Automatic Measuring Results of Particulate Matter Concentration from Diesel Engines*

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INTRODUCTION

Particulate matter is a common by-product formed in diesel engines operating at high pressure and temperature conditions. Although most of the particulate matter emitted from diesel engine is generated in the combustion chamber due to incomplete combustion of hydrocarbon fuels, but the process of formation of aggregation still happens in the distribution path. To attain the satisfactory improvement in diesel performance and control of particulate emission, of course, detailed understanding of complex particulate behaviors in the exhaust system is necessary.

The particulate matter, however, may be of any size including Rayleigh size of which diameters are much smaller than light wavelength and it is particularly difficult to be observed visually because of low concentration [1]. The flow pattern of the PM in exhaust gas from combustion chamber shown by Schlieren photography turns out that the PM concentration changes simultaneously with elapsed time and it gives difficulties to the measuring of PM concentration at real time. (Photo 1)

Photo 1: Schlieren method Photograph of Exhaust Gas Flow from Combustion Chamber.
As described in previous approach, in an effort to measure these parameters, we applied the optical measuring system, which based on the Rayleigh-Debye theory of scattering light and attenuation technique to make clear the particle sizes, number density and mass concentration of PM distributed from combustion chamber outlet \(^2\) and simulated diesel engine\(^3\). The results obtained by the optical system were compared to those of filtering system (JIS) and there is no significant difference between these results. The difference of two methods is within 8%. The principle of measuring method is fully described in reference\(^2\) and \(^3\).

The results show that the air-gas supplied ratio influences the concentration of distributed PM. Depend upon the flow-rate of C\(_2\)H\(_6\) and 1.3 C\(_3\)H\(_6\) gas and air supplied to the combustion chamber, when the equivalent dilution ratio increased the mass concentration of PM obtained in exhaust gas was also increased, respectively. (Fig.1)

Besides, the results imply that a well-designed PM concentration measuring system enhances the sensitive of measurement, especially for the low PM concentration zones. In this paper, detailed information of the PM concentration in exhaust gas from practical diesel engine, according to engine operation condition, is investigated, using above-mentioned optical measuring system.

### EXPERIMENTAL APPARATUS AND CONDITION

The schematic diagram of experimental apparatus is also described in detail in the reference \(^2\) but it is necessary to emphasize that the intensities of scattered light from PM have been measured at fixed angular positions of 40° and 140° (angles between the direction of observation and direction of the incident light beam) as in the figure 2. Figure 3 displays the attenuation technique layout with a 15mW output laser light source and a photo multiplier receiving intensity signal. All signals then have been sent to an oscilloscope and computer via analog-digital (A/D) converter, to be processed. The number of signals sent to Lock In Amplifier is one thousand signals, once, to avoid a manual fringe count.

![Fig.2: Scattering Technique Layout](image)

![Fig.3: Attenuation Technique Layout](image)

**Fig. 1:** Relation between Equivalent Dilution Ratio and Mass Concentration of Aggregated PM in Exhaust Gas.
Figure 4 displays the schematic figure of practical diesel engine with the load changer equipment. The engine specification is shown as in table 1. The experiments were carried out with the engine revolution of 2400 rpm. The exhaust pipe diameter is 60 mm. The ambient temperature is around 25 degree.

The diesel oil with the properties shown as in table 2 was used at diesel engine operating condition of 25%, 50%, 75% and 100% of engine load.

EXPERIMENTAL RESULTS AND DISCUSSION

In this section, the experimental results are summed up and discussed. All light intensity signals are measured in equal unit of mV pointed out by Lock-in Amplifiers.

Figures 5 shows the light intensity signals (I_{40} and I_{140}) attained from the scattering technique, from which the volume mean diameter of aggreg-
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The value of volume mean diameter is around 96 nm. Figures 6 and figures 7 show representative values of light intensity signals of attenuation technique \( I_0, I_R \) in experiments carried out on the 9M-Yanmar diesel engine with 0% of load and 75% of load condition.

The change in mass concentration of PM in exhaust gas according to load of this diesel engine can be seen as in the figure 8. When the engine load increases, the volume mean diameter of PM does not change incredible but the number density, the volume fraction and the mass concentration changed slightly at 50%, 75% load, especially, at 100% of engine load the mass concentration of PM was particularly high.

Air dilution ratio, oxygen concentration and the exhaust gas volume per one kilogram of supplied fuel oil decreased but the fuel oil consumption increased as the engine load increased. Normally, when the operating load of engine increase, the PM mass concentration decreases but in this case of test engine, the PM mass concentration increase at the operating load of engine of 75%, especially of 100%. It seems that at condition of low engine load, the combustion took place in good process and vise versa the combustion process at higher
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Fig. 8: Distribution of Exhaust Gas and Engine Parameter against load of 9PS Diesel Engine.

Figures 9, 10 and figures 11 display the results of experiments carried out on the NFD-17E Yanmar diesel engine at 0% and 75% of engine load when A-heavy oil were used, respectively.

On the contrary to NFD-9M Yanmar diesel engine, when the engine load increased the concentration of PM distributed from NFD-17E Yanmar diesel engine decreased, simultaneously (fig. 12). Figure 13 shows the comparison between the results of experiments with different engine loads.
Fig.11(a): Light Intensity Signals I₀, Iᵣ & Ratio I₀/Iᵣ

Fig.11(b): Number Density, Volume Fraction and Mass Concentration of PM
carried out on NFD-9M Yanmar engine and those on NFD-17E Yanmar engine. It is obviously approved that the PM concentration distributed in the case of using the light oil was lower than that in the case of using the A-oil. Moreover, because of good condition (new engine) the concentration of PM distributed from NFD-17E Yanmar diesel engine using the same diesel oil is lower than that from NFD-9M Yanmar smaller engine. This means the measuring results of PM concentration distributed from diesel engine can be considered as a parameter for examining the condition of operating diesel at real time.

In order to compare the measuring results of experiments using optical system and those of filtering system, the filters of which effective diameter is 37 mm (JIS standard) were used to measure the PM mass concentration distributed from 17 PS diesel engine, representatively. As shown in the table 3 and figure 14, the difference between two methods is quite small. The average value of difference is 8.46%.
Table 3: Results of Experiments using Optical System and Filtering System.

<table>
<thead>
<tr>
<th>Engine Load</th>
<th>Result of Optical System (A)</th>
<th>Results of Filtering System (B)</th>
<th>Comparison=[(B-A)/A] x100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.02018</td>
<td>0.02163</td>
<td>+7.1</td>
</tr>
<tr>
<td>25%</td>
<td>0.01647</td>
<td>0.01590</td>
<td>-3.4</td>
</tr>
<tr>
<td>50%</td>
<td>0.00954</td>
<td>0.00890</td>
<td>-6.7</td>
</tr>
<tr>
<td>75%</td>
<td>0.00736</td>
<td>0.00815</td>
<td>+10.7</td>
</tr>
<tr>
<td>100%</td>
<td>0.00473</td>
<td>0.00405</td>
<td>-14.4</td>
</tr>
</tbody>
</table>

Fig.14: Comparison between Experimental Results of Optical System and those of Filtering System on 17 PS Diesel Engine.

CONCLUSIONS

A new method using light scattering and attenuation technique for PM size and concentration measurement was applied to exhaust gas from diesel engine with very low concentration at various operating condition. The results demonstrated the successful application of this technique to practical diesel engine.

With a certain diesel engine provided with exhaust gas pipe, the concentration of distributed PM depends mainly on the engine condition and fuel oil properties.

For present test engine, the PM volume mean diameter is around 90 nm to 120 nm, the number density is from 0.83\times10^7 to 11.85\times10^7 particles/cm^3, the volume mean fraction is from 0.35\times10^{-8} to 6.45\times10^{-8} cm^3/cm^3 and the mass concentration is from 0.05 g/m^3 to 0.13 g/m^3 depend on operating engine load condition and quality of test fuel oils.

The results attained by this measuring method allows the well-understanding of diesel engine condition at real time and emission control strategies as well as engine automatic control.

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