrease of NO_X formation in combustion process but it also effect to produce more smoke number and CO.

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