The harmful exhaust emissions from marine diesel engines are NOx, SOx, and PM (Particulate Matter). In recent years, there are problems of global warming and rising sea levels. When the BC (Black Carbon) in the PM falls on sea ice in the high-latitude region, an albedo of the sea ice surface decreases and its absorption of solar radiation increases. This promotes sea ice melting. Then marine diesel engines are strongly required to reduce the PM emission in the exhaust gas. However, the actual state of the PM emission from marine diesel engines has been not entirely cleared. In this paper, particle size distribution and mass concentration of PM from a high speed four-stroke engine (3L13AH, 73.55 kW) were measured by hot dilution method. In the hot-dilution method, exhaust gas from the engine is diluted by the rotary disk type diluter with high temperature air. This method allows exhaust gas dilution while preventing condensation of volatile component in the PM. PM particle size distribution in the diluted exhaust gas was measured by the SMPS (Scanning Mobility Particle Sizer). The effect of the dilution ratio on the particle size distribution and mass concentration of the PM was examined. In the experiment, the test engine was operated according to a propeller load curve and a constant speed with four load conditions (25%, 50%, 75% and 100%). Furthermore, the change of the number concentration of the PM in the sampling tube was examined. The results of this experiment are as follows: The particle diameter distributions obtained by the hot dilution show the mono-modal distribution and the bi-modal distribution depending on the operating condition of the engine. The mode diameters are 100 to 120 nm, except for the low load condition. It is found that the dilution ratio has a great effect on production of nucleation mode particles of small size region at the low engine load under constant speed operation. Therefore, it can be understand that volatile components are contained at a high concentration on exhaust gas. For the total number concentration measured by the SMPS, the maximum value is obtained at 75% load of the propeller load operation. The number concentration of the PM in the diluted exhaust gas decreases in the sampling tube for transfer from the diluter to the SMPS. The decrease rate of number concentration of the PM becomes higher for smaller particle sizes. While the dilution ratio of exhaust gas does not affect the decrease rate, the decreases rate increases as the tube length increases.

1. Introduction

The diesel engine has high thermal efficiency, and can use the low-quality fuel. Therefore, it is used a lot as the main engine for the ship and the engine for power generation. However, exhaust gas from diesel engines contains a great deal of PM. PM is a cause of the health hazard and the environment damage. The restriction and environmental standards concerning PM have been decided on land. The strong harmful effects of the fine particles on human body, in particular, have been reported recently. It is important to measure the particle size distribution and the number concentration of particles. The PM from the diesel engine is measured by use of the dilution tunnel system. For example, the method of PM measurement is standardized in ISO 8178-1[1]. According to the ISO standard, The PM from diesel engines is collected on a filter and measured by a weight concentration. The PM can be divided into soluble and insoluble.
organic fractions (SOF and ISF). The PM in the exhaust gas from the marine four-stroke diesel engine operating with a low load in the generator mode contains a lot of SOF [2].

Most of the SOF is considered to be volatile components and condensed under normal temperature condition. In the measurement of the PM including volatile components, the number concentration and the particle size distribution are strongly affected by the behavior of volatile components [3][4]. As the exhaust gas including the volatile components is cooled, a nucleation of the volatile components occurs. When the volatile component concentration is high enough, the nucleation occurs without cooling. The nucleation situation is different by dilution procedures [5]. In this study, measurements of the PM concentration and the particle size distribution of PM in the exhaust gas from a marine diesel engine are carried out. Four-stroke high-speed marine diesel engine (3L13AHS) was used in the experiments. In the experiment, the test engine was operated according to propeller load curve and constant speed with four load conditions (25 % (30 %), 50 %, 75 % and 100 %).

2. Experimental Apparatus and Method

2.1 Test Engine

A three-cylinder four-stroke trunk-piston type marine diesel engine was used as the test engine. Table 1 shows the specifications of the four-stroke test engine. Model name of the engine is 3L13AHS (Niigata power systems). Maximum output of the engine is 73.55 kW (1,200 rpm). The engine is installed on a test bench. Figure 1 shows a photograph of the test engine.

2.2 Dilution Method

Figure 2 shows the experimental apparatus for a hot dilution method. In the hot dilution method, exhaust gas from the test engine was diluted in a rotary disk type dilution device (MD19-3E, Matter aerosol). A part of exhaust gas flowing in the exhaust pipe was branched and was supplied to the dilution device through the transfer tube. In the rotary disk type diluter, the dilution unit and the dilution air are heated up and dilution of the exhaust gas conduct under high temperature condition to avoid condensation of volatile component in the exhaust gas. Another feature of the diluter is its high dilution ratio (up to 1:3000). The transfer tube was wrapped by a flexible heater and the exhaust gas flowing in the transfer tube was heated and insulated. The dilution air temperature in the dilution device was 423K. The measurement of the particle size distribution and the number concentration in the hot dilution method was conducted by use of the SMPS. Figure

| Table 1 Specifications of the test engine (Marine four-stroke diesel engine) |
|-----------------------------|----------------|
| Name                       | 3L13AHS        |
| Bore [mm]                  | 130            |
| Stroke [mm]                | 160            |
| Number of cylinder         | 3              |
| Output [kW]                | 73.55          |
| Engine speed [rpm]         | 1,200          |

Fig. 1 Test engine (3L13AHS)

Fig. 2 Experimental apparatus for hot dilution method

Fig. 3 Relationship between the gas temperature and concentration of volatile component for schematic diagram of nucleation.
3 shows the relationship between the gas temperature and concentration of volatile component for schematic diagram of nucleation. When the hot dilution method is applied for the measurement of PM from diesel engines, dilution and cooling processes of the exhaust gas progress along the path of $A \rightarrow B' \rightarrow C'$ in Fig. 3. On the other hand, as the exhaust gas is diluted with air at room temperature in the dilution tunnel method, the dilution process of the exhaust gas happens along $A \rightarrow B \rightarrow C'$. During the process, the volatile components in the exhaust gas pass their dew points and nucleation occur. Thus, the nucleation of volatile components of the PM is reduced by the hot dilution method.

2.3 Specifications of the Fuel Oil

The MDO (Low-sulfur fuel) with a sulfur content of 0.088 %, were used as a fuel oil in the test. Table 2 shows a summary of the specifications of the fuel oil.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>0.001 (mass %)</td>
</tr>
<tr>
<td>Cetane number (JIS K2204)</td>
<td>50</td>
</tr>
<tr>
<td>Cetane number (JIS K2280)</td>
<td>49.7</td>
</tr>
<tr>
<td>Density (15 degC)</td>
<td>0.8557 (g/cm³)</td>
</tr>
<tr>
<td>Sulfur content</td>
<td>0.088 (mass %)</td>
</tr>
<tr>
<td>Water content</td>
<td>0.05 (mass %)</td>
</tr>
<tr>
<td>Calorific value (gross)</td>
<td>45462 (kJ/kg)</td>
</tr>
<tr>
<td>Calorific value (net)</td>
<td>42696 (kJ/kg)</td>
</tr>
</tbody>
</table>

2.4 Scanning Mobility Particle Sizer

In the measurement of PM particle size distribution, SMPS (Scanning Mobility Particle Sizer, Particle Size Range: 7.69-289 nm, Particle Resolution: 102 Channels) was used. The SMPS classifies particles based on its mobility diameter and consists of a DMA (Differential Mobility Analyzer) and a CPC (Condensation Particle Counter, Butanol CPC). The Particles entering the system are classified according to electrical mobility by the DMA. Then the number concentration of the particles is measured by the CPC.

3. Results and Discussion

3.1 PM Number - Size Distribution by SMPS

The particle size distribution of the PM in the exhaust gas from the marine four-stroke diesel engine was measured at four different engine loads, namely, 30, 50, 75 and 100 % load. Measurements were carried out by the hot dilution method. A dilution ratio is fixed to 1000, and a temperature of diluted exhaust gas is controlled at a constant temperature 423 K. Figure 5 shows the relationship between particle size and number concentration of the PM in the exhaust gas at four different engine loads under the constant speed operation.

![Fig. 5 Relationship between particle size and number concentration of PM](image)

Fig. 5 Relationship between particle size and number concentration of PM
(Constant speed operation, Engine speed : 1,200 rpm)

![Fig. 6 Relationship between particle size and number concentration of PM](image)

Fig. 6 Relationship between particle size and number concentration of PM
(Propeller load operation)
Figure 6 shows the relationship between particle size and number concentration of the PM in the exhaust gas at four different engine loads under the propeller load operation. The number concentrations shown in the Figs. 5 and 6 are converted values from measured concentration to the concentration in the exhaust gas by the dilution ratio.

In Fig. 5, the number size distributions of the PM are composed a mono-modal distribution at the 50 %, 75 %, 100 % engine load under constant speed operation. At the 30 % engine load under the constant speed operation, the particle size distribution of the number concentration shows bi-modal distribution. The PM measured at 30 % load under the constant speed operation contains a large amount of SOF. Therefore, the particles of less than 30 nm in diameter at 30 % load are thought to be the nucleation mode particles. Most of the particles in the exhaust gas are composed of the particles of 300 nm or less in diameter.

In Fig. 6, the particle size distribution of the number concentration are composed a mono-modal distribution at the all engine loads under the propeller load operation. The mode diameter of the particle size distribution of the number concentration is 100-200 nm. The maximum value of the number concentration on particle size distribution is observed at 75 % engine load. The excess air ratio of the engine increases with a decrease in engine load under the constant speed operation. At low engine load, especially at the constant load operation, as the quantity of fuel injected is small and the excess air ratio is large, a lean mixture zone tends to be produced in the combustion chamber and much SOF produced in that zone. This is the reason why the number size distribution of the PM at 30 % load of constant speed operation shows the bi-modal distribution.

At 30 % and 75 % engine loads, the effect of dilution ratio on the particle size distribution was examined. In the experiment, the diluter temperature is 423 K and the dilution ratios were set to 200, 600, 1000, 1500, and 1800. Figure 7 shows the relationship between particle size and number concentration of the PM in the exhaust gas at 30 % engine loads under the constant speed operation. The number concentration corresponding to the diameter of smaller peak decreases with increase in the dilution ratio, whereas the number concentration does not change for the particles having the diameter of 30 nm or larger.

Figure 8 shows the relationship between particle size and number concentration of the PM in the exhaust gas at 75 % engine loads under the constant speed operation. In the case of 75 % engine load, the particle size distributions show the mono-modal distribution, and the mode diameters are around 100 nm. Even when the dilution ratio changes, the number concentration does not change for the particles of the diameter of all range. The PM measured at 30 % load under the constant speed operation contains a large amount of SOF in compared with the PM at 75 % load. Therefore, in Figs.7 and 8, most of the particles measured at 30 % load are the nucleation mode and the particles measured at 75 % load include the accumulation mode particles in addition to the nucleation mode.

3.2 PM Mass Size Distribution by SMPS
The measured results shown in Figs.5 and 6 were
converted to the mass concentration, where the shape of the particles assumed to be a perfect spheres and the density of the particles assumed to be 1.0 g/cm².

Figures 9 and 10 show the relationship between particle size and mass concentration of the PM measured by the SMPS under the constant speed operation and the propeller load operation, respectively. In Figs. 9 and 10, most of the PM in the exhaust gas are composed of the particles of more than 200 nm in diameter. As small particles are lightweight and large particles are heavy, the large particles even with a small number concentration show the large weight. Then, the distribution of the mass concentration shows mono-modal distribution.

3.3 Total Number Concentration by SMPS

The total number concentration was calculated from the measurement results shown in Figs. 5 and 6. The particle size range of the target is the same as the measurement range measured here is from 7.69 to 289 nm. Figure 11 shows the total number concentration under constant speed operation. The total number concentration of PM per unit volume is lowest at 50 % engine load under the constant speed operation and becomes higher with engine load. Figure 12 shows the total number concentration under the propeller load operation. The total number concentration of the PM per unit volume shows the highest value at 75 % engine load under the propeller load operations. When measured under the condition of hot dilution, the particle discharged from the marine four-stroke diesel engine is about 4.5x10⁶ to 1.3x10⁷ particles per cubic cm.

3.4 Decrease of PM Number Concentration in the Sampling Tube

The decrease of PM number concentration in the sampling tube between the dilutor and the SMPS was examined. A conductive polyurethane tube was used as the sampling tube. In the experiment, the sampling tube length was changed from 400 mm to 4640 mm. The residence times of the diluted exhaust gas in the sampling tubes are 4 sec (tube length 400 mm), 29.7 sec (2520 mm), 51.5...
Four. Conclusions

The particle size distributions of number concentration and mass concentration of the particulate matter from the four stroke marine diesel engine were measured. The following results of the tests were obtained.

[1] The particle diameter distributions obtained by the hot dilution show the mono-modal distribution and the bi-modal distribution depending on the operating condition of the engine. The mode diameters are 100 to 120 nm, except for the low load condition. It is found that the dilution ratio has a great effect on production of the nucleation mode particles of small size region at the low engine load under the constant speed operation. Therefore, it can be understand that volatile components are contained at a high concentration in the exhaust gas.

[2] For the total number concentration measured by the SMPS, the maximum value is obtained at 75% load of the propeller load operation.

[3] The number concentration of the PM in the diluted exhaust gas decreases in the sampling tube for transfer from the diluter to SMPS. The decrease rate of number concentration of the PM becomes higher for smaller particle sizes. While the dilution ratio of exhaust gas does not affect the decrease rate, the decrease rate increases as the tube length increases.

References


