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Effect of Biodiesel Fuel on Direct Injection Diesel Engine Performance

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The effect of biodiesel fuel on direct injection diesel engine performance was investigated. Biodiesel fuel used in this study was made by an esterification of palm oil. It was blended with diesel fuel, and the blend ratio was changed from 0 to 20 wt%. The direct injection diesel engine used here was a single-cylinder general-purpose engine. The excess air ratio was changed from 1.85 to 3.0. CO, CO_2, NO, NO_2, and N_2O concentrations in the exhaust gas were measured. Exhausted particulate matter was collected by a quartz glass filter and its components, such as soluble organic fraction, dry soot, and sulfate, were analyzed. Moreover, the size distribution of the particulate matter was analyzed using a scanning mobility particle sizer. The heat release rate and fuel injection rate in each condition were also measured to examine the relation between emission characteristics and combustion conditions. There was no apparent dependence of the biodiesel fuel blend ratio on the heat release rate and exhaust gas composition. This result shows that the combustion characteristics, such as ignition delay, did not change with the blended ratio, because the cetane index of the biodiesel fuel was equivalent to that of the diesel fuel. On the other hand, the particulate matter had a clear dependence on the biodiesel fuel blend ratio. When the blend ratio was 20 wt%, the amount of particulate matter was more than that in the 5 wt% and 10 wt% blended fuels. It was shown that, moreover, the amount of soluble organic fraction increased with an increase of the blend ratio. In the measured results of particulate matter size distributions, it was noteworthy that nanosize particulates (ranging from 10–20 nm) increased when 20 wt% biodiesel fuel blended fuel was used. From these results, it was inferred that the nanoparticles in the range of 10–20 nm were soluble organic fraction related particles. From the viewpoint of the reduction of particulate matter emission, we concluded that the optimum biodiesel fuel blend ratio was 5–10 wt%.

I. Introduction

BIODIESEL fuel (BDF) made from biomass is a carbon neutral fuel for the greenhouse problem and is receiving much attention as an alternative and renewable fuel for diesel engines [1,2]. BDF is made from various kinds of vegetable oils, such as corn, olive, palm, and coconut oils. Palm oil is particularly important as a raw material of BDF in Southeast Asia, because the yield of palm oil per planting area is about 5000 kg-oil/ha, which is much larger than the others. However, the use of crude palm oil as a diesel fuel is very difficult owing to such properties such its cetane index and viscosity. For example, its high viscosity often causes fuel spray and fuel delivery problems. Therefore, BDF is produced by an esterification process of palm oil, and the properties of palm oil are improved so as to be suitable for use in diesel engines.

BDF is an ester, and its molecular structure contains oxygen atoms. It is known that a fuel that contains oxygen can reduce the particulate matter (PM) emission from diesel engines. The diesel engine is superior to other internal combustion engines in thermal efficiency, but the PM in its exhaust gas is a troublesome problem. Because the PM in diesel exhaust emission causes lung injury and cancer, it has been considered a harmful substance to human health [3]. To keep a healthier air environment, more strict and effective regulations have to be imposed on PM emissions. Therefore, an advantage of BDF is an increase in the reduction of PM from diesel engines. Recently, the applicability of various kinds of BDF, for example, made from coconut [4], soybeans [5], sunflower, and cynara [6] oils as diesel fuel, have been investigated. The applicability of BDF as a diesel fuel should be studied further to expand the utilization in the future.

In this study, we took up a BDF made from palm oil. BDF blended diesel fuels were used as test fuels, and combustion and emission characteristics including heat release rate, exhaust gas compositions such as CO, CO_2, NO, NO_2, N_2O, and PM of a direct injection (DI) diesel engine were investigated. As for the emission of PM, components such as soluble organic fraction (SOF), dry soot, and sulfate were analyzed, and size distributions including nanosize particles (less than 50 nm) were measured. SOF is an organic compound that can be extracted from PM with organic solvents and consists mainly of unburned fuel and compounds produced by the polymerization and condensation of hydrocarbons. Dry soot is carbonaceous particles that are contained in PM. Sulfate is a compound containing SO_4 produced by the oxidation of sulfur in a fuel and lubricant. The objectives of this engine test were to survey the optimum ratio of blended BDF to a conventional diesel fuel and to observe the general trend of exhaust emission characteristics.

II. Experimental Apparatus and Method

A. Properties of Test Fuel

Properties of pure BDF, diesel fuel, and 20 wt% BDF blended diesel fuel are shown in Table 1. The BDF used in this study was produced by an esterification of palm oil with methanol. The cetane index of the BDF was slightly larger than that of the base diesel fuel; the cetane index of the blended fuel of 20 wt% BDF is the same as that of the base diesel fuel. The flash point of the BDF is much higher than that of the diesel fuel (40–50°C), but that of the 20 wt% BDF blended fuel is not as high as that of the diesel fuel. The most popular weak point of BDF is poor cold flow properties. The pour and cloud points of the BDF used in this study are 10.0°C and 14°C, respectively. Therefore, the BDF is generally blended with diesel fuel to improve the cold flow properties. For example, the pour point is improved to −7.5°C for the 20 wt% of the BDF blended with the

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Table 1 Properties of test fuels

Properties	Pure BDF	20 wt% BDF blended diesel fuel	Diesel fuel (base)
Density, kg/m^3	875.1	841.7	833.5
Viscosity at 40°C, cSt	4.678	3.257	3.038
Flash point, °C	144	68	——
Pour point, °C	10.0	−7.5	−25.0
Cloud point, °C	14	−2	−2
90% Distillation Temp., °C	339.0	338.5	338.5
Cetane index	58.1	56.1	56.1

base diesel fuel. The diesel fuel used as the base fuel was a low-sulfur Japanese standard fuel, which was commonly used in Japan in 2004. The main elemental composition (carbon and hydrogen) and properties of this fuel were not different from conventional diesel fuel, but its sulfur content was less than 50 ppm. In the experiment, the BDF blended diesel fuels were used and the blend ratios of the BDF were 0 wt%, 5 wt%, 10 wt%, and 20 wt%. The blended fuel of over 20 wt% BDF was not tested because it was impractical given the cold flow properties. The blended fuels did not damage the rubber parts in the fuel line, such as the "o" ring, in this study. The thermal stability of the blended fuel in long-term storage could not be confirmed because the fuel was used immediately after blending.

B. Test Engine

The engine used in the experiment was a single-cylinder DI diesel engine, and specifications are shown in Table 2. The engine speed was set to 1080 rpm and the fuel injection timing was set to 20 deg before top dead center (BTDC). The test engine was operated under excess air ratios (λ) of 1.85, 2.2, and 3.0. Those values corresponded to high-, middle-, and low-load conditions, respectively. The excess air ratio was changed by controlling the amount of injected fuel.

C. Experimental Setup

The experimental setup is shown in Fig. 1. It consists of a test engine, an air intake system, a dynamo meter, several sensor systems to analyze combustion characteristics in the engine, an exhaust gas sampling system, and a measurement system for exhaust gas composition. The cylinder head of the test engine was equipped with a piezoelectric pressure transducer (Kistelr 6125B), and pressure in the cylinder was measured continuously. The heat release rate was obtained by measuring the temporal change of the cylinder pressure. The fuel line was equipped with a piezoresistive pressure sensor (Kistler 4065A) to measure the fuel injection rate. The engine speed was measured using the timing sensor. Data from the sensors were recorded by the analyzing recorder. The flow rate of intake air was measured by an orifice flowmeter. The sampling location of the exhaust gas was far downstream of the engine (1100 mm from the exhaust muffler of the engine), and no dilution tunnel was used because of the lab-scale experiment. The exhaust gas sampling probe (a stainless pipe with a 6 mm inner diameter) was inserted into the exhaust pipe at that location. The exhaust gas was sampled for 10 s with a sample gas flow rate of 12 l/ min, and the gas was collected in the sampling bag. The sampled exhaust gas was diluted 12 times with air, and then CO, CO_2, NO, NO_2, and N_2O concentrations were measured with the emission gas analyzer (MEXA 4000 FT, HORIBA, Ltd.). For the measurement of the size distributions of the PM, the exhaust gas collected in the sampling bag was diluted 100 times, and the size distribution of the PM in the diluted gas was analyzed using a scanning mobility particle sizer (SMPS) (TSI Model-3034). In the analyses of the exhausted PM components, a PM sampling probe (a stainless pipe with a 3.5 mm inner diameter) was inserted into the exhaust pipe 150 mm downstream from the aforementioned gas sampling location. The exhaust gas of 356 ml was sampled with a suction pump, and the PM was collected on a quartz glass filter. Components of the PM, such as SOF, dry soot, and sulfate, were analyzed by a PM analyzer (MEXA 1370 PM, HORIBA, Ltd.).

III. Results and Discussion

A. Effect of BDF Blend on the Heat Release Rate

Heat release rates at various operating conditions are shown in Figs. 2–4. Data shown here were calculated from pressure diagrams obtained with three cycle averaging. In those figures, the fuel injection timing and injection rate are indicated with dashed lines. The premixed combustion peak and diffusion combustion which followed the peak were obviously observed in $\lambda = 1.85, 2.2$, and 3.0. From these three figures, it was found that the premixed combustion peak did not change with the blend ratio of the BDF in every excess air ratio. The amount of diffusion combustion which followed the premixed combustion decreased with a decrease of the excess air ratio. However, it was not affected by the blend ratio of the BDF. Generally, patterns of heat release rate were greatly affected by an ignition delay. The ignition delay was controlled by the cetane index shown in Table 1. Thus, the less sensitivity of the blend ratio on combustion resulted from the equivalent cetane index number among the fuels.

B. Effect of BDF Blend on Exhaust Gas Compositions

Changes in the exhaust gas compositions with the blend ratio are shown in Figs. 5–7. Exhaust gas compositions were measured two times, and the measured data are plotted in these figures. Dispersions of the data are small in CO, CO_2, NO, and NO_2 concentrations and, therefore, it seems that the reliability of the data is high. On the other hand, the data dispersion of N_2O is relatively large, especially in $\lambda = 1.85$ and 2.2. The data dispersion was probably caused by the very low concentrations of N_2O.

The CO concentration was extremely low in every excess air ratio and BDF blend ratio, and that shows that the injected fuels were burned completely. On the other hand, the NO and NO_2 concentrations had a decreasing tendency with regard to increasing the excess air ratio and were slightly dependent on the blend ratio of the BDF. The relation between the excess air ratio and the concentration of NO can be explained with the temperatures of the

Table 2 Engine specifications

Engine name	YANMAR, NFD170
Engine type	DI diesel, four stroke, single cylinder, overhead valve, two valve
Bore × Stroke, mm	102 × 105
Displacement, cc	857
Top clearance, mm	0.85
Cavity volume, cc	38
Compression ratio	20.1
Cooling type	Water cooled

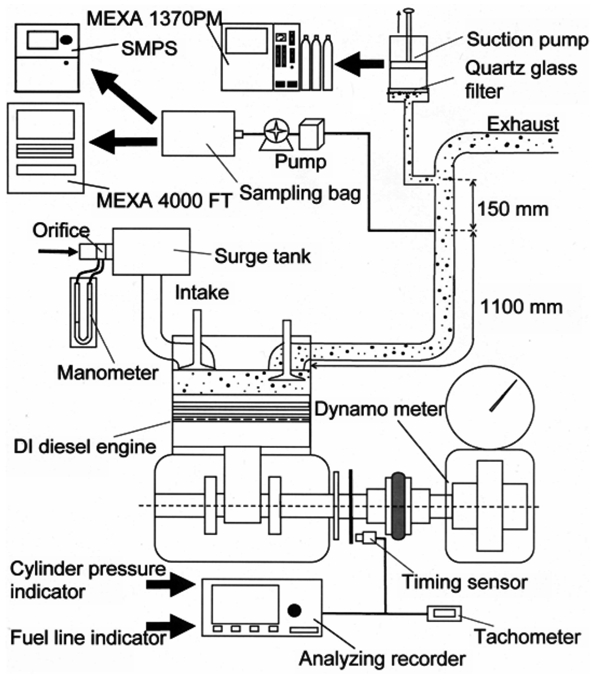

Fig. 1 Engine test apparatus.

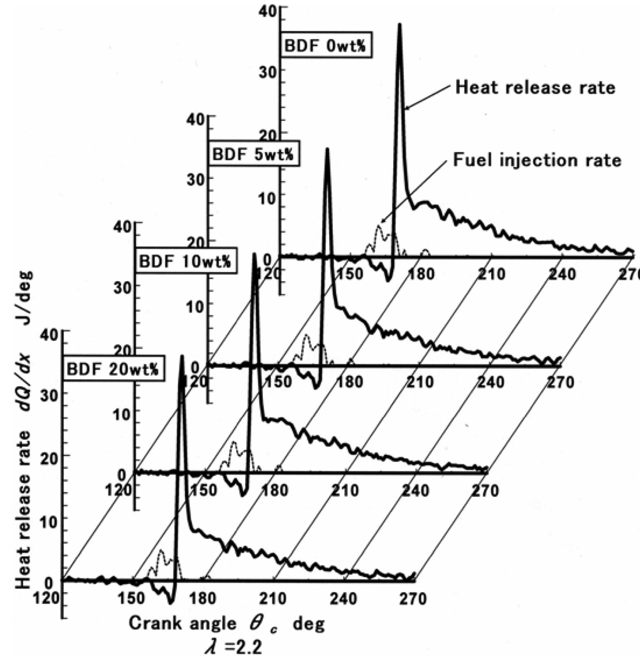

Fig. 3 Heat release rate, λ = 2.2.

burned gases. Thermal NO is formed with a Zeldovich mechanism, and it is controlled by a burned gas temperature in the cylinder. Generally, the temperature in a lower excess air ratio is higher than that in a higher excess air ratio and, therefore, the thermal NO formation rate is higher in a lower excess air ratio. The less sensitivity of the BDF blend ratio on NO and NO_2 emissions is also explained by the combustion characteristics in the cylinder. From the less sensitivity of the BDF blend ratio on the combustion process as shown in previous figures, it was concluded that the less sensitivity of the BDF blend ratio on NO formation was a quite reasonable result. As for the N_2O emission, the concentration at 20 wt% blended fuel was lower than that of the other cases. The reason for the reduced emission of N_2O was not clear, but the decreasing trend was acceptable because of the high greenhouse effect of N_2O.

C. PM Concentration

The relation between the BDF blend ratio and the PM emission are shown in Figs. 8–10. The total PM was the sum of the SOF, soot (dry soot), and sulfate, and it was expressed as an emission index of output power base. The measured total amount of PM may be affected by a PM sampling system, such as the length and size of the sampling line and the gas flow rate in a sampling. In this study, however, the effect of the sampling line on the data was not examined. As for the measured value of the SOF, soot, and sulfate, we have not analyzed them with different methods and, therefore, absolute accuracies of their concentrations are not discussed here.

With the BDF blend ratio of 5 wt%, the total PM showed the minimum in every excess air ratio. With the 20 wt% blended fuel, the total PM in $\lambda = 1.85$ and 2.2 was lower than that of the base fuel.

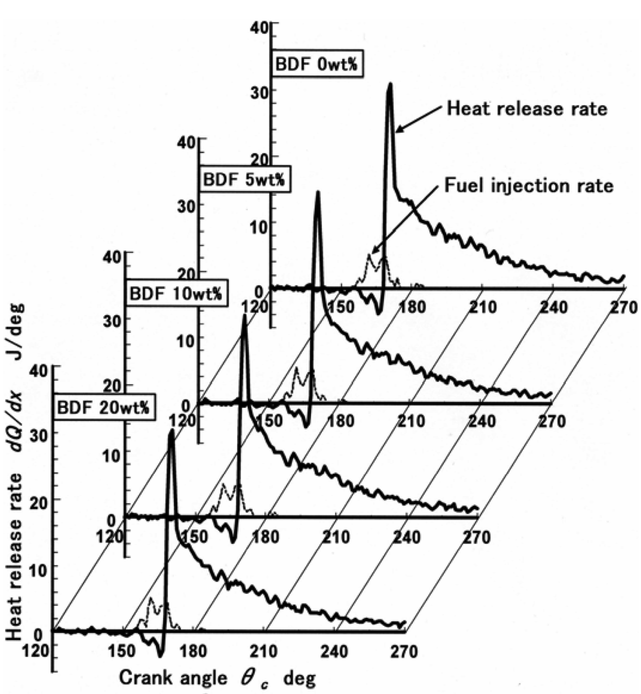

Fig. 2 Heat release rate, λ = 1.85.

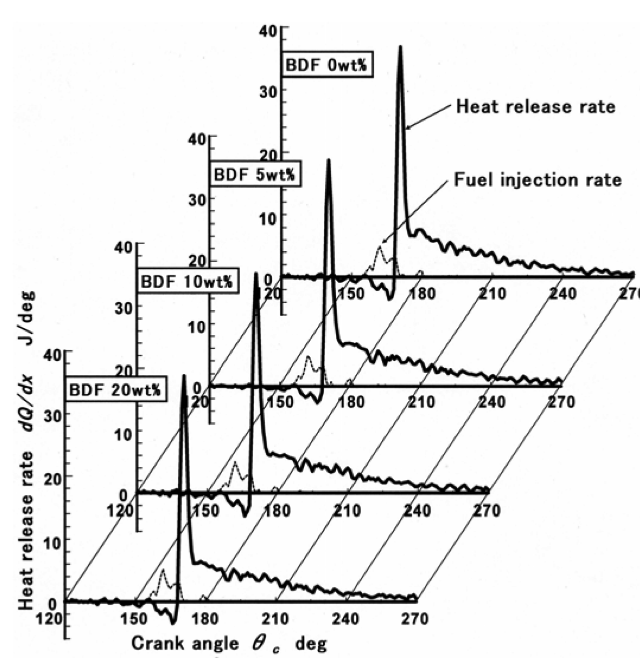

Fig. 4 Heat release rate, λ = 3.0.

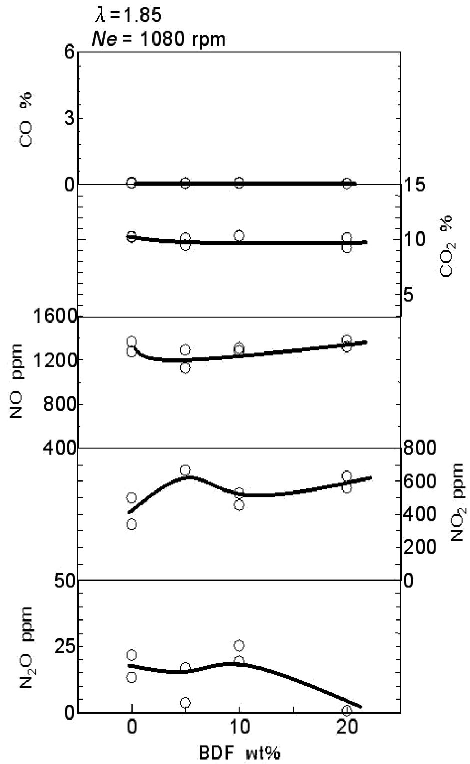

Fig. 5 Relation between the exhaust gas composition and the BDF blend ratio (λ = 1.85).

However, it was higher in the case of λ = 3.0. The soot component in the total PM decreased with an increase in the excess air ratio in every BDF blend ratio. This is probably associated with the temperature of burned gas. The temperature increases with a decrease in the excess air ratio, that is, the lower the excess air ratio, the more the polycondensation of hydrocarbon progresses. As for the SOF component, it had the minimum at the BDF blend ratio of 5 wt%, and

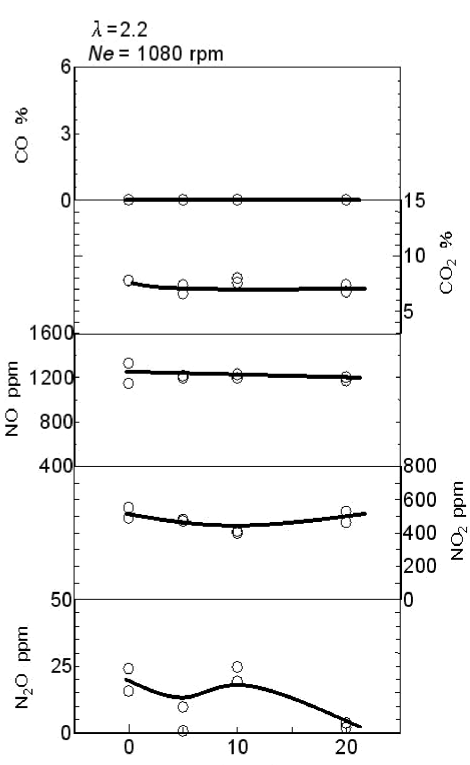

Fig. 6 Relation between the exhaust gas composition and the BDF blend ratio (λ = 2.2).

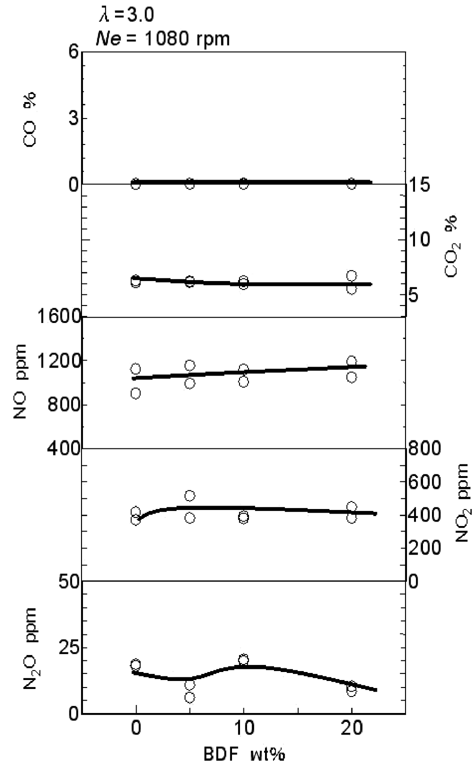

Fig. 7 Relation between the exhaust gas composition and the BDF blend ratio (λ = 3.0).

then it increased with an increase of the BDF blend ratio. It was clear that the trend of the total PM was mainly controlled by the trend of the SOF in λ = 2.2 and 3.0. Moreover, it was shown that the BDF had the effect of reducing the PM emission in the lower excess air ratio.

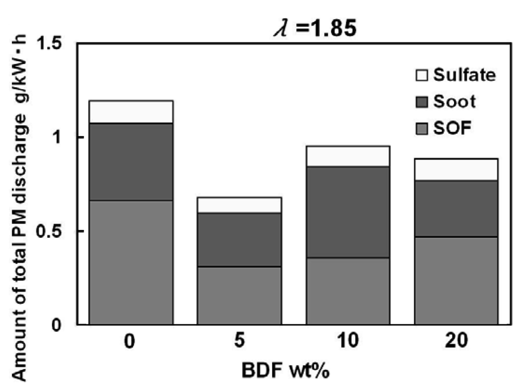

Fig. 8 Relation between the PM emission and the BDF blend ratio (λ = 1.85).

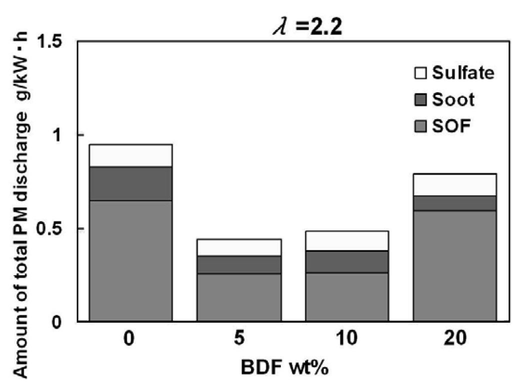

Fig. 9 Relation between the PM emission and the BDF blend ratio (λ = 2.2).

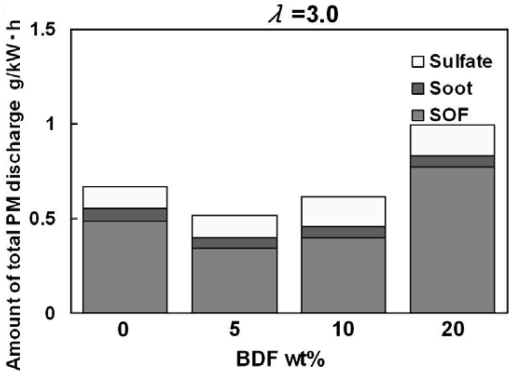

Fig. 10 Relation between the PM emission and the BDF blend ratio ($\lambda = 3.0$).

On the other hand, it was also shown that an excessive addition of the BDF to diesel fuel mainly increased the SOF emission in the higher excess air ratio.

D. PM Size Distribution

The PM size distributions measured with the SMPS are shown in Figs. 11–13. The measured number concentrations of PM were probably influenced by a sampling system like the measurement of the PM amount, but we did not evaluate the effect of it. Moreover, the absolute number concentration of the nanosize measurement was hard to calibrate, because there was no reference nanosize particles available for the diesel PM measurement.

The peak diameter of the PM was not clear at $\lambda = 1.85$, but those at $\lambda = 2.2$ and 3.0 could be found clearly. From these results, it seems that the peak diameter of the PM decreased with an increase of the excess air ratio, namely, the decrease of engine load. The effect of the BDF blend ratio on the peak diameter appeared obviously at $\lambda = 2.2$, and it seems that the distribution had the tendency that the peak diameter decreased with an increase of BDF blend ratio. As for the PM under 50 nm, it seems that the number concentration increased with an increase in the excess air ratio (a decrease of engine load) and with an increase in the BDF blend ratio except for the 10 wt%. It is especially noteworthy that the peaks around 20 nm appeared at $\lambda = 1.85$ and 3.0 when the BDF blend ratio was 20%. The ratio of SOF in the total PM in the 20 wt% blend ratio was higher than that in the other blended fuels as shown earlier and, therefore, it is inferred that the peak was caused by coagulation particles that mainly consisted of SOF.

E. Discussion

From the measured results shown in this study, it can be seen that the macroscopic combustion characteristics, such as the heat release

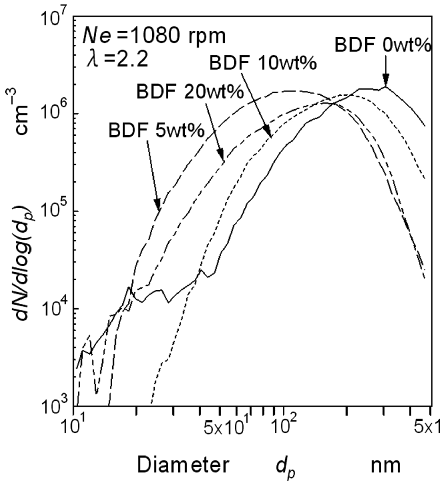

Fig. 12 PM size distribution in the exhaust emission ($\lambda = 2.2$).

rate and the exhaust gas compositions, hardly depended on the BDF blend ratio, although the BDF blend ratio apparently affected the PM characteristics such as the composition and size distribution. In considering the effect of the BDF blend ratio on the PM characteristics, the behavior of the SOF component with the change of the BDF blend ratio should be noted. SOF increased when the excess air ratio was 3.0 and the 20 wt% BDF blended fuel was used, as shown in Fig. 10. From these results, we speculated that the overlean mixture, whose equivalence ratio is leaner than the lean combustion limit, was partially and locally quenched, and an excessive addition of the BDF promoted this quenching more. The unburned hydrocarbon formed by the quenching resulted in SOF. As soon as fuel injection into the cylinder begins, a distribution in the equivalence ratio across the fuel spray develops. The amount of fuel that is mixed leaner than the lean combustion limit increases with time. It seems that the amount of overlean mixture in the higher excess air ratio is more than that in the lower ratio. There is a possibility that the overlean mixture containing the BDF excessively is easy to quench locally on a cylinder wall. However, the mechanism of quenching in the mixture containing the BDF cannot be discussed in this study, because we have no data for quenching. The fundamental combustion characteristics of diesel fuel containing the BDF should be investigated to discuss the quenching mechanism in a cylinder.

IV. Conclusions

In this study, BDF tests using a direct injection diesel engine were carried out. Exhaust gas compositions, the amount and components of emitted particulate matters, and size distributions of the particulate

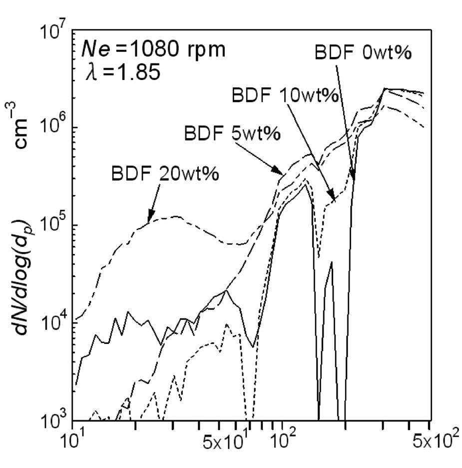

Fig. 11 PM size distribution in the exhaust emission ($\lambda = 1.85$).

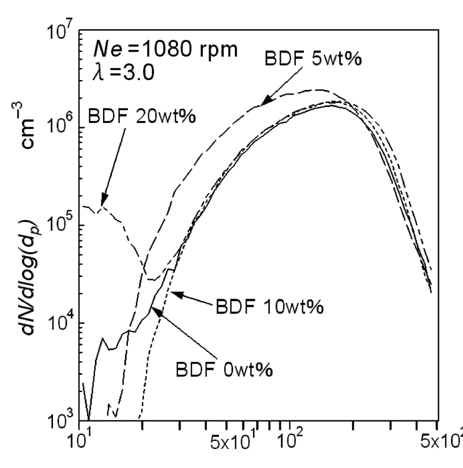

Fig. 13 PM size distribution in the exhaust emission ($\lambda = 3.0$).

matters including nanoparticles were measured. A BDF made by an esterification of palm oil was used and was blended with diesel fuel. The blend ratio of the BDF and the excess air ratio was varied from 0–20 wt% and 1.85–3.0, respectively. The effect of the BDF blend ratio on the macroscopic combustion characteristics in the cylinder, such as heat release rate and exhaust gas compositions, did not appear clearly in high-, middle-, and low-load conditions. As for the characteristics of the particulate matter, the amount of particulate matter decreased when the BDF blend fuel was used, but it increased when 20 wt% BDF blend fuel was used in the low-load condition. The components of the particulate matter were obviously dependent on the BDF blend ratio. The ratio of soluble organic fraction in the total particulate matter increased when the 20 wt% BDF blend fuel was used in the low-load condition. The diameter distribution of the particulate matter was also measured using the scanning mobility particle sizer. It was shown that the peak diameter of particulate matter was shifted to the smaller size, and nanoparticles under 50 nm increased in the higher blend ratios, except for the 10 wt% when the BDF blend fuel was used. It is inferred that the nanoparticles under 50 nm mainly consisted of soluble organic fraction. It was also speculated that the increase of nanoparticles was caused by the local quenching of flame in the cylinder.

As the result of this study, we found that the optimum BDF blend ratio was 5–10 wt% from the standpoint of the emission characteristics of NOx and particulate matter.

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