Measurement of Bunker Oil / DME Blended Fuel Viscosity for Diesel Engine Application *

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Currently, around 80% of large ships use Bunker oil (JIS C heavy oil) as the base fuel in marine diesel engines. With its very high kinematic viscosity, this oil is considered the lowest grade of fossil fuel. Thus, it needs to be heated to reduce its viscosity. The authors have reported that the blending of liquefied DME improved the combustion performance of Marine Diesel Oil (JIS A heavy oil). This study aims to clarify the effectiveness of DME – Bunker oil blends. The kinematic viscosity measurement of DME and Bunker oil blended fuel was performed using a capillary tube type viscometer. A pressure cell which contains the viscometer was developed to measure the fuel viscosity while keeping DME in a liquid state. From experiments, it was shown that the cell pressurization resulted in smaller values of kinematic viscosity, and modification was needed to obtain true viscosity values. It was shown that at 323K, the kinematic viscosity of Bunker oil can be reduced drastically from 54~89% with DME blending.

1. Introduction

DME (Dimethyl ether) has been considered as one of alternative fuels for diesel engines, because of its advantages in physical and chemical properties such as the higher Cetane number and the smokeless combustion, and so on. Authors have carried out some experimental studies to improve the diesel engine performance by blending liquefied DME to Marine Diesel Oil (JIS A heavy oil)⁽¹⁾⁽²⁾. From those studies, it was clarified that the DME blending was effective to reduce the harmful exhaust emission, such as smoke, as well as the global warming substance, CO₂. In this study, it is aimed to clarify whether the DME blending is also effective to improve diesel combustion of coarse fuel, namely Bunker oil (JIS C heavy oil).

The kinematic viscosity is an important factor of fuel oils which determines a fuel pumping quality, an atomization process, a pipeline design and storage, and so on. Thus, it needs to maintain the fuel viscosity at an optimal value to get a stable engine operation. Currently, around 80% of large size ships are using Bunker oil as the base fuel in marine diesel engine. Bunker oil is the lowest grade of fossil oil whose kinematic viscosity is very high, in a range from 150

to 400 mm²/s (cSt), and a preheating is needed to reduce its viscosity. It is usually heated up around 100 degrees centigrade to reduce its kinematic viscosity less than 15 mm²/s. The Bunker oil used in this study is JIS heavy oil type 3 No.1 (JIS C heavy oil No.1), whose property is almost equivalent to RME180 or RMG180 of ISO 8217:2010 classification. On the other hand, the liquefied DME has a problem of poor lubricity due to its lower kinematic viscosity (0.184 mm²/s at 25 degrees centigrade⁽³⁾). Properties of each fuel are shown in Table 1. It is guessed that a blending liquefied DME to Bunker oil may give a moderate viscosity to operate in diesel engines.

Table 1 Properties of test fuels

	DME	Bunker Oil
Chemical formula	CH ₃ OCH ₃	—
Boiling point (K)	248	< 623
Calorific value (MJ/kg)	28.9	40.8
Ignition point (K)	508	813~894
Latent heat (kJ/kg)	467.13	282
Cetane number	55~60	—
CCAI	—	854
Carbon residue (wt. %)	0	12.0
Sulfur content (wt. %)	0	1.77
Kinematic viscosity (mm ² /s)	0.184 @ 298K	103 @ 323K
Density (kg/m ³)	661 @ 298K	977 @ 288K

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In this article, the kinematic viscosity measurement of DME and Bunker oil blended fuel is described that is done by means of a capillary tube type viscometer. DME is a volatile substance which needs to be pressurized or cooled to maintain a liquid state at an atmospheric condition. There are some investigations to examine the kinematic viscosity of volatile liquid fuels. Sivebaek et al. have been designed and constructed the measurement system of volatile substances such as DME, and reported the neat liquid DME viscosity⁽³⁾. Nakasato et al. presented the kinematic viscosity of DME / BDF (Bio Diesel Fuel) blended fuel⁽⁴⁾, and Bhide et al. also reported the viscosity of various DME blended fuels⁽⁵⁾. From those reports, DME blended fuels showed reduced kinematic viscosities, but an effect of pressurization of blended fuels was not clear. That is, the pressurization of blended fuel with inert gases to avoid the evaporation of DME will change a movement of blended fuel in the viscometer, and the measured viscosity values might be changed with the levels of pressurization.

In this study, we adopt the measurement system of Sivebaek et al.⁽³⁾. A pressure cell which contains a capillary tube type viscometer is pressurized with an inert gas to maintain a liquid state of DME. And the effect of pressurization levels is investigated with standard viscosity liquids. From the experiments of this study, it is obtained that the pressurization gives a smaller value of kinematic viscosity, and a modification is needed to obtain a true viscosity value. Also it is obtained that the kinematic viscosity of Bunker oil can be reduced drastically by the blending DME, namely 54~89% at 323K.

2. Experimental Apparatus and Method

2.1 Kinematic Viscosity Measurement Equipment

The kinematic viscosity of DME and Bunker oil blended fuels was measured by a capillary tube type viscometer (Cannon Instrument Co, Zeitfuchs cross-arm viscometer). As DME has a higher vapor pressure than the atmospheric pressure, the fuel system needs to be pressurized to maintain DME at a liquid state. Thus, in order to measure the kinematic viscosity of volatile blended fuels, a kinematic viscosity measurement system was constructed as provided in Fig. 1. A pressure cell consists of a transparent cylindrical vessel, two flat rounded flanges and six tightening long rods. The transparent cylindrical vessel (length: 330mm, outer diameter: 76mm, thickness: 5.5mm) was designed with a polycarbonate to obtain a pressurized atmosphere up to 2.0MPa. The viscometer was installed inside the pressure

Fig. 1 Pressure cell type viscosity measurement system

vessel and introduced the blended fuel under pressurized atmosphere with an inert gas, namely nitrogen gas. In order to hold the viscometer in the vessel, collars (acrylic plate, thickness: 3mm) were installed under the viscometer. The two stainless flat rounded flanges were tightened with six stainless long bolts (M8) from both sides of the vessel. Gaskets (Gore Highper Sheet, thickness: 1.5mm) were inserted between the cylindrical vessel and the stainless flanges to prevent a leakage of nitrogen gas. The upper side stainless flange had 3 holes for a fuel supplying, a nitrogen gas supplying and a thermocouple installing.

The pressure cell was pressurized higher than a vapor pressure of DME to maintain a liquid state with nitrogen gas. Table 2 shows the relation of pressures according to the vapor pressure of DME⁽⁶⁾. The test fuel was supplied into viscometer at the pressure slightly higher than the cell pressure. The temperature of nitrogen gas was measured with a thermocouple (Yamari Thermic, 316L, diameter: $\phi 1.6$). The experimental setup of viscosity measurement with temperature control is shown in Fig.2. The whole pressure cell was inserted into a water bath whose temperature was controlled with a heater. Temperature of test fuel was assumed to be the same with the gas temperature after passing enough time (20 minutes). Figure 3 shows a schematic cross sectional diagram and an outlook photograph of the fuel tank used in this study. A pressure-resistant closed vessel of stainless steel was used as the fuel tank to adjust the fuel supplying pressure.

Table 2 Cell pressure with N₂ gas and DME vapor pressure

Temperature of fuel (K)	DME vapor pressure (MPa)	Cell pressure with N ₂ gas (MPa)
308	0.8	1.0
323	1.2	1.3
343	1.9	2.0

Fig. 2 Experimental setup for temperature control

Fig. 3 Cross sectional diagram and outlook of fuel tank

2.2 Kinematic Viscosity Measurement Method

Figure 4 shows the schematic diagram of the capillary tube viscometer used in this study. This model is suitable to measure the viscosity of an opaque liquid, such as the Bunker oil. The measurement procedure is as follows. The test fuel was introduced into the viscometer through the port A (designated in Fig.4) until the leading edge of test fuel reaching up to mark B. Then, the whole pressure cell was held inside the water bath about 20 minutes for becoming to the set temperature. Then, the movement of the test fuel was induced by adding a small portion of fuel into the port A. Test fuel flew into the capillary tube D and reached to the measuring section of G. The passing time t was measured while the leading edge flowing the timing mark from H to F. Subsequently, the kinematic viscosity ν (mm^2/s) of test fuel is calculated by the following equation.

Fig. 4 Zeitfuchs cross-arm viscometer

$$\nu = t \times C_1 \times C_2 \quad (1)$$

where, t : passing time (sec.), C_1 : viscometer constant (mm^2/s^2), C_2 : modification coefficient for pressurization

Coefficient C_1 in the eq. (1) is given according to the size of Zeitfuchs cross-arm viscometer. The recommended viscosity measurement ranges, as well as the constant C_1 , are shown in Table 3. The different size viscometers were used in this study according to the measurement range. Coefficient C_2 in the eq. (1) is originally added in this study to eliminate an effect of pressurization of the test fuels. That is, the passing time might be changed by the pressurization of the fuel surface, and the measured kinematic viscosity of the test fuel will be assumed smaller value. In this study, C_2 is defined with using a standard viscosity liquid for a viscometer calibration (Nippon grease, JS series, JIS Z 8809:2000).

Table 3 Recommended viscosity ranges for the Zeitfuchs cross-arm viscometer

Viscometer Size	Constant C_1 (mm^2/s^2)	Measurement range (mm^2/s)
1	0.002846	0.6 to 3
2	0.01066	2 to 10
3	0.03335	6 to 30
4	0.1017	20 to 100
5	0.3049	60 to 300

3. Results and Discussion

3.1 Modification Coefficient for Pressurization

The modification coefficient, which is explained in the section 2.2, was defined with using the standard liquid of calibrating viscometers in variations of the cell pressures, 1.0,

1.3, 1.6, 2.0MPa respectively, and the viscosities with 3 different liquid, JS2.5, JS20, JS100 respectively. The numbers of liquid designate the kinematic viscosity (mm^2/s) at the temperature of 20 degrees centigrade. The change of liquid viscosity with temperature is based on the Japanese Industrial Standards, JIS Z 8809:2000.

Figure 5 gives the correlation of viscosities between the standard liquids viscosity and the measured viscosity under pressurized ambient at 1.3MPa. The horizontal axis represents the kinematic viscosity of standard liquids which are designated true value by inspections. The vertical axis represents the measured kinematic viscosity with using the pressure cell type viscometer. And solid straight line in the figure means the 1:1 correlation between the true value and the measured value. It is obtained that all measured kinematic viscosities indicate smaller values than the true values. It is assumed that the pressurized atmosphere accelerates the test fuel motion in the viscometer. That is, the inlet position of viscometer has much larger cross sectional compared to the outlet position. And the pressurization of

test fuel's surface results in the acceleration of movement in the viscometer.

From the correlation of Fig.5, it is concluded that the measured kinematic viscosity becomes smaller value by the effect of pressurization on the liquid surface. Subsequently, the modification coefficient for pressurization C_2 is required to eliminate the effect as described in the section 2.2. C_2 is defined with the following equation.

$$C_2 = \nu(\text{true value}) / \nu(\text{measured value}) \tag{2}$$

Figure 6 shows the calculated modification coefficient C_2 for each of the experimental result. The calculated C_2 give almost same value regardless the values of kinematic viscosity. The arithmetical mean value of C_2 is 1.27, as shown with the horizontal straight line in the figure. The values of C_2 with other cell pressures are investigated with the same procedure, and summarized in Table 4 and Fig.7.

It is obtained that the value C_2 increases with increasing in the cell pressure. It is obvious that the pressurization of the test fuel surface enhances the movement of the test fuel in the viscometer. The approximate line in Fig.7, the two-dotted dashed line, can be represented with the following equation.

$$C_2 = 0.076P + 1.18 \tag{3}$$
$$R^2 = 0.96$$

where, C_2 : modification coefficient for pressurization, P : pressure inside the cell (MPa, from 1.0 to 2.0)

Fig. 5 Correlation of viscosities of standard liquids under pressurized ambient

Fig. 6 Calculated modification coefficient C_2

Fig. 7 Change of modification coefficient C_2 with cell pressure

The error of calculated C_2 with the eq. (3) compared to the actual experimental data is in the range from 0.1 to 0.7%. The value R^2 shown with the eq. (3) stands for a coefficient of determination of the approximate line, which has a value between 0.0 and 1.0. The R^2 closer to 0.0 means no correlation between the actual data and the approximate equation, while the value closer to 1.0 shows a perfect correlation. The R^2 value of 0.96 for the eq. (3) means a strong correlation.

3.2 Change in Viscosity of Blended Fuel with Mixing Ratio of DME

The kinematic viscosity of DME and Bunker oil blended fuel was measured in variation of DME blending ratio.

Figure 8 shows the measurement result of kinematic viscosity at the fuel temperature of 50 degrees centigrade (323K). And Fig.9 gives the reduction rate of kinematic viscosity of Bunker oil by blending DME. The temperature, 50 degrees centigrade, is the reference temperature giving the kinematic viscosity value in the JIS standard. In the figure, the blended fuel is expressed with the mixing weight

Fig. 8 Change of viscosity of Bunker oil with DME blending ratio

Fig. 9 Reduction rate of viscosity of Bunker oil with DME blending ratio

ratios of each fuel. That is, C90D10 means the blend fuel comprise of 90% Bunker oil and 10% DME in weight ratio.

It is obtained that the kinematic viscosity of Bunker oil can be reduced drastically with blending liquefied DME. The reduction rate of viscosity, as shown in Fig.9, is not linearly proportional to DME blending ratio. The approximate line in Fig.8 is represented by the following equation.

$$\nu_{mix} = 103 \times \exp(-0.054X) \quad (4)$$

$$R^2 = 0.98$$

where, ν_{mix} : Kinematic viscosity of blended fuel (mm²/s),
X: DME blending ratio (weight %, from 0 to 40)

The kinematic viscosity of blended fuel can be correlated with an exponential equation with the DME blending ratio. The eq. (4) gives a strong correlation between the measured data and the approximate value, because the R^2 value is very close to 1.0. The measurements are carried out 4 times in the same experimental condition. Table 5 shows the variations of each measurement. COV of kinematic viscosity measurement varies among each experimental condition, and the average of COV is around 8% for this study.

Table 5 Variation in viscosity of DME/Bunker oil blend fuel

	DME ratio to Bunker oil (%wt.)			
	10	20	30	40
Average viscosity (mm²/s)	49.6	34.9	23.5	11.4
Standard deviation (mm²/s)	4.4	4.4	0.3	1.2
Coefficient of variation (%)	8.9	12.6	1.3	10.4

3.3 Change in Viscosity of Blended Fuel with Temperature

Figure 10 shows the change of kinematic viscosity of Bunker oil/DME blended fuel with the fuel temperature and the blending ratio. And, the reduction rate of kinematic viscosity of Bunker oil by blending liquefied DME is shown in Table 6.

All viscosities reduce with increasing in their temperature as the natural feature of liquid fuel. The reduction rate of kinematic viscosities increases with the DME blending ratio for all fuel temperature cases. And the reduction rates at same DME blending ratio cases show maximum value for the lowest temperature case (25 degrees centigrade, 308K). But the difference between the reduction rates is not so much changed among the temperature condition. The reduction rates, however, seem to show strong correlations with DME mixing rate.

Table 6 Reduction rate of kinematic viscosity of Bunker oil by blending liquefied DME

Temp. of fuel (K)	Kine. viscosity of Bunker oil (mm ² /s)	Reduction rate of kinematic viscosity (%)			
		C90D10	C80D20	C70D30	C60D40
308	239	78.0	83.6	88.6	94.3
323	103	51.8	66.1	77.1	88.9
343	44.8	67.2	77.5	82.6	86.8

Fig. 10 Kinematic viscosity of Bunker oil/DME blend fuel

4. Conclusions

Bunker oil is commonly used as the base fuel in marine diesel engines. It is the lowest grade oil among fossil oil whose kinematic viscosity is very high. Thus, it needs to be heated up to reduce its viscosity. In this study, the kinematic viscosity of Bunker oil and DME blended fuel is experimentally investigated by means of the capillary tube viscometer installed into the pressure cell pressurized with the inert gas. From experiments, following results are obtained.

1. The measured viscosity with the pressure cell type viscometer shows smaller viscosity compared to the true value due to the effect of pressurization.
2. Modification coefficient of pressurization is required and defined in the pressure range from 1.0 to 2.0MPa, where the coefficient C_2 is related with the pressure P (MPa) as $C_2 = 0.076P + 1.18$. This equation can be applied for the capillary tube viscometer of Zeitzfuchs cross-arm type.
3. It is obtained that the blending liquefied DME to

Bunker oil can be reduced drastically the kinematic viscosity of fuel oil. 52~89% reduction is possible at fuel temperature of 323K.

4. The kinematic viscosity of blended fuel ν_{mix} (mm²/s) at the temperature 323K can be given with the relation of DME blending ratio X (weight %, from 0 to 40) as $\nu_{mix} = 103 \times \exp(-0.054X)$.

From the experimental study in this article, it is concluded that the kinematic viscosity of Bunker oil (JIS C heavy oil) can be reduced by blending liquefied DME. At certain amount of blending ratio of DME, namely 40% at room temperature (308K), the kinematic viscosity becomes optimal value (around 14mm²/s) to use in a marine diesel engine. This suggests that a preheating of Bunker oil will not be necessary by the blending DME. Further studies will be carried out to investigate engine performances with Bunker oil/DME blended fuel.

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