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Effect of DMC blend ratio on emission characteristics for diesel engine generator fueled with DMC/diesel blend fuel

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In this study, the DMC/diesel blend with 5%, 10%, 15% DMC by volume are prepared to investigate the emission characteristics. Since the combustion process is strongly influenced by the addition of low boiling point DMC boosts the atomization and liquid fuel mixture, the emissions of hydrocarbons and particulate matter are significantly reduced by the DMC addiction especially on the high-load conditions. Also, the nitrogen oxide emission has reduction on the high-load conditions. The scope for balancing NO_x and HC emissions exists.

Key words: *dimethyl carbonate, oxygenate fuel, diesel engine, emission characteristics, blend fuel*

1. Introduction

Diesel engines are well-known for the high thermal efficiency and extensively utilized in various applications due to their reliability and durability. However, the combustion of fossil fuels in internal combustion engines, including diesel engines, has contributed significantly to the increasingly severe climate issues [2]. It is imperative to seek solutions for reducing consumption of traditional fossil fuel and emission for diesel engines [11]. In response to these challenges, diesel engines have adapted many technical solutions like the innovation of injection method or the application of alcohol fuel to meet both the strict emission regulation and the depletion problems of fossil fuel resources [3, 5], like using higher injection pressure [12], the HEUI fuel injection system [9], the HCCI diesel engines [22], also the adaption of air filter to reduce the HC and CO emission [7]. many efforts about engine with alternative fuel and adaption on engine have been made. The possible attempt of prechambers in hydrogen internal combustion engines is discussed [15]. Research about LPG+DME blend fuel on SI engine is conducted [14]. Previous research indicated the efficiency of oxygenated fuel application on diesel engines can benefit those two purposes as well, such as using the alcohols, ethers, and esters for its good performance on diesel engines and the merits as the renewable fuels [18]. As the mostly investigated oxygenate, the biodiesel is also attracting attention. It is widely accepted for compression ignition (CI) engine for its renewability [19]. Biodiesel has many advantages such as reducing dependence on imported petroleum, mitigating global warming, improving lubrication, and reducing harmful emissions by its oxygen content. However, it can affect in-cylinder parameters like atomization, vaporization, and fuel-air mixing which considered as disadvantages. Insufficient cetane quality in biodiesel can lead to unfavorable starting characteristics, higher fuel consumption, and elevated exhaust emissions [6]. To solve these problems, the use of fuel additives can achieve effective atomization and fuel-air mixing. The cetane number plays an important role. Fuel with higher cetane numbers have shorter ignition delays, completing a shorter duration of the combustion process [1, 21]. Previous studies found that dimethyl carbonate (DMC)-diesel can lead to reduction on smoke and particulate mass with little change in NO_x emission [16].

DMC can be used as an oxygenated additive to blend with diesel fuel to improve combustion and reduce pollutant emission of diesel engines since it has a high oxygen fraction of 53.3% by mass. It is non-toxic and highly miscible with diesel fuel. DMC exists in liquid state at room temperature, which makes storage and transportation convenient. Research suggested that DMC is a suitable oxygenated additive with good blend fuel properties, and there exists a relationship between the amount of soot reduction and the oxygen content of the blended fuel [17]. Others [10, 23] investigated the combustion and emission characteristics of diesel engine fueled with diesel–DMC blends and found that smoke emission can be reduced without sacrificing NO_x emission and thermal efficiency. Dimethyl carbonate (DMC) added into diesel can help fuel atomize and produce a uniform air-fuel mixture due to its favorable evaporation attribute. It is a nontoxic compound and can easily dissolve in diesel at ambient temperature. Previous studies have indicated the potential of DMC in emissions reduction and thermal efficiency enhancement [5, 17, 20].

The emissions of an indirect injection diesel engine were compared while operating on ultra-low sulfur diesel oil blended with up to 30% DMC by volume [4]. Researchers employed a new approach that involved combining internal exhaust gas recirculation with a small injection of diesel fuel to ignite the DMC, which was directly injected into the engine cylinder [13]. The results demonstrated that the engine fueled with DMC exhibited lower NO_x emissions, almost zero smoke levels, and a 2–3% higher effective thermal efficiency compared to the engine fueled with diesel fuel, particularly under moderate and high load conditions. Additionally, the blended fuel showed a reduction in particulate number concentrations, highlighting its potential in mitigating emissions in diesel engines.

In this study, the DMC/diesel blend with 5%, 10%, 15% DMC by volume are prepared to investigate the emission characteristics of low DMC blend ratio on a diesel engine. Since the combustion process is strongly influenced by the addition of low boiling point, DMC boosts the atomization and liquid fuel mixture, the emissions of hydrocarbons and soot are significantly reduced by the DMC addiction especially on the high-load conditions. Also, the nitrogen oxide emission show reduction on DMC15 with all load conditions, meanwhile the CO emission increased.

2. Experiment and method

2.1. Experiment apparatus

The schematic diagram of the experimental setup is shown in Fig. 1. In this experiment, we used a diesel generator which has a single-cylinder 4-stroke diesel engine (model YDG300VS, by Yanmar Holdings Co., Ltd.) as the test engine. We used the AVL Di-com4000 and an opacity meter (ALTAS-5100D, Yanaco Opacimeter) to measure the exhaust characteristics. The main specifications of the engine shown in Table 1. It should be noted that the engine specifications indicate the conditions under standard atmospheric conditions (ambient temperature of 298 K, atmospheric pressure of 100 kPa, and relative humidity ranges from 20~30%).

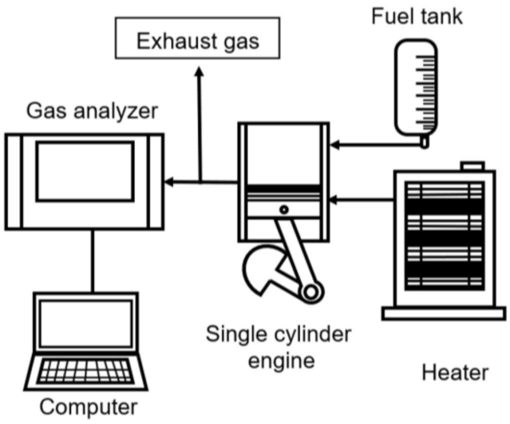

Fig. 1. Experimental apparatus

2.2. Test fuel properties and experiment method

Table 2 show the fuel properties of diesel and DMC. Diesel and DMC (Dimethyl Carbonate) were mixed for 30 minutes at 1500 rpm by using a magnetic stirrer. DMC/diesel blend fuels were prepared with a volumetric ratio at 5vol%, 10vol% and 15% vol% DMC with diesel. These are abbreviated as DMC5, DMC10 and DMC15 in the following. The calculation formula for the blending ratio (W) is shown in Eq. (1) below

$$W = \frac{\text{Volume of DMC}}{\text{Volume of Light oil} + \text{Volume of DMC}} \times 100\ [\%] \qquad (1)$$

The DMC/diesel blend fuel was supplied into the test engine. After the engine warm-up stage ended, the exhaust characteristics were measured by the exhaust measurement device (AVL Di-Com 4000). The measurements data for each load condition were averaged using arithmetic mean. Load conditions were set at nine levels by using heaters: 0 W, 300 W, 600 W, 900 W, 1200 W, 1500 W, 1800 W, 2100 W and 2400 W. The experiment environment condition stays same for each load condition. Furthermore, viscosity measurements were conducted using an SV-10 fork-type vibrating viscometer (AND Co., Ltd). Table 3 shows the viscosity of diesel and DMC/diesel blend fuels. With the DMC blend ratio increase, the viscosity of DMC/diesel blend fuel decrease.

Table 1. Engine specifications

Engine type	4 stroke cycle diesel engine
Injection system	Direct injection
Bore × stroke [mm]	ϕ78×67
Rated output [kW/min^{-1}]	4.0/3000
Cooling system	Forced air cooling
Displacement [dm^3]	0.320
Compression ratio [-]	21.1

Table 2. Properties of Diesel and DMC

	Diesel	DMC
Chemical formula	–	$C_3H_6O_3$
Kinematicviscosity @20℃[mm^2/s]	2.77	0.63
Density @20℃ [kg/m^3]	822	1079
Boiling point [℃]	160~360	90.1
Oxygen content rate [% by weight]	0.09	53.3
Cetane number	52	36
Laten heat of vaporization [kJ/kg]	280	369
Lower heat value [MJ/kg]	42.50	15.78

Table 3. Viscosities of test fuel

	Viscosity [mPa·s]	Kinematic viscosity [cSt]
Diesel	2.06	2.46
DMC	0.568	0.529
DMC5	1.76	2.07
DMC10	1.26	1.46
DMC15	0.87	1.02

3. Results and discussion

The emission characteristics of diesel fuel and DMC/diesel blend fuel for various blend ratio are examined and discussed in this section.

Effect of DMC on HC emission with load for diesel, DMC/diesel blend fuels shown in Fig. 2. From Fig. 2, with the engine load increased, the HC emission decreased for all fuel conditions. This is attributed to the increased combustion chamber temperature resulting from higher loads, which leads to a decrease in incomplete combustion. Regarding the impact of DMC blending, it shows a general tendency of reducing HC emissions. With the oxygenate additive DMC blended in, it can be observed that the HC emissions reduction exist with the use of DMC5 and DMC10 under all load conditions. However, when the DMC blend ratio raises up to 15%, the HC emission at low load region (from 0 W to 900 W) show substantial increase, but still show the reduction effect on the mid and high load region (from 1200 W to 2400 W). Since the DMC additive has lower viscosity than diesel, with the small amount DMC additive (DMC blend ratio under 10%), the evaporability of DMC improves the mixing process of liquid fuel and boosts the combustion, its oxygen content contributes to the HC emission reduction effect. On the other side, while the DMC blend ratio raises up to 15%, due to the low cetane number of DMC, which has impact on the ignition delay time, also lead to incomplete combustion thus caused higher HC emission at the low-load region. Still, under the high-load region, since the combustion chamber temperature raised thus accelerate the physical ignition delay, with the high oxygen content and lower kinematic viscosity which forms better liquid fuel mixture and promotes the fuel atomization effect, the DMC15 realized lower HC emission than that of diesel on the high-load area.

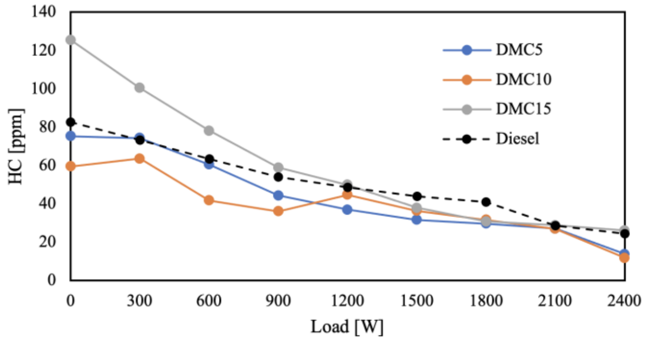

Fig. 2. HC emission

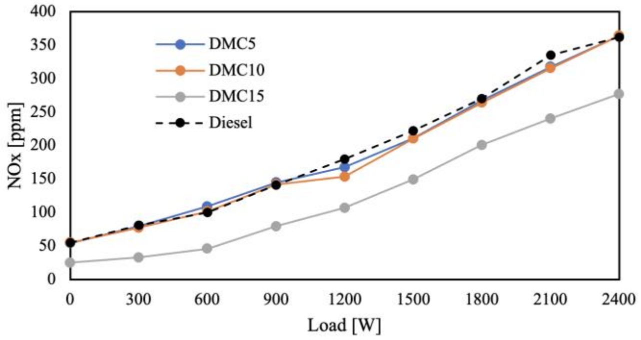

Fig. 3. NO_x emission

Figure 3 shows the nitrogen oxides (NO_x) emission at each load condition with diesel and DMC/diesel blend fuels. From Fig. 3, the NO_x emissions increase with load increase under all fuel conditions. This is because with the load increase, the combustion temperature increase, resulting in increased emissions of NO_x derived from thermal sources.

Focus on the effect of DMC additive, compare to the diesel, with the DMC additive, the NO_x emission reduction effect exists with all DMC/diesel blend fuels. The maximum reduction rate of DMC5 is 6.7%, that of DMC10 is 14.5%, both exist at 1200 W load condition. However, when the DMC blend ratio raises to 15%, the minimum and maximum NO_x reduction ratio of DMC15 is 23.4% and 59.6% at 2400 W and 300 W, respectively. The main reason is that, with the DMC blend ratio increased, the LHV of DMC/diesel blend fuel decreased. Since the fuel injection amount is at same with same engine load condition, under the interact of evaporation laten heat of DMC, the lower LHV of DMC/diesel blend fuel release less heat that improves the thermal NO_x reduction effect. The maximum NO_x emission reduction ratio appears in low load region, which is affected by the combustion temperature. On the other hand, the low cetane value of DMC increases the ignition delay time with the increasing DMC blending ratio, thereby leading to the incomplete combustion as mentioned in Fig. 2, lowering the combustion temperature, and suppressing the formation of thermal NO_x. Furthermore, due to the lower boiling point of DMC compared to diesel, the evaporation enthalpy of DMC reduced the flame temperature, which considered as a factor of the NO_x emission reduction effect.

From Fig. 2 and Fig. 3, due to the high oxygen content, low LHV, low cetane number and kinematic viscosity of DMC, with the use of 15% DMC, it achieved simultaneous reduction of NO_x and HC emission under the high load region (from 1500 W to 2400 W).

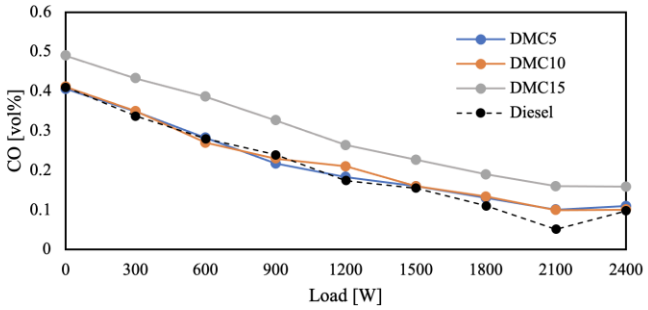

Fig. 4. CO emission

$$CO + OH \Leftrightarrow CO_2 + H$$

$$\boxed{\begin{gathered} 2OH \Leftrightarrow O_2 + H_2 \\ 2H_2O \Leftrightarrow O_2 + 2H_2 \\ H_2 \Leftrightarrow 2H \\ O_2 \Leftrightarrow 2O \\ N_2 \Leftrightarrow 2N \end{gathered}}$$

Fig. 5. Kinetic oxidation of CO

Figure 4 shows the CO emission at each load condition with diesel and DMC/diesel blend fuels. Figure 5 shows the main reaction pathways of CO oxidation. From Fig. 4, with the use of DMC5 and DMC10, under low load region (from 0 W to 900 W), the CO emission show little decrease. On the 1200 W to 2400 W load region, the CO emission of DMC/diesel fuel show increase compared to that of diesel fuel. The main reason is considered as that, at the low load region, the interaction between the increase of oxygen content and low combustion temperature caused by the DMC additive makes the little CO emission decrease. Meanwhile, on the high load region, the combustion temperature raised up, but the insufficient oxygen content in the rich region at the flame front lead to the CO emission increase [8]. For DMC15, the CO emission is higher than all other fuel conditions under all load regions. Since the DMC15 has more oxygen content, the main reason is considered as that the low LHV of DMC lead to a lower combustion temperature, which has been proved in Fig. 3, the NO_x emission data. The lower combustion temperature didn't satisfy the temperature of CO oxidation condition.

Figure 6 shows the CO_2 emission at each load condition with diesel and DMC/diesel blend fuels. From Fig.6, CO_2 has little increasement with the use of DMC additive on low and mid load region with all DMC/diesel blend fuels. Since DMC15 has highest DMC blend ratio, the higher oxygen content benefits the CO oxidation process that led to higher CO_2 emission. For high load region, the increase rate of DMC5 and DMC15 decreased, which is considered as the CO oxidation process is suppressed with DMC5 and DMC15. The main reason is considered as the interaction between the oxygen content and the low LHV of different DMC/diesel blend fuel.

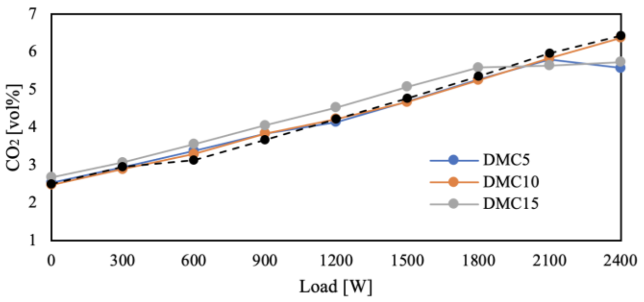

Fig. 6. CO_2 emission

An opacimeter is used to measure the contamination level of exhaust gases caused by particulate matter by passing light through the exhaust gas collected from the exhaust pipe and measuring the transmittance (optical absorption coefficient [m^{-1}]). Figure 7 shows the soot emission at each load condition with diesel and DMC/diesel blend fuels. From Fig. 7, with the use of DMC additive, soot emission significantly decreased at the DMC15 under the low load region (from 0 W to 1200 W), except the mid load region, the soot extremely decreased at 2400 W. However, the DMC blend ratio has great influence on the soot emission decrease tendency. Further studies needed to investigate the influence of DMC blend ratios under different engine load conditions.

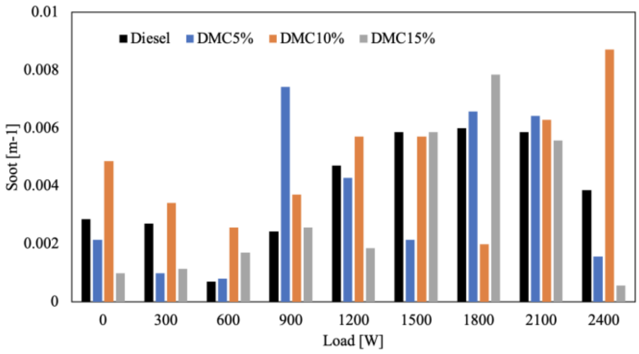

Fig. 7. Soot emission

4. Conclusions

In this study, we observed the effect of DMC blend ratio on emission characteristics with a use of diesel generator. The DMC/diesel blend fuels with three DMC blend ratio are used as test fuel. Through the observation of HC, NO_x, CO, CO_2, and soot, we discussed the influence of DMC's fuel properties on emission characteristics. Further studies about the proper DMC blend ratio are need. The main conclusions show as follows:

(1) The DMC/diesel blend fuel can realize the simultaneous reduction of HC and NO_x emissions under the high load region by the influence of DMC fuel properties.

(2) The HC and CO can not simultaneously reduce with the use of DMC15.

(3) It is possible to realize the soot reduction effect under the low and high load region by using DMC15. The impact of the DMC blend ratio on soot reduction exhibits varying tendencies across different load regions.

Nomenclature

CO	carbon monoxide
CO_2	carbon dioxide
DMC	dimethyl carbonate
DME	dimetyloeter
HC	hydrocarbon
HCCI	homogeneous-charge compression ignition
HEUI	hydraulic electronic unit injector
LPG	liquified petrolum gas
LHV	lower heat value
NO_x	nitrogen oxides
SI	spark ignition

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