An Environmentally Compatible Lubricant for Sterntubes and Marine Hydraulic Systems

Hiroyuki Sada[1], Seiji Yamajo[1] and David W. Hawkins[2]

1: Kobelco Eagle Marine Engineering Co. Ltd., Takasago, Japan
2: Kobelco Eagle Marine Inc., New York, NY

ABSTRACT

Medium and large ocean-going vessels use oil-lubricated shafting and bearings in the sterntube. Oil leakage from the sterntube is a serious environmental issue in these vessels. In this paper, a newly developed, environmentally compatible lubricant for such sterntube systems is outlined. Properties required for a sterntube lubricant and a suitable base fluid are discussed. Environmental properties, viscosity, corrosion prevention, water contamination lubrication, seal compatibility and field experience of the new lubricant are described. Application in marine hydraulic systems is also discussed.

1. INTRODUCTION

Medium and large ocean-going vessels use an oil-lubricated sterntube system, which consists of white metal bearings supporting the propeller shaft, oil lubrication of the shaft and bearings, and seals preventing oil leakage. In sterntube bearings, the radial movement of the shaft is considerably larger than that of bearings for general industrial application. In addition, external disturbances such as rough seas and vibration are considerable. It is very difficult to seal the sterntube oil perfectly and oil leakage can be an issue. Another area of concern is oil leakage from below water hydraulic systems, controllable pitch propeller hydraulic systems and thruster drives. Therefore, a few of the serious environmental issues in medium and large commercial vessels are sterntube, thruster and controllable pitch propeller oil leakage.

In order to solve the oil leakage issue from sterntubes, considerable efforts are being made to improve seal performance. The introduction of highly reliable seals with an air chamber between the oil and the seawater, so-called air seals [Shiomi 1987; Yamajo 2003], has made a big improvement in the environmental compatibility of sterntubes. The air seals have a drawback in that they require the installation of piping system in existing vessels. On the other hand, the requirements for the environmental compatibility of vessels are being increased. Recently severe crackdowns against vessels with oil leakage have been carried out. Oil leakage can result in heavy fines or imprisonment.

Biodegradable lubricant is attracting keen interest as a solution for the oil leakage issue. Biodegradable lubricants, which are decomposed quickly to carbon dioxide and water in the natural environment, are environmentally friendly. Such lubricants can be easily applied to existing vessels by simply replacing the conventional mineral oil. Some biodegradable lubricants have already been used in sterntube applications [Wholley 2005]. Existing biodegradable lubricants, however, do not satisfy all the properties required for sterntube lubricants.

In this paper, a newly developed, environmentally compatible lubricant for sterntube shafting and bearing systems is outlined. Properties required for sterntube lubricants and base fluids suitable for sterntube application are discussed. Environmental properties, viscosity, and corrosion prevention related to the new lubricant, based on the most suitable fluid, are described. Concerning lubrication under water contamination, which is the most important property of a sterntube lubricant, the results for translatory oscillation and journal bearing tests are also described. In addition, the seal compatibility and field experience are described. Finally the application of the sterntube lubricant in marine hydraulic systems is discussed.

Presented at the Advanced Naval Propulsion Symposium 2008 of the American Society of Naval Engineers (ASNE) in Arlington, VA on December 15-16, 2008.

Table 1 Comparison of Potential Base Fluids

	Non-Sheening	Water Tolerance	Seal Compatibility
Triglyceride	Poor	Weak, Hydrolysis can occur.	OK
Synthetic Ester	Poor	Weak, Hydrolysis can occur.	OK
Polyethylene Glycol	Good	Good	High swelling effect on FKM

2. BASE FLUID

Base fluid suitable for an environmentally compatible sterntube lubricant is discussed.

2.1. Properties Required for Sterntube Lubricants

The following environmental properties are required for sterntube lubricants:

- Biodegradability
- Low toxicity
- Non-sheening

Biodegradability means that a lubricant is decomposed quickly to carbon dioxide and water in the marine environment. Low toxicity means that a lubricant is practically non-toxic to aquatic life. Non-sheening means that a lubricant forms no sheen on seawater surface. The impact of sheen on marine environment cannot be ignored.

In addition to these properties, the following properties are required:

- High viscosity
- Water tolerance
- Seal compatibility

Sterntube lubricants generally have a viscosity grade of 68 or 100. The base fluid needs to have an equally high viscosity. Seawater ingress into the sterntube is also a possibility. The base fluid needs to absorb this seawater. As a seal for sterntubes, a radial lip seal made of fluoro-elastomer (FKM) is the most common. The base fluid needs to be compatible with the seal material.

2.2. Selection of Base Fluid

From the viewpoints of biodegradability, low toxicity and high viscosity, triglyceride, synthetic ester and polyethylene glycol were selected as potential base fluids. Triglyceride is a natural oil derived from animals or plants. Synthetic ester is made of natural oil or petrochemical oil. Polyethylene glycol is a petrochemical lubricant. A comparison of these fluids is given in Table 1.

Triglyceride and synthetic ester form surface sheen because they are not very soluble and lighter than seawater. At high temperatures, hydrolysis can occur in these fluids with water contamination. Polyethylene glycol forms no surface sheen and tolerates water well because of its water-solubility. The fluid has a drawback in that it causes excessive swelling of the seal material (FKM). Poor solubility, specific gravity and hydrolysis are essential fluid properties, and they cannot be easily changed. However, the seal compatibility problem can be solved by modifying the seal material. In conclusion, polyethylene glycol is the most suitable base fluid for a sterntube lubricant.

3. ENVIRONMENTAL PROPERTIES

An environmentally compatible sterntube lubricant, KEMEL ST-77, has been newly developed. Its base fluid is polyethylene glycol. The ST-77 environmental properties, biodegradability, low toxicity and non-sheening, are described below.

3.1. Biodegradability

For biodegradation testing, the CO_2 evolution test [OECD 301B] and the O_2 uptake test [OECD 301C] are commonly applied. For the development of ST-77, the O_2 uptake test was applied, because it is more stringent and severe than the CO_2 evolution test [Batterby 2005]. The biodegradation of ST-77 in the O_2 uptake test was 83% after 28 days. When a test substance has greater than 60% biodegradation after 28 days in the O_2 uptake test, it is defined as readily biodegradable. Thus, ST-77 is highly biodegradable. Figure 1 shows the biodegradation curve of ST-77 for the O_2 uptake test. The biodegradation reached the pass level of 60% after 14 days. The biodegradation curve of a mineral oil, which is commonly applied in sterntubes, is also shown in Fig. 1. The mineral oil had less than 20%

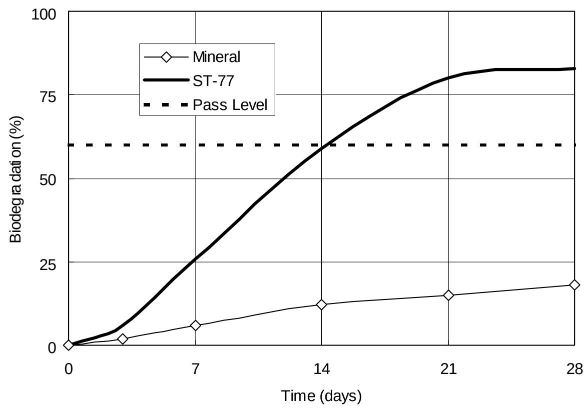

Fig.1 Biodegradation vs. Time

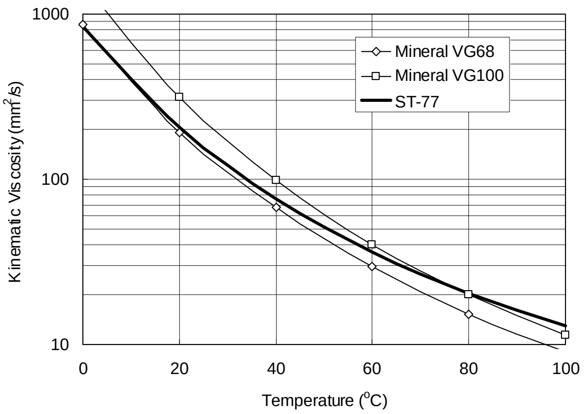

Fig.2 Viscosity vs. Temperature

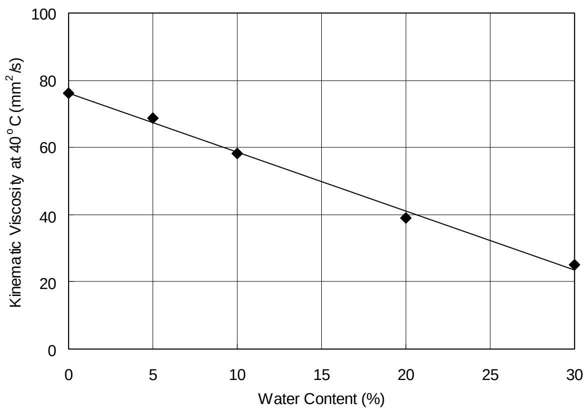

Fig.3 Viscosity vs. Water Content

biodegradation after 28 days.

The mineral oil was tested with emulsification by ultrasonication, because it is poorly soluble. Biodegradation of poorly soluble substances is very dependent on the emulsification level applied in the test. In one case, a poorly soluble substance had 88% biodegradation with full emulsification and 18% biodegradation with no emulsification [Batterby 2000]. Because ST-77 is water-soluble, it needs no emulsification in the biodegradation test. The biodegradability of ST-77 in the field is expected to be much higher than that of a poorly soluble lubricant even if both lubricants have the same biodegradation in the O_2 uptake test.

3.2. Low Toxicity

Polyethylene glycol, which is the base fluid of ST-77, is a well-known non-toxic material. It is generally applied in cosmetics and medicines. The toxicity of ST-77 was evaluated by the acute fish toxicity test [OECD 203]. The result for 50% lethal concentration after 96 hours, 96h-LC_{50}, exceeded 100 mg/l. ST-77 is defined as practically non-toxic according to the classification defined by the United Nations [UN GHS].

3.3. No Sheen Formation

The base fluid of ST-77, polyethylene glycol, is water-soluble. Since the additives, such as the corrosion inhibitor, are also water-soluble, ST-77 is completely water-soluble. The environmental impact of surface sheen cannot be neglected. ST-77 forms no surface sheen because of its solubility, and is more environmentally friendly than poorly soluble, biodegradable oils.

4. VISCOSITY

The ST-77 viscosity characteristics, related to temperature and water contamination, are described below.

4.1. Viscosity-Temperature Relationship

The relationship of kinematic viscosity and temperature is shown in Fig. 2. The typical value of kinematic viscosity is 77 mm^2/s at 40 ^{o}C, and 13 mm^2/s at 100 ^{o}C. Standard sterntube mineral oil has a viscosity grade of 68 (VG68) or a viscosity grade of 100 (VG100). In the figure, the relationship between kinematic viscosity and temperature is also shown. As shown in the figure, ST-77 is as thick as the mineral oils, but the curve of ST-77 is flatter. ST-77 has superior temperature-related viscosity characteristics. The specific gravity of ST-77 at 15 ^{o}C is 1.12.

4.2. Water Contamination Viscosity

Because mineral oil is poorly water-soluble, water contaminated in the mineral oil becomes free water. The free water causes a considerable decrease in lubrication performance. On the other hand, water contaminated in ST-77 does not become free water because ST-77 is water-soluble. Therefore, the lubrication performance under water contamination does not decrease dramatically. For ST-77, the relationship of kinematic viscosity at 40 ^{o}C and water content is shown in Fig. 3. The viscosity decreases as the water content increases, but the relationship is linear. No sudden drop occurs.

5. CORROSION PREVENTION

Seawater ingress into the sterntube is possible. Corrosion prevention is a key lubricant property for sterntube shafting and bearing systems.

The corrosion prevention under seawater contamination of ST-77 was evaluated according to the JIS K2510 test method. The test metal was carbon steel (S20C). The test temperature and the test period were 60 ^{o}C and 72 hours, respectively. For

Table 2 Corrosion Test Results

	ST-77	Mineral Oil
Lubricant + 5% Seawater	Corrosion-free	Corrosion-free
Lubricant + 10% Seawater	Corrosion-free	Corroded
Lubricant + 15% Seawater	Corrosion-free	Corroded
Lubricant + 20% Seawater	Corroded	Corroded

comparison, a mineral oil commonly used in sterntubes was also tested. In total, eight fluids were tested:

1) ST-77 + 5% seawater
2) ST-77 + 10% seawater
3) ST-77 + 15% seawater
4) ST-77 + 20% seawater
5) Mineral oil + 5% seawater
6) Mineral oil + 10% seawater
7) Mineral oil + 15% seawater
8) Mineral oil + 20% seawater

The test results are given in Table 2. Carbon steel was not corroded in ST-77 with 15% seawater, but was corroded in the mineral oil with 10% seawater. ST-77 has sufficient corrosion protection performance as a sterntube lubricant.

6. LUBRICATION UNDER WATER CONTAMINATION

The lubrication under water contamination of ST-77 was compared with a VG68 mineral oil, which is commonly applied in sterntubes, through translatory oscillation and journal bearing tests. The translatory oscillation test and the journal bearing test are for evaluating the anti-wear performance and the anti-scoring performance, respectively.

6.1. Translatory Oscillation Test

The translatory oscillation test [DIN 51834], a type of ball-on-plate sliding test, was carried out. As the test specimens, a bearing steel ball (diameter: 10 mm, material: SUJ2) and a bearing steel disk (diameter: 24 mm, thickness: 7.85 mm, material: SUJ2) were used. The lubricants of 0.03 cc were supplied at the contact point of the ball and the disk. The test method is schematically outlined in Fig. 4. A frequency of 50 Hz, an amplitude of 2 mm, an ambient temperature of 40 ^{o}C, a test period of 10 minutes, and a normal load of 100 N were applied. The maximum Herzian stress at the contact point was 2.16 GPa. In total, six fluids were tested:

1) Neat ST-77
2) ST-77 + 5% water
3) ST-77 + 10% water
4) ST-77 + 15% water
5) ST-77 + 20% water
6) Neat mineral oil

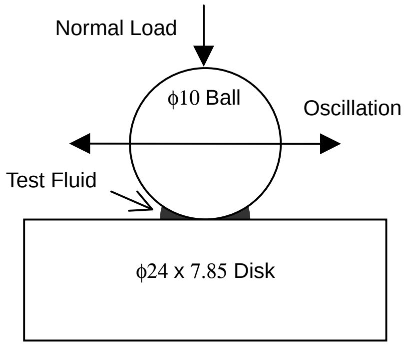

Fig.4 Translatory Oscillation Test

Figure 5 shows the diameters of the wear scars on the balls. The wear scar diameters of ST-77 with a water content of 15% or less were nearly the same, and were less than that of the neat mineral oil. The anti-wear performance of ST-77 with a water content of 15% or less is superior to that of a neat mineral oil.

6.2. Journal Bearing Test

Using a small journal bearing system with the same materials used in an actual sterntube system, the anti-scoring performance of ST-77 was tested. As the test specimens, a carbon steel shaft (diameter: 80 mm, surface roughness: 1.5 µm Ra, material: S45C) and a tin-based white metal bearing (length: 20 mm, radial clearance: 0.11 mm, surface roughness: 1.2 µm Ra, material: WJ2) were used. The bearing test specimens are shown in Fig. 6.

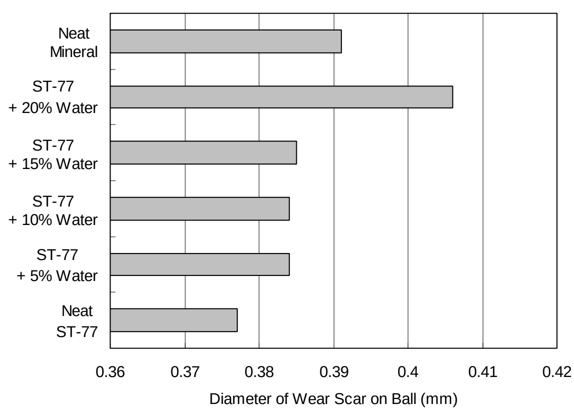

Fig.5 Wear Results in Translatory Oscillation Test

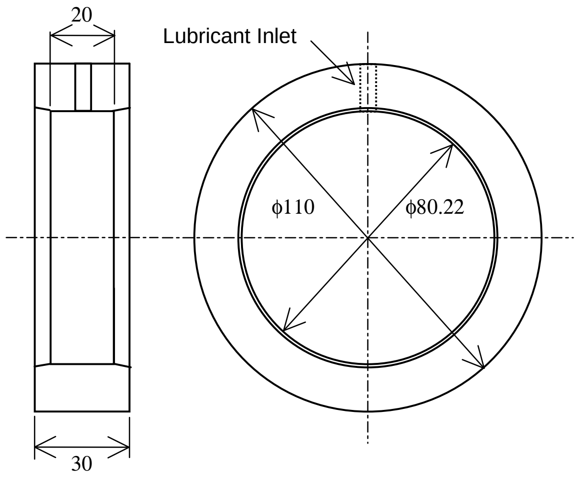

Fig.6 Bearing Specimens used in Journal Bearing Test

The lubricants were fully mixed in the tank during the test at a given temperature, and were supplied at a flow rate of 5 cc/s from the bearing top center. A shaft revolution of 360 rpm (peripheral velocity: 1.51 m/s), and a lubricant temperature of 50 °C were used. The shaft and bearing were soaked at 50 °C until the start of the test. Bearing pressure (=W/(DL), W: bearing load, D: shaft diameter, L: bearing length) was increased with a load step of 0.1 MPa and a time interval of 1 minute up to the bearing scoring. In total, five fluids were tested:

1) Neat ST-77
2) ST-77 + 10% water
3) Neat mineral oil
4) Mineral oil + 5% water
5) Mineral oil + 10% water

The absolute viscosity at 50 °C of these fluids is shown in Fig. 7. As described above, the viscosity of ST-77 decreases with increasing water content. In contrast, the viscosity of the mineral oil increases.

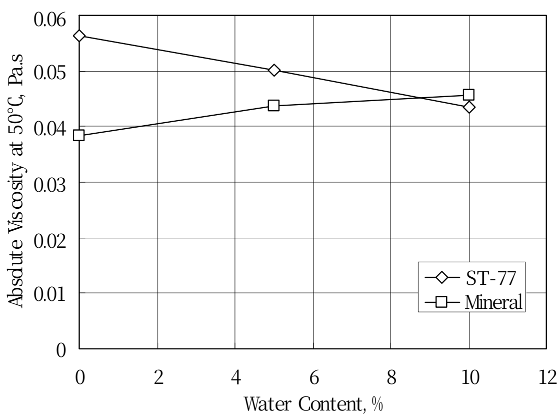

Fig.7 Viscosity of Fluids used in Journal Bearing Test

This is because the emulsified water in the mineral oil creates higher viscosity.

The Stribeck curves, friction coefficient vs. duty parameter, of ST-77 and the mineral oil are shown in Figs. 8 and 9, respectively. The duty parameter is defined as ηN/p (η: absolute viscosity in Pa·s, N: shaft revolution in 1/s, p: bearing pressure in Pa). Comparing the fluids with water contamination, ST-77 with 10% water formed a hydrodynamic film up to the scoring, and the mineral oil with 10% water formed no hydrodynamic film. In the mineral oil with 5% water, the friction coefficient dramatically increased when the duty parameter was $3x10^{-7}$ or less. The lubrication was switched from hydrodynamic lubrication to mixed lubrication at a duty parameter of $3x10^{-7}$. ST-77 with 10% water provided excellent lubrication, but the mineral oil with 5% water did not. It is recommended by a ship classification society that the alarm criterion of 2% water contamination be applied for conventional mineral oil in sterntubes [NK GSTL]. The value of 2% is considered valid from the viewpoint of

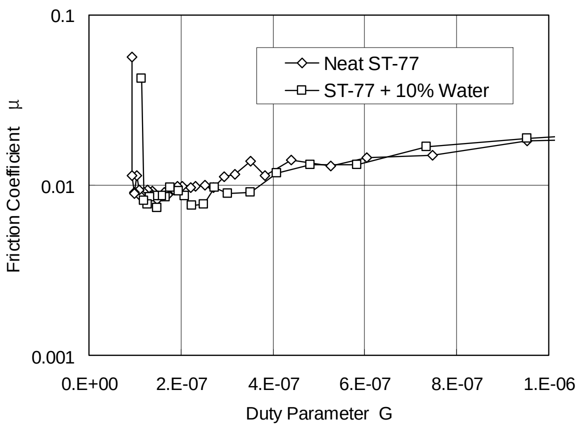

Fig.8 ST-77 Stribeck Curves

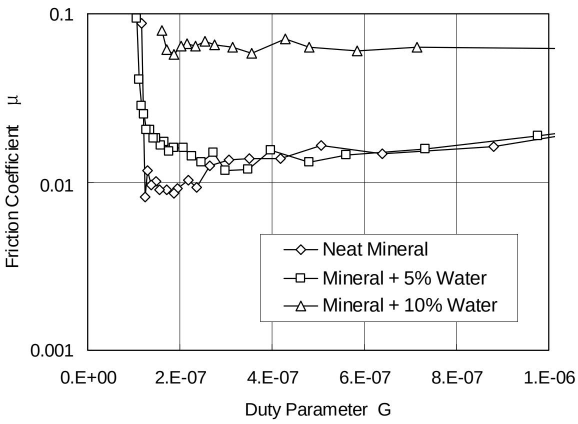

Fig.9 Mineral Oil Stribeck Curves

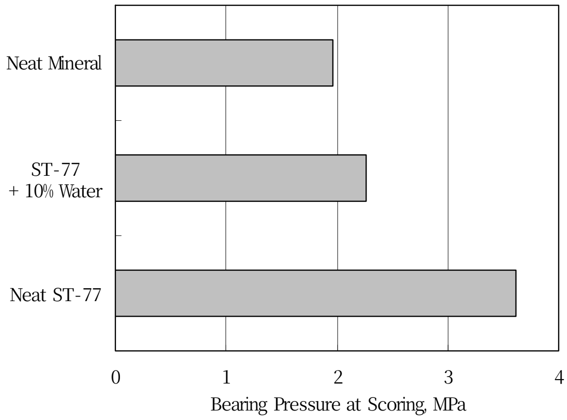

Fig.10 Bearing Pressures at Scoring

lubrication.

As shown in Fig. 7, the viscosity of the mineral oil with 10% water is greater than that of ST-77 with 10% water. However, the mineral oil with 10% water provided no hydrodynamic lubrication. It is noted that the lubrication performance of a poorly soluble lubricant with water contamination cannot be evaluated with its physical property of viscosity. For the evaluation, functional test such as journal bearing test is required.

The bearing pressures at scoring are shown in Fig. 10. In the figure, the results for the mineral oil with 5% and the mineral oil with 10% water, which had lubrication problems, are excluded. The bearing pressure at scoring of ST-77 with 10% water was less than that of neat ST-77, and was greater than that of neat mineral oil. Even when ST-77 contains 10% water, it provides a higher scoring load than VG68 neat mineral oil.

In order to compare the lubricants in anti-scoring performance, the effect of viscosity differences need to be excluded. The anti-scoring performance of fluids is

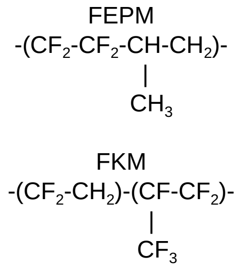

Fig. 12 Structure of FEPM and FKM

evaluated using a duty parameter at scoring. A smaller duty parameter at scoring means a higher anti-scoring performance. The duty parameters at scoring are shown in Fig. 11. The duty parameters at scoring of the three fluids were nearly the same. Even when ST-77 has 10% water, it provides the same anti-scoring performance as mineral oil with no water contamination.

7. SEAL COMPATIBILITY

A new seal material was developed for ST-77, because, as mentioned above, polyethylene glycol, which is the base fluid of ST-77, causes extensive swelling in commonly used seal material, fluoro-elastomer of vinylidene fluoride and hexafluoro-propylene (FKM), under high temperature conditions. The new seal material is a fluoro-elastomer of tetrafluoro-ethylene and propylene (FEPM). FEPM has excellent resistance to chemicals. The structure of FEPM and FKM is shown in Fig. 12.

The volume change results for the seal compatibility test are shown in Fig. 13. The seal material test specimens were immersed in the test lubricants. A test temperature of 150 ^{o}C, and a test period of 70 hours were applied. In the figure, the results for a standard sterntube mineral oil are also

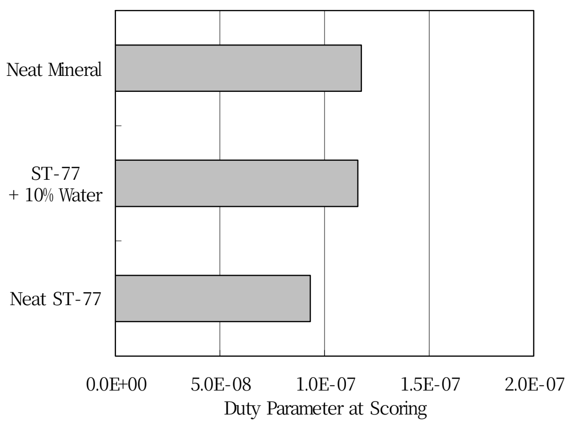

Fig.11 Duty Parameters at Scoring

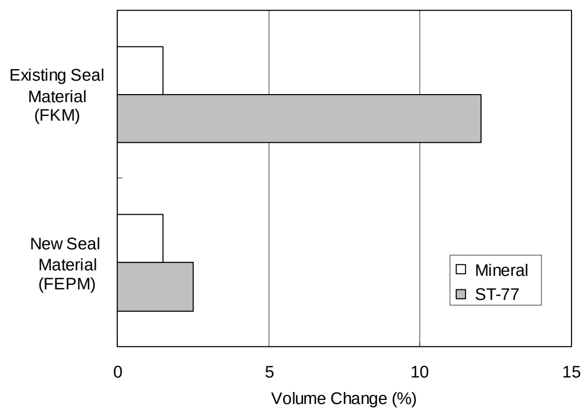

Fig.13 Volume Change Results in Seal Compatibility Test

Table 3 Comparison of ST-77 and Typical Hydraulic Fluid

Properties	Test Method	ST-77	Typical Hydraulic Fluid (Mineral Oil)
Viscosity @40°C	-	77 mm^2/s	68 mm^2/s
Viscosity @100°C	-	13 mm^2/s	8.5 mm^2/s
Viscosity Index	-	175	95
Density @15°C	-	1.12 kg/L	0.87 kg/L
Pour Point	ASTM D97	-10 °C	-30 °C
Flash Point	ASTM D92	225 °C	220 °C
Anti-Rust for Steel	ASTM D665 seawater: 5, 10, 15, 20%	No rust @15% seawater	No rust @5% seawater
Anti-Corrosion for Copper	ASTM D130	1a	1b
Oxidation Stability	ASTM D2893 121°C, 312 h, air: 10 L/h	Viscosity: -6% @100°C	Viscosity: +7% @100°C
Foam Suppression	ASTM D892	I: 40/0, II: 20/0, III: 60/0	I: 20/0, II: 10/0, III: 20/0
Air Release	ASTM D3427	6 minutes	4 minutes
Four-Ball Wear	ASTM D4172 40 kgf, 1200 rpm, 1 h, 75°C	0.50 mm	0.55 mm
Scuffing Load Capacity	DIN 51354 FZG A/8.3/90	Fail Stage: 9	Fail Stage: 8

shown. The results clearly show that ST-77 has a low swelling effect on the new seal material. The results also show that the new seal material is applicable for conventional sterntube oil.

8. FIELD EXPERIENCE

The first trial in sterntube application began in November 2005 on a fishing boat. By March 2006 this had extended to 4 vessels. No adverse indications were given in these vessels, and in September 2006 ST-77 was commercially launched as an environmentally compatible sterntube lubricant. Totally the lubricant has been applied to more than 30 vessels. This has included newly built large containers. Used lubricant analysis has shown the lubricant to be stable against oxidation under normal operating conditions with no indications of wear or corrosion. Used lubricant analysis and lubricant consumption check have shown that the new seal material works well in combination with the lubricant.

9. APPLICATION TO HYDRAULIC SYSTEMS

Vessels use hydraulic systems under water surface such as controllable pitch propeller and stabilizer. Oil leakage from the marine hydraulic systems is also a serious environmental issue. In the systems, mineral oil is applied as a hydraulic fluid.

A comparison of ST-77 and typical hydraulic fluid is given in Table 3. Except for pour point, the performances of ST-77 are superior or similar to those of typical hydraulic fluid. Pour point shows application limit at low temperature. Fluid temperature in marine hydraulic systems is usually greater than 0 °C, because the systems are used under water surface. The pour point of ST-77 is acceptable. In conclusion, ST-77 is applicable to marine hydraulic systems.

The first trial in marine hydraulic system application started in July 2008 on a controllable pitch propeller system of a vessel operating in an environmentally sensitive region.

10. CONCLUSIONS

An environmentally compatible lubricant for sterntube shafting and bearing systems, KEMEL ST-77, of which the base fluid is polyethylene glycol, was developed. The lubricant has excellent environmental properties (biodegradability, low toxicity and no sheen formation), and good water contamination lubrication and corrosion protection properties, which are essential for sterntube lubricants. From the viewpoints of lubrication and corrosion prevention, the new lubricant can tolerate a seawater content of 10%, while standard mineral oil cannot tolerate a seawater content of 5%.

Application to marine hydraulic systems is another promising area for this technology.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Sanyo Chemical Industries, Ltd. for its support.

REFERENCES

Batterby, N. S. "The Biodegradability and Microbial Toxicity Testing of Lubricants - Some Recommendations." Chemosphere, 41-7 (2000)

Batterby, N. S. "Biodegradable Lubricants: What Does 'Biodegradable' Really Mean?." Journal of Synthetic Lubrication, 22-1 (2005)

DIN 51834, Tribological Test in the Translatory Oscillation Apparatus

JIS K2510, Testing Method for Rust-Preventing Characteristics of Lubricating Oil

NK GSTL, Guidance for the Survey and Construction of Steel Ships, Part B, Chapter B8, Class NK

OECD 203, Test Guideline on Acute Fish Toxicity, Organization for Economic Co-operation and Development

OECD 301, Test Guideline on Ready Biodegradability, Organization for Economic Co-operation and Development

Shiomi, S., Suzuki, T., Kudo, Y., Ikeda, M., Yazawa, H. and Hirabayashi, H. "Sealing Status of Newly Developed Stern Tube Seals in Practical Application to Ships." 42nd Annual Meeting of the Society of Tribologists and Lubrication Engineers, Anaheim (1987)

UN GHS, Globally Harmonized System of Classification and Labeling of Chemicals, United Nations

Wholley, C. "Development of an Environmentally Adapted Sterntube Lubricant." 7th International Symposium on Marine Engineering, Tokyo (2005)

Yamajo, S. and Matsuoka, I. "Advanced Technology of Propeller Shaft Stern Tube Seal." 10th Propellers/Shafting Symposium of the Society of Naval Architects and Marine Engineers, Virginia Beach (2003)
