Liquefied Petroleum Gas and Dimethyl Ether Compression Ignition Engine

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ABSTRACT

The combustion and exhaust emission characteristics of a liquefied petroleum gas (LPG) and dimethyl ether (DME) compression ignition engine were investigated under homogeneous charge and stratified charge conditions. LPG was used as the main fuel and injected into the combustion chamber directly, while DME was used as an ignition promoter and injected into the intake port. A commercial variable valve train was used to control the volumetric efficiency and the amount of internal residual gas. Different LPG injection timings were tested to verify the characteristics of the LPG and DME compression ignition engine.

The homogeneity of fuel affects the exhaust emissions and combustion characteristics. The fuel was stratified by changing the injection timing of the LPG direct injection. Three different types of combustion phenomena were observed. The homogeneous charge, stratified charge, and diffusion combustion conditions were identified. The injection timing was retarded as the LPG stratification and localized rich zone were intensified. The hydrocarbon emission decreased under stratified combustion, due to a reduced amount of trapped Hydrocarbon in the crevice volume of the combustion chamber. However, the carbon monoxide emission increased, due to a lack of oxidation reaction during expansion stroke. Moreover, the nitric oxide emission increased, due to the increased localized rich zone size.

The start of combustion was advanced as the injection timing was retarded. This is attributed to the cetane number of the total mixture. The particulate matter emission was observed during the stratified combustion. The high particulate matter emission originated from the localized fuel-rich zone. The operating range of high load operation is limited by the heavy knock and noise. The knock intensity decreased with the stratified combustion by the occurrence of a longer burn duration compared to the homogeneous charge combustion. The indicated mean effective pressure was decreased with stratified charge combustion, due to early combustion, leading to the increased compression work.

INTRODUCTION

The diesel engine is a type of stratified charge compression ignition (SCCI) engine. This self ignited stratified charge leads to high nitric oxide (NOx) and particulate matter (PM) emissions, due to the high combustion temperature and fuel rich zone [1]. In order to reduce the NOx and PM emission simultaneously, the homogeneous charge compression ignition (HCCI) combustion concept is introduced [2]. However, the HCCI combustion leads to high hydrocarbon (HC) and carbon oxide (CO) emissions. High HC and CO emissions are the result of low combustion temperature, which leads to low NOx emission. The ultra lean mixture releases less heat than the rich mixture. The HC and CO emissions are insufficiently oxidized, due to a lower combustion temperature [3]. However, the CO emission originates, due to a lack of oxidation reaction during the expansion stroke. The CO emission is an index of incomplete combustion [4].

In order to increase the combustion temperature, the stratified charge concept is introduced similarly to that of the compression ignition (CI) diesel engine. The results of previous research show that the stratified charge increases the combustion temperature at a rich operating limit [5,6]. The stratified charge has potential for reducing the exhaust emission, which indicated that the mean effective pressure (IMEP) increased by increasing the combustion temperature and burn duration. The HC and CO emissions can be reduced by changing the injection timing, which controls the grade of the stratified charge [7]. Rich operation leads to a high combustion temperature, which provides more heat for the CO molecules to oxidize into carbon dioxide (CO_2).

The HCCI engine combustion depends on the air/fuel mixture distribution at the compression stroke. However, it is hard to control the air/fuel mixture at the compression stroke, after the intake valve close, using the port fuel injection [3,8,9]. In order to overcome this problem, the direct injection system is introduced. The direct injection system can control the air/fuel mixture distribution at the timing of ignition, through the fuel injection, during the intake and compression stroke [9,10]. The major problem of the direct injection engine is PM emission. To eliminate the PM emission, a gaseous fuel can be used. Liquefied petroleum gas (LPG) and dimethyl ether (DME) are the most promising alternative fuels for near future applications. LPG contains less carbon molecules than that of gasoline and diesel, so that the carbon dioxide (CO_2) and HC emissions are reduced, by using LPG fuel in the vehicle engines [11]. DME is regarded as an alternative fuel to diesel. DME contains oxygen molecules and they are vaporized very easily, which can lead to soot free combustion [12].

Hot internal residual gas is the source of heat that can promote HCCI combustion [13]. This hot internal residual gas can be controlled by a VVT device [14]. A VVT device can improve volumetric efficiency by varying the intake valve's open and close timing [15]. The VVT system can control the internal residual gas amount, which affects the start of combustion and the subsequent combustion process. The HCCI engine combustion depends on the air/fuel mixture distribution at the compression stroke.

In this research, LPG SCCI combustion and emission characteristics are investigated. A VVT is used to control internal residual gas. DME is used as an ignition promoter, by intake port injection. The effects of LPG direct injection timing and intake valve open and close timing on the LPG SCCI combustion were investigated.

EXPERIMENTAL APPARATUS

ENGINE

Figure 1 shows a schematic diagram of the experimental setup. The engine speed and load were controlled by an alternating current (AC) dynamometer. A swirl injector (Mitsubishi Motor Co.) was used to inject LPG at a constant supply pressure of 5 MPa using pressurized nitrogen gas. The LPG injector was located at the spark plug hole. A slit injector (Denso Co.) was used to inject

Table 1 Engine specifications

Bore (mm)		82
Stroke (mm)		93.5
Compression ratio		13
Displacement (cc)		494
Intake / Exhaust valve duration		228 / 228
Intake / Exhaust valve lift		8.5 / 8.4
Valve timing (CAD)	Intake Valve Open (ATDC)	-29 ~ 11
	Intake Valve Close (ABDC)	59 ~ 19
	Exhaust Valve Open (BBDC)	42
	Exhaust Valve Close (ATDC)	6
DME and LPG injection pressure (MPa)		5
LPG injector		Swirl injector

DME with the same pressure as that of the LPG. The DME injector was located at the intake port 30 cm up from the intake valve. A lubricity enhancer (Infineum, R655) of 500 ppm was added to the DME, in order to avoid any damages to the fuel injection system. The incylinder pressure was measured by a piezoelectric pressure transducer (Kistler, 6052b). The intake and exhaust manifold pressures were measured by two piezo-resistive pressure transducers (Kistler, 4045A5). The intake and exhaust temperatures were measured by two K-type thermocouples, which fitted on the intake and exhaust manifolds. A wide band lambda meter (ETAS, LA4) was installed for the measurement of the relative air / fuel ratio. Exhaust gases were analyzed with a gas analyzer (Horiba, Mexa 1500d) to measure the HC, NOx, CO, and CO_2 emissions. The air flow rate was measured, in order to obtain volumetric efficiency, by a laminar flow meter (Meriam Co., 50MC2-2S). A data acquisition

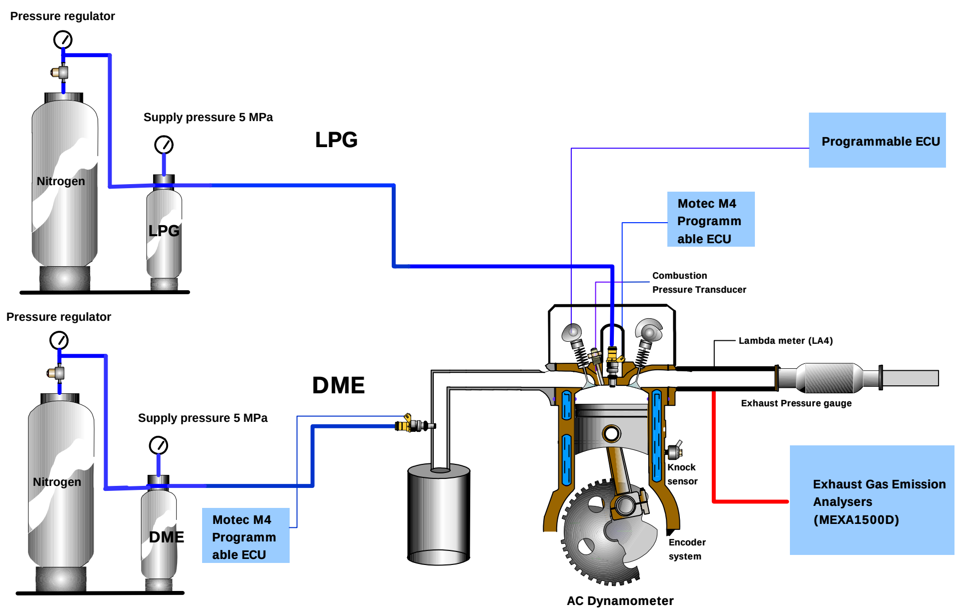

Figure 1 Schematic diagram of experimental apparatus

Table 2 Experimental conditions

Engine speed (rpm)	1000
Intake Valve Open timing (CAD)	-29, -19, -9, 1, 11
LPG injection timing (CAD)	0, 100, 200, 300, 320, 325, 335, 340, 350
λ_{TOTAL}	1.667
λ_{DME}	3.7
Intake charge temperature (^{O}C)	30
Coolant / Oil temperature (^{O}C)	80 / 80

system (IOtech, Wavebook 512H) was employed to acquire all engine combustion and exhaust gas data. The indicated mean effective pressure (IMEP) and heat release rate were calculated from the cylinder pressures [16].

The specifications of the engine are given in Table 1. It is a single cylinder, double over head camshaft (DOHC) engine equipped with a VVT, LPG direct injection DME port injection system. An engine control unit (ECU) (Motec Co., M4) was employed to precisely control the LPG quantity and injection timing. The LPG injector signal converted the saturate type into the peak and hold type with an injector driver (Mitsubishi Co.). Another ECU (ETAS Co.) was used to control the DME injection quantity, timing, and intake valve timing.

The intake valve open timing was varied in the range of 29 crank angle degree (CAD) before top dead center (BTDC) to 11 CAD after top dead center (ATDC), while the valve duration was fixed as 228 CAD.

EXPERIMENTAL CONDITIONS

Figure 1 shows a schematic diagram of the experimental setup. The engine speed and load were controlled by an alternating current (AC) dynamometer.

Table 2 shows the experimental conditions used in this study. Figure 2 shows the intake valve timing and the DME injection timing. The engine was operated at 1000 rpm for various intake valve timings and equivalence ratios. The intake valve open (IVO) timings were varied from -29 CAD ATDC to 11 CAD ATDC. At -29 CAD of IVO timing, the volumetric efficiency was 80%. At 11 CAD of IVO timing, it was 66.2%. The LPG injection timing was varied from 0 CAD to 350 CAD. DME was injected at the intake manifold during the exhaust stroke.

In order to quantify the knock intensity, the ringing intensity (RI) was employed. The RI indicates the pressure oscillation energy of the knock (1) [17].

$$\mathrm{RI}=\frac{1}{2\cdot\gamma}\cdot\frac{\sqrt{\gamma RT}}{P}\cdot\frac{1}{N}\cdot\sum_{1}^{N}(0.05\cdot(\frac{\partial p}{\partial t})_{\max})^2 \quad (1)$$

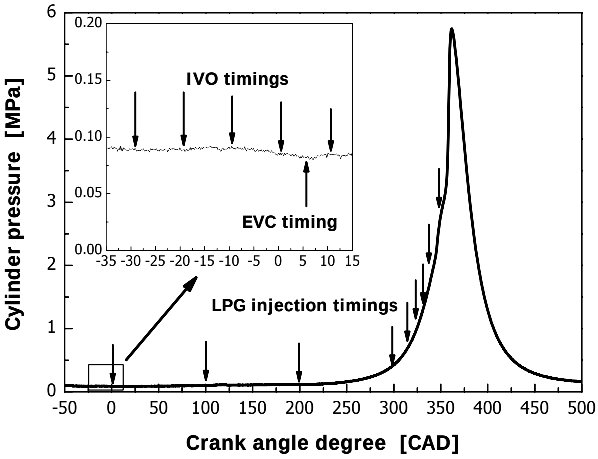

Figure 2 Intake valve open, exhaust valve close and DME injection timing at 1000 rpm

100 cycles of combustion pressure analysis was carried out for each experimental condition. The indicated mean effective pressure (IMEP) and heat release rate were calculated from the cylinder pressures using equation (2) [16].

$$\frac{dQ}{d\theta}=\frac{\kappa}{\kappa-1}P\frac{dV}{d\theta}+\frac{1}{\kappa-1}V\frac{dP}{d\theta}+\Delta Q_{heattransfer} \quad (2)$$

The well-known DME oxidation reaction has a two-stage auto-ignition process, heat release with low temperature reaction (LTR) and high temperature reaction (HTR) [17].

The heat release of the LTR was approximately 8~12% of the total heat released. In order to eliminate the effects of the LTR, the burn duration is defined as the period between the duration for 20% mass fraction burned (MFB) and the duration for 90% MFB.

λ (relative air/fuel ratio) is defined as the ratio; $(A / F)_{actual} / (A / F)_{stoichiometric}$. λ_{TOTAL} is defined as [6],

$$\lambda_{TOTAL}=\frac{\lambda_{gasoline}\lambda_{DME}}{\lambda_{gasoline}+\lambda_{DME}} \quad (3)$$

EXPERIMENTAL RESULTS

The main objective of stratified charge combustion is the reduction of HC and CO emissions in the lean condition [7]. Figure 3 shows the effect of injection timing of the LPG on the HC emission of LPG-DME combustion. The horizontal axis represents the injection timing of the LPG direct injection. The vertical axis represents the HC emission of each test condition.

The HC emission remained constant as the injection timing advanced, for the case in which the injection timing was varied from 0 CAD to 300 CAD. The homogeneity of the LPG was also not changed when the

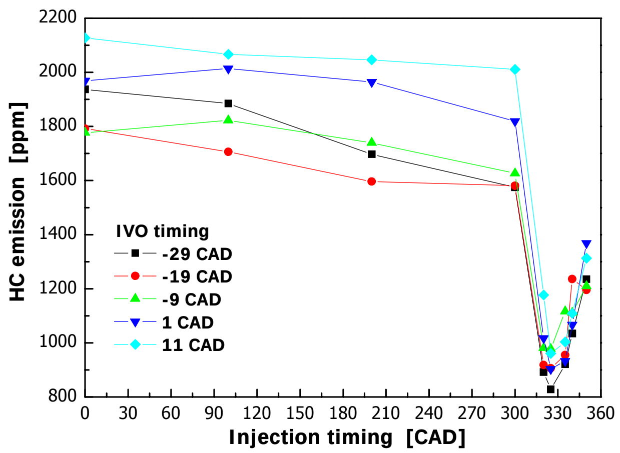

Figure 3 HC emission of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

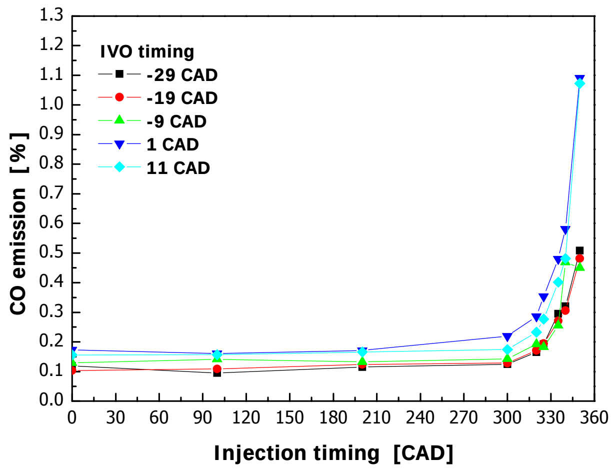

Figure 4 CO emission of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

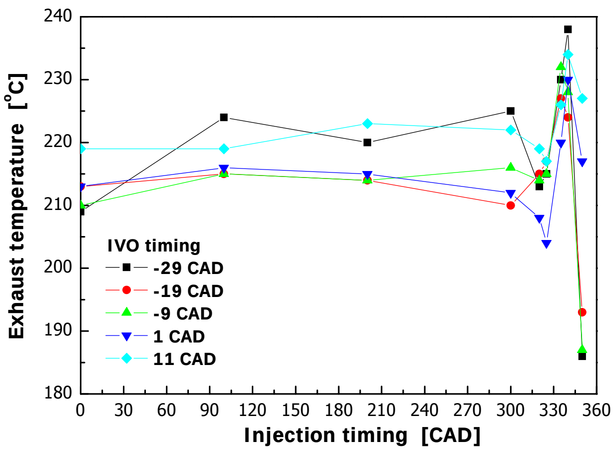

Figure 5 Exhaust temperature of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

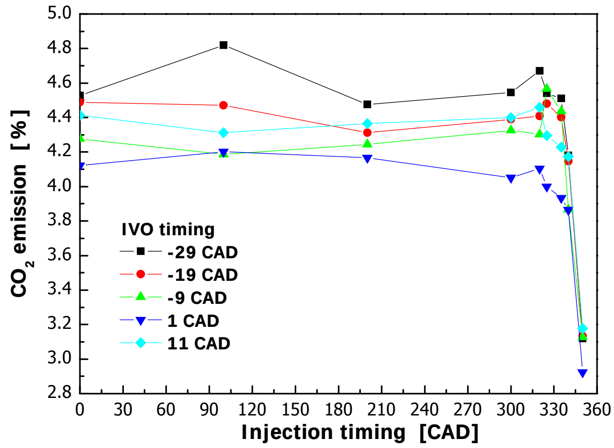

Figure 6 CO_2 emission of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

start of injection initiated during intake and the early compression stroke. From now on in this paper, these four injection timing conditions are defined as the homogeneous charge conditions.

In the case of the 320 CAD and 325 CAD injection timing, the HC emission was reduced by half. The main source of the HC emission is trapped HC molecules in a crevice volume in the combustion chamber [16]. Trapped HC emission is released during the expansion stroke, due to a lowered combustion chamber pressure. The oxidation reaction during the expansion stroke can reduce the trapped HC molecules. However, the CO emission trend, which is shown in Fig. 4, is opposite to the HC emission trend. The effect of the oxidation reaction during the expansion stroke on the HC and CO emissions is the same. The CO emission can be oxidized by the combustion heat during the expansion stroke. From the CO emission results, the oxidation reaction during the expansion stroke was reduced. This fact is also confirmed by the exhaust gas temperature. The exhaust gas temperature is shown in Fig. 5. The exhaust gas temperature of the 320 and 325 CAD was approximately 2~10°C lower than the homogeneous charge region. The oxidation reaction was reduced, due to a lower gas temperature. However, the dominant factor of HC emission decrease was the reduced amount of molecules in the crevice volume. The spray structure of the swirl injector used for the LPG direct injection in this study is a hollow cone shape. The injected LPG was gathered at the center of the combustion chamber. This is a possible reason for the reduction in HC emission, which is opposite to the CO emission trend. The amount of CO_2 emission is shown in Fig. 6. There was a slight reduction, in the case of CO_2 emission, which was due to the oxidation reaction reduction during the expansion stroke.

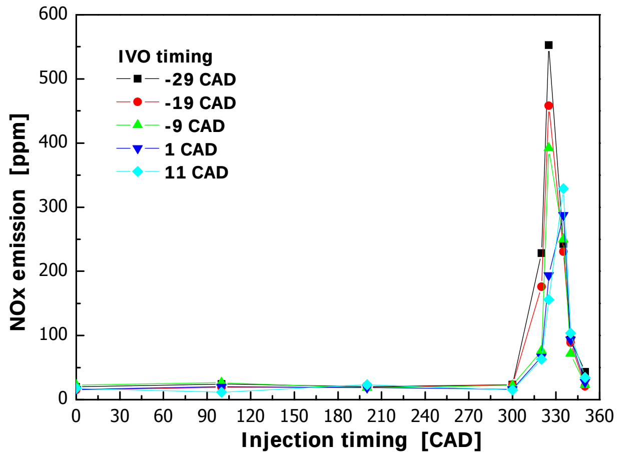

Figure 7 NOx emission of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

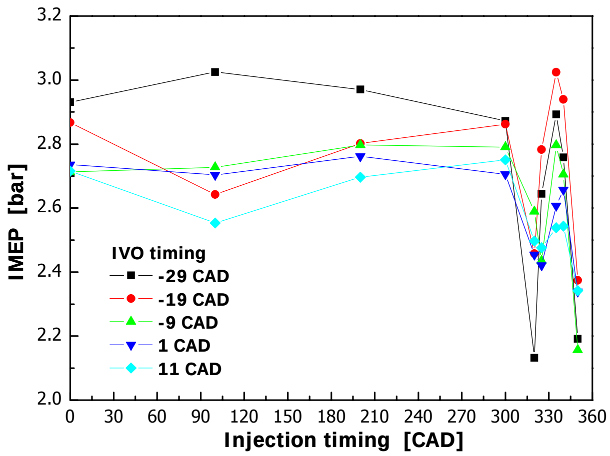

Figure 8 IMEP of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

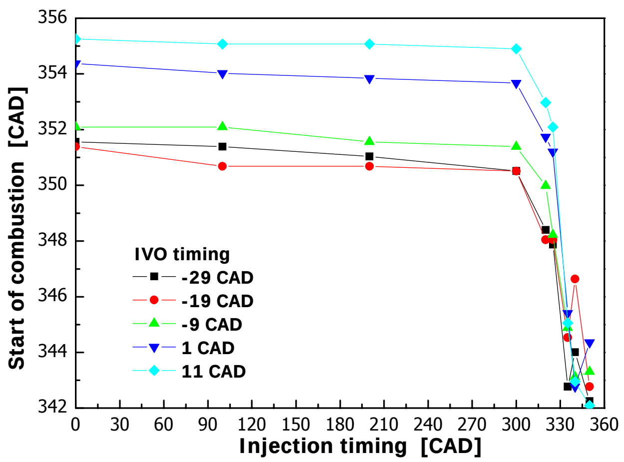

Figure 9 start of combustion timing of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

In contrast, the amount of NOx emission was increased dramatically, due to a localized high temperature region. Generally, the NOx emission formed in this localized high temperature region. However, at these conditions, the soot emission was almost zero. These two exhaust emissions verify that the charge is stratified and that most of the fuel was fully combusted and oxidized. The temperature and equivalence ratio of charge are approximately similar to region A, which shows no soot emission and low NOx emission. The injection timing at 320 and 325 CAD are defined as the stratified charge conditions.

The indicated mean effective pressure of these two injection conditions was quite lower than that of the homogeneous charge conditions. The IMEP results are shown in Fig. 8. The IMEP loss of the stratified charge can be explained utilizing the start of combustion, which is shown in Fig. 9. The start of the combustion timing of the stratified charge combustion was faster than that in the homogeneous charge combustion. The auto-ignitibility of charge is dependent on the fuel cetane number [3]. The addition of high octane number fuel into the high cetane number fuel reduces the cetane number of fuel mixture. For this case, the auto-ignitibility of the charge is made poorer and the start of the combustion is retarded. In homogeneous charge combustion, the charge of fresh air, dimethyl ether, and liquefied petroleum gas were mixed, in order to create a cetane number that was lower than that of the DME. The start of the ignition timing was retarded. However, in the case of the stratified charge combustion, the LPG was stratified in the combustion chamber and the combustion chamber was divided into two sections, of which one was at a high cetane number with a low LPG concentration and the other was at a low cetane number with a high LPG concentration. The combustion was initiated with a high cetane number and then the LPG rich zone was combusted by the heat of the precombustion. Due to these reasons and the stratified LPG, the start of combustion of the stratified charge was earlier than that of the homogeneous charge. The start of combustion occurred between 350 and 355 CAD. Moreover, the combustion was finished before the top dead center in the homogeneous charge combustion region. A large portion of the fuel was combusted before the TDC. The IMEP of the homogeneous charge combustion was decreased, due to earlier combustion. The objectives of the stratified charge combustion in a spark ignition engine are stability and increased power output under lean operating conditions. However, the IMEP decreased as the injection timing was retarded, due to earlier combustion. In conclusion, the IMEP drop was observed in the stratified charge combustion, due to increased negative work.

Another effective methodology of retardation of the combustion is needed to increase the IMEP. Finally, the stratified combustion region was extended.

The HC emission increased as the injection timing was retarded when the injection timings of the LPG were 335

CAD and 340 CAD. The CO emission also increased for the same injection timing conditions. Moreover, the soot emission increased dramatically. This indicates that the heterogeneity of the LPG increased. These two injection conditions are defined as the diffusion combustion region. The HC emission of the diffusion combustion increased, due to high heterogeneity of charge.

The exhaust temperature of these conditions was higher than that of the early injection conditions, due to a localized stoichiometric zone. However, the size of the localized rich zone also increased. The HC and soot emissions increased simultaneously, due to the localized rich zone. The injection duration of the LPG direct injection was approximately 2.5 ms, while the engine operated at 1000 rpm. From a simple calculation, the crank angle of the injection duration was 15 CAD.

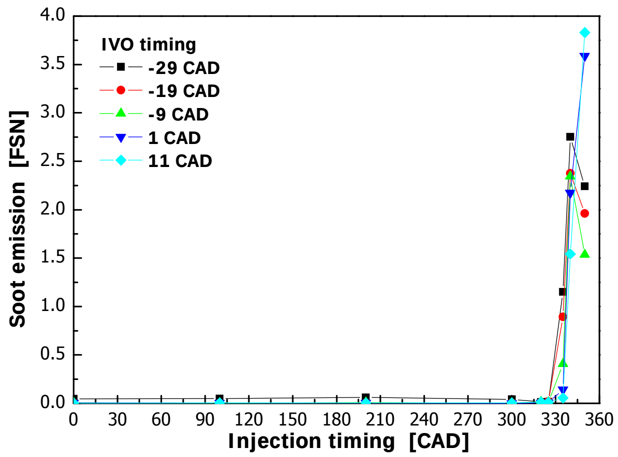

Figure 10 Soot emission of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

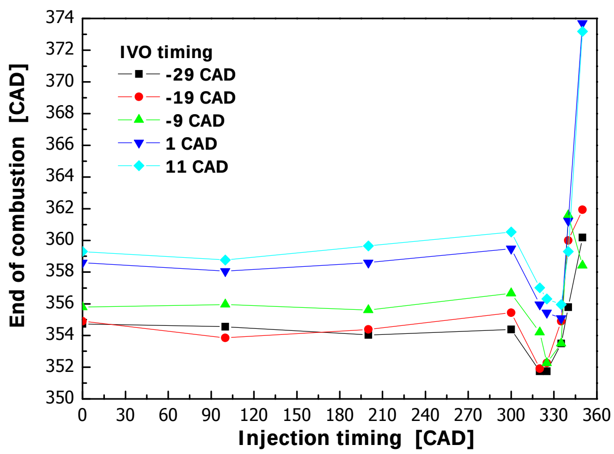

Figure 11 end of combustion timing of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

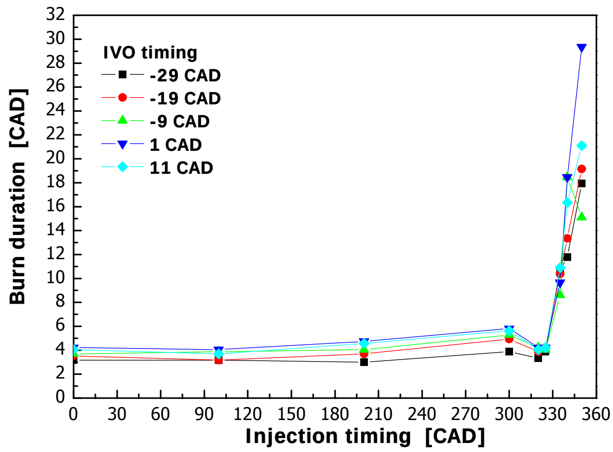

Figure 12 burn duration of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

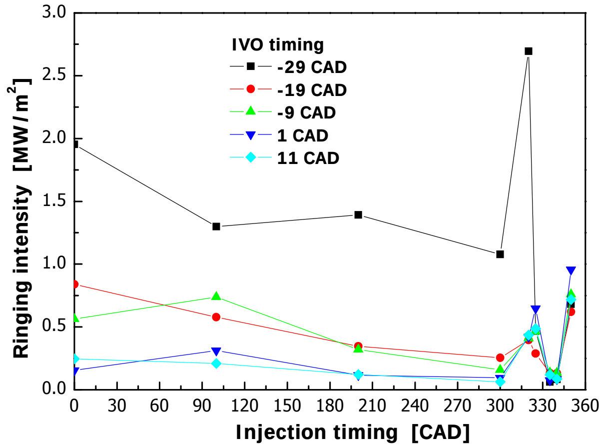

Figure 13 Ringing intensity of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

In the case of the 325 CAD injection timing, the injection finished just before low temperature oxidation occurred. With this condition, there was not enough time to adequately mix the air and fuel. For the case of the 335 CAD injection timing, the injection started just before low temperature oxidation occurred. In this case, there was not enough time to mix the air and fuel. Thus, a localized rich zone formed.

The IMEP of the diffusion combustion decreased as the injection timing was retarded, due to early combustion. However, the burn duration was longer than that of the stratified charge and the homogeneous charge combustion conditions. This longer burn duration is due to the diffusion combustion characteristics. The localized LPG rich zone was oxidized later. Fig. 13 and 14 show the ringing intensity and maximum combustion pressure of the LPG-DME combustion. The high load operating range limitation of the test engine is under the RI of 0.5 MW/m^2 [19]. The RI of the stratified charge combustion was slightly higher than that of the homogeneous charge combustion even at the maximum combustion pressure. The relation between the maximum combustion pressure and the RI was previously reported [19]. The RI was reported as a function of the maximum combustion pressure. From previous results, the RI increased when the maximum combustion pressure was above 6.5 MPa. However, the start of combustion advanced when subjected to stratified charge combustion conditions. Due to early combustion, the RI of the stratified charge combustion was higher than that of the homogeneous charge combustion. The crank angle of the maximum combustion pressure advanced when subjected to the stratified charge combustion. This timing is shown in Fig. 15. The RI almost reached a zero level under these diffusion combustion conditions. This is attributed to an extended and retarded combustion. The maximum

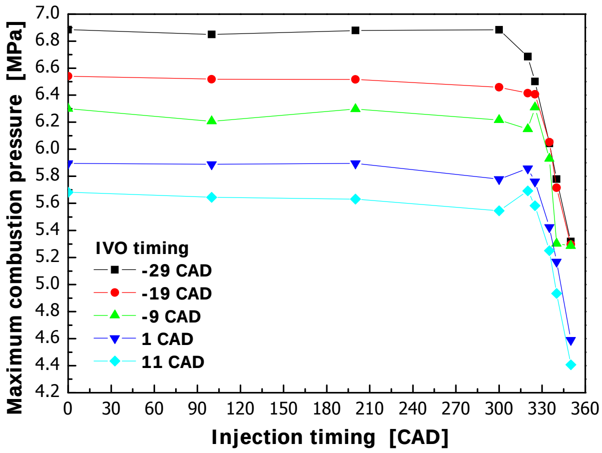

Figure 14 Maximum combustion pressure of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

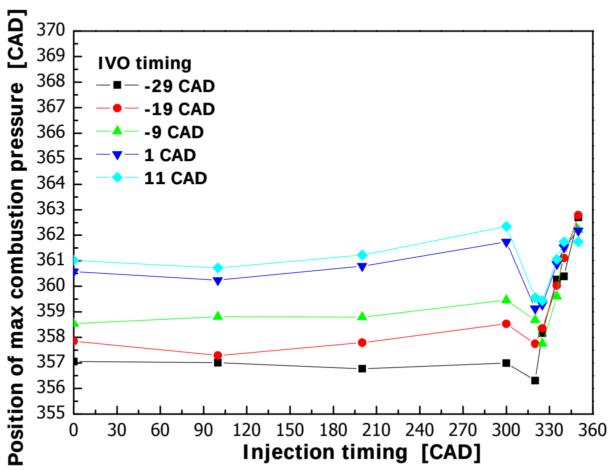

Figure 15 Position of maximum combustion pressure of LPG-DME CI engine with respect to injection timing and intake valve open timing at 1000rpm

combustion pressure also decreased under these diffusion combustion conditions.

CONCLUSIONS

The LPG homogeneity affects the exhaust emissions and combustion characteristics. The LPG was stratified by changing the injection timing of the LPG direct injection. Three different types of combustion phenomena were observed. The homogeneous charge, stratified charge, and diffusion combustion conditions were defined. The injection timing was retarded as the LPG stratification and localized rich zone were increased. The HC emission decreased under stratified combustion, due to a reduced amount of trapped HC in the crevice volume of the combustion chamber. However, the CO emission increased, due to a lack of oxidation reaction during the expansion stroke. Moreover, the NOx emission increased, due to an increased localized rich zone size.

The start of combustion advanced as the injection timing was retarded. This is attributed to the cetane number of the total mixture. The soot emission was observed during the stratified combustion. The high soot emission originated from the localized rich fuel zone. The knock intensity decreased with the stratified combustion by the occurrence of a longer burn duration compared to the homogeneous charge combustion. The IMEP decreased with stratified charge combustion, due to early combustion. However, the IMEP of the diffusion combustion was almost at the same level as the homogeneous charge combustion.

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