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Effect of low load combustion and emissions on fuel dilution in lubricating oil and deposit formation of DI diesel engines fueled by straight rapeseed oil

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ABSTRACT

The objective of this study is to apply neat biomass fuel to a DI diesel engine and investigate the effect of in-cylinder gas flow and combustion on the deposit formation and the fuel dilution in lubricating oil. The study focuses on the low load combustion and emissions considering that low load exhaust contain much unburned fuels and the unburned fuels are the source of the deposit formation and the fuel dilution. Piston configuration and swirl velocity were altered in the engine test. The engine was fueled by neat rapeseed oil. The test was carried out through the four hours continuous engine operation with keeping low load. After the operation, state of deposit formation and fuel dilution in lubricating oil were investigated. Results indicate that Re-entrant piston which creates strong reverse squish and high swirl forms the deposit annular on the piston top. Toroidal piston easily produces deposit on the undersurface of cylinder head. The deposit in the cavity accumulates where initial rapeseed oil spray impinges regardless of piston types. The carbonization of the deposit is promoted on the wall surface where the burned gas with high temperature and high velocity comes into contact. It is important to avoid extremely strong reverse squish to the cylinder liner in order to control the fuel dilution. The deep-bowl chamber changes the direction of reverse squish from the cylinder liner direction to the cylinder head direction. The low velocity outflow from the piston cavity reduces the adhesion of unburned fuel on the cylinder liner, resulting in the smaller amount of unburned fuel scraped off by a piston ring.

1. Introduction

Biomass fuel is substitute for petroleum and has a carbon neutral property. The fuel can contribute to improve energy security and prevent global warming. Therefore, it has been studied on application of a biomass fuel to a diesel engine as a carbon neutral alternative fuel [1–7]. The majority of the researches apply fatty acid methyl ester as biomass fuel. According to these researches, exhaust emission, in particular, high load particulate emission can be reduced by using biomass fuel with a direct injection (DI) diesel engine. An et al. [8] and E et al. [9] investigated combustion and emissions of diesel engine fueled by biodiesel at partial load conditions. They showed that the thermal efficiency is reduced at lower engine loads and the efficiency is improved at higher engine loads. At lower engine loads, the CO emissions increase with the increase of the biodiesel blend ratio. Liu et al. [10] and E et al. [11] further developed a skeletal mechanism and predicted soot formation characteristics for biodiesel blends. They indicated that the kinetic viscosity is a very important factor to the combustion of biodiesel fuels. In most of these researches, biomass fuel was esterified generally and used as fatty acid methyl ester as mentioned above. The esterification brings a biomass fuel property close to gas oil, which makes it easy to use the alternative fuel with an existing engine. However, the esterification requires an industrial plant and the treatment process of the by-product, which raises the fuel cost. In this kind of situation, it is desirable to apply a biomass fuel directory to a DI diesel engine. Concerning the researches supplying neat biomass fuels to DI and prechamber type diesel engines, engine performance and emissions have been investigated from the past [12–15]. These researches showed that applying neat biomass fuel instead of gas oil can improve emissions at high load. Biomass fuel is oxygenated fuel, which is favorable at high load that needs much oxygen. However, low load emission will deteriorate more than the case of using fatty acid methyl ester. This is because neat biomass fuel has the high kinetic viscosity and high evaporation temperature characteristics as compared with the fatty acid methyl ester.

Moreover, researches of the past [12,16–19] pointed out that deposit formation is one of the problems when a biomass fuel is directly used with a DI diesel engine. Kawasaki et al. [16] evaluated the deposit

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formation in the combustion chamber and investigated the effect of fuel injector deposit on engine performance and emissions. They suggested that deposit formation in the nozzle hole affects engine performance and emissions. Biomass fuel has poor atomization and evaporation characteristics due to high distillation temperature with high viscosity [20,21]. These characteristics results in deposit formation. Once the deposit is formed in the fuel injector hole, the spray characteristics changes, and subsequently, combustion and emission get worse. When neat biomass fuel is applied to a DI diesel engine, some of the liquid phase spray impinges on the wall of piston chamber without fully evaporation. Further, in the case of neat biomass combustion, burned gas contains some amount of unburned fuel in particular under low load condition. The unburned component cools off on the wall surface and stick to the wall, forming deposit.

Another problem in applying neat biomass fuel to diesel engines is fuel dilution in lubricating oil [22–24,17]. Kitazaki et al. [22] suggested the mechanism of the fuel dilution as follows. The fuel which sticks on the wall surface of cylinder liner is scrapped off by a piston ring, and then the fuel gets mixed with the lubricating oil. Sem [17] indicated that the deposit formation is affected by type of lubrication oil. When the fuel is diluted in the lubricating oil, the lubrication performance deteriorates and causes the abrasion and ghosting of the slide parts.

Both deposit formation and fuel dilution in lubricating oil affect the engine durability greatly. It is necessary to reduce them with keeping low emission. As for the emissions, soluble organic fraction (SOF) emissions and unburned fuel are much produced at low load as compared with higher load when the biomass fuel is applied [13]. These emissions may be the source of the deposit formation and the fuel dilution. It is also likely that the in-cylinder gas flow during combustion affects the adhesion of unburned fuel on the wall surface of cylinder liner as well as the emission itself. However, it is not clear the influence of combustion and emissions on the deposit formation and the fuel dilution. And furthermore, there are few researches on detail investigation of the effect of engine combustion on deposit formation and fuel dilution.

This study investigates the effect of in-cylinder gas flow and combustion on the deposit formation and the fuel dilution focusing on low load operation that produces much unburned fuels. Authors previously attempted to improve emissions from a DI diesel engine when applying neat rapeseed oil as biomass fuel [13,25]. Fig. 1 shows one of the results [25]. Generally, as compared with gas oil (indicated by the broken line), rapeseed oil combustion (the thin line without plots) reduces particulate emission (PM) at high load, mainly insoluble fraction (SOLID), but soluble organic fraction (SOF) increases with the lowering of the load. We presumed that combustion with high SOF emission is closely related to the increase of deposit. Furthermore, burned gas with high SOF emission also contains the component similar to the original fuel. When such burned gas comes to the cylinder liner, fuel component adheres to the cylinder liner. Then, the component is scrapped off by a piston ring, resulting in the increase of fuel dilution in lubricating oil. Based on such supposition, we tried to reduce SOF emission at low load. Rapeseed oil spray is hard to be atomized and evaporated in the low temperature atmosphere at low load. The poor spray characteristics causes SOF emission. We attempted to utilize in-cylinder gas flow by modifying piston configuration as shown in Fig. 1 so as to improve the atomization and evaporation of rapeseed oil spray. The flat bottom cavity can elongate the spray penetration and atomization after the wall impingement. Re-entrant shape can create high turbulence in the chamber, which supports the mixing of fuel with air and also avoiding the wall impingement itself in the cavity. Both techniques finally result in the reduction of SOF emission at low load as shown in the figure. In particular, re-entrant piston with a flat bottom offers the greatest effect of the reduction.

This study applied the above combustion with low SOF emission and investigated the mechanism of deposit formation and fuel dilution affected by combustion. The experiment was conducted by continuous four hours engine operation with fueling straight rapeseed oil and keeping engine load at low level. The long-time engine operation formed deposit and caused fuel dilution in lubricating oil. The piston configuration and swirl velocity were altered to change the in-cylinder gas flow and combustion.

2. Experimental method

The test engine was a four-stroke single cylinder naturally aspirated direct-injection diesel engine (YANMAR NFD-170). Table 1 shows the engine specifications. This study used two classes of swirl ratio, r_s, that is original swirl ratio of 2.2 and higher swirl ratio of 3.1.

This study also changed piston configurations. Detail of piston specifications is shown in Table 2 and Fig. 2. The piston geometries are designed based on our previous research [25] as shown in Fig. 1. Toroidal base for reference is the original piston geometry with this engine. Toroidal flat has a flat bottom which promotes evaporation and atomization of rapeseed oil spray after the wall-impingement at low load. R35 and R45 are re-entrant type pistons with a flat bottom. Re-entrant piston can generate high turbulence and improve particulate emissions at high load as well as low load. The aperture ratio D_{out}/D which is the ratio of cavity-exit diameter D_{out} to piston diameter D is about 35% for R35 and 45% for R45. R35 and Toroidal flat have three types respectively with different bowl diameter D_{in}. There are 7 types of pistons used in this study. All pistons have the same volume of piston bowl with different bowl depth H. The spray arrows in Fig. 2 indicate the spray injecting direction at TDC (Top dead center).

Table 3 shows the test condition of the engine. Rapeseed oil was supplied to the engine. Table 4 compares fuel property between rapeseed oil and gas oil. Rapeseed oil is oxygen-containing fuel with high viscosity and high distillation temperature. Fig. 3 shows the schematic diagram of experimental setup. Exhaust emissions such as NOx, CO and THC were measured by an engine exhaust gas analyzer (HORIBA: MEXA-1500D). A mini-dilution tunnel and filters were employed for

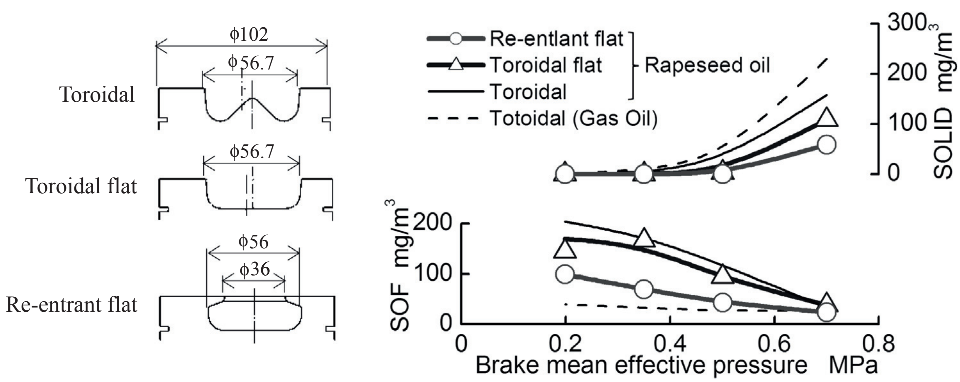

Fig. 1. Reduction of particulate emissions by means of combustion chamber configurations.