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Marine Slow-Speed Diesel Engine Diagnosis with View to Cylinder Oil Specification

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Abstract: The possibility of marine slow-speed diesel engine cylinder-piston group diagnosis with view to the specification of waste oil taken from the under-piston space has been discussed. The specifics of using high-base cylinder oils in marine slow-speed diesel engines to prevent sulfur corrosion of the cylinders have been described. Typical challenges, arising in the process of using oils for lubricating the cylinder-piston group and ways to overcome such challenges have been specified. Empirical data that allowed for determining the optimum cylinder oil consumption and ensuring minimum wear diesel engine cylinder bushings have been provided. The experiments that were carried out in sea ship conditions are proved by findings of an oil analysis at a third-party onshore research laboratory.

Keywords: Adaptive Cylinder Oil Control (ACC), Base Number (BN), Cylinder Oil, Cylinder-Piston Group, Feed Rate (FR), Marine Diesel Engine Fuel, Marine Slow-Speed Diesel Engine, Particle Quantity Index (PQI), Sulfur Wear

Introduction

Introducing the Problem

The problems of ensuring operation reliability and required lubricating conditions for engines, mechanisms and elements have always been urgent and important; therefore, research in the area of developing and applying of lubricants has been transformed into a large scientific direction (Kicha *et al*., 2011). Acquired positive outcomes in this area affect directly the technical and economic efficiency of use of all types of equipment, including marine equipment.

Marine internal combustion engines are the most popular type of heat engines and are used on sea and river ships (Konks and Lashko, 2005; Sizykh, 2002). Oils that are used on the ships are divided into engine oils and oils for auxiliary mechanisms and devices. Engine oils are further subdivided into cylinder oils that are used for lubricating crosshead slow-speed diesel engine cylinders; cylinder oils that are used for lubricating trunk piston medium-speed diesel engines; and circulating oils that are used for lubricating and cooling bearing assemblies.

Main and auxiliary ship power plants are rather small fuel and oil consumers within the overall volume of the global transport and power system. Nevertheless, it should be mentioned that engines that are used at the marine fleet are most doped with additives and known for their high quality reserve in terms of their original properties. Average content of additives in marine oils exceeds this indicator for oils used in other engineering and power industries by several times. This is principally due to the specifics of marine equipment operation, such as: High thermal and mechanical stresses in the contact area; unavoidable ingress of fuel, water and mechanical impurities into the lubricating material; operation under variable environmental conditions, etc. All this determines the exclusive high requirements for oil properties (Voznitskii, 2007).

Exploring Importance of the Problem

Various dilemmas arise in the process of operation of marine internal combustion engines, which include the use of high-viscosity fuels with high sulfur content in marine engines. Such fuels are less expensive; therefore their use in marine power industry started from boiler units and spread to internal combustion engines. The use of similar fuels is now observed in crosshead, as well as trunk piston diesel engine models.

Further oil processing is accompanied by quality worsening for all types of fuel, leading to reduced reliability and life time of marine diesel engines. The intensity of engine oil wear, diesel engine surface contamination with carbon deposits and their rapid wear are observed at the same time.

At the moment, international oil companies (Mobil oil, Shell, ESSO, Castrol, BP, Agip, Nippon Petroleum, Chevron Texaco, etc.) are engine oil development leaders. There is a tough competitive battle for oil product sales markets going on between them. Therefore, research centers of the companies never stop to seek ways of raising oil quality by improving their composition. A special attention is paid to the issues of engine oil saving when applying oils on ships and prospective regeneration of their operational properties. For this purpose, diesel engine building companies develop, together with lubricating material manufacturers, lubricating schedules that ensure maximum possible oil flow to the contact areas; also, special installations are designed to restore oil operational properties (Sagin and Matskevich, 2011; Matskevich, 2013).

Basic oil functions can be reduced to ensuring a reliable operation of friction nodes, reducing friction and consequential wear; preventing wear in any other forms; eliminating contaminating materials from the friction area; cooling by extracting heat from the friction surfaces; ensuring tightness in the seal ring area of pistons; and preventing corrosion.

Oils operate in marine diesel engines in far versatile conditions that are defined by the variability in the level of forcing the operation process of the diesel engines, their specific speed, design, fuel specification and operating conditions. Oil operating conditions in cylinders and friction nodes of crank mechanisms are essentially different. To endure sulfur corrosion, alkali compounds are always introduced into cylinder oils and alkali content is defined in mg of KOH per 1 g of oil and can make up to 100 mgKOH/g (Kamkin and Voznitskii, 1996).

Describing Relevant Scholarship

Issues associated with the necessity to develop new cylinder oils arose as early as at the beginning of sixties of the last century and were connected to installation of supercharged slow-speed diesel engines on sea ships and switching them to more feasible fuels of higher viscosity. Creation of special cylinder oils with original base number of 40...50 mgKOH/g by a number of oil companies was the answer to the toughened operating conditions for the oils and the necessity to give them corresponding properties. Such oils were capable of reducing adverse effects of power boost in low-speed diesel engines to a certain degree and using lower quality fuels in such engines, thus impacting the life time of the cylinder-piston group. Further trends in operation of marine slow-speed diesel engines were associated with a broad use of heavier fuels with high content of sulfur and other undesirable components, which coincided with an abrupt increase in oil and oil product prices as a result of the global power crisis of the seventieth. First generation base cylinder oils do not meet the increased requirements for their quality anymore and anti-wear, washing and neutralizing properties in particular. Leading foreign oil companies (Mobil oil, Shell, ESSO, Texaco, Castrol etc.) developed and launched cylinder oils with base number of 60…70 mgKOH/g, which excelled the first generation oil in terms of their operational properties, at that time.

Second generation high base cylinder oils (Mobilgard 570, Shell Alexia 50, Castrol S/02, etc.) were used successfully for a long time in forced marine low-speed diesel engines in the conditions of running on fuels with viscosity of 120…320 cSt at 50°C and with sulfur content up to 3…4%.

Marine diesel engines ran on fuels and oils of similar grades up till the very beginning of the current century, when they started to furnish the fleet with longs-stroke models of two-stroke diesel engines and high-power four-stroke diesel engines; moreover, they made environmental requirements for the overall marine power plants and internal combustion engines in particular more stringent (Vaskevich, 2009; Pakhomov, 2007).

At the moment, global ship engineering, marine diesel engine engineering and trends towards changing oil processing methods and quality of fuels supplied for the fleet have entered a new developmental area with significant improvement of cost effectiveness of power plants and ensuring the possibility of using super-heavy fuels produced with the help of oil by-products in such plants. Such development resulted in creating long-stroke and super long-stroke models of low-speed engines, which are characterized by their ratio of piston stroke to cylinder diameter up to 4.0…4.3 and up to 5.0 in the latest models. Uniflow cylinder scavenging was adopted for low-speed diesel engines of all prospective types as the one ensuring the best gas exchange in these conditions (Konks and Lashko, 2005; Pakhomov, 2007).

Long-stroke low-speed diesel engines differ from engines with conventional piston stroke-cylinder diameter ratio by a reduced revolution at nominal power, which provides for a higher indicative factor of engine efficiency and propulsive factor of overall installation efficiency. High cost effectiveness of such engines has been achieved due to increased maximum combustion pressure and improved indicator process. All these changes affect directly the formation of an oil film on the surface of lubricated parts of the cylinder-piston group. In fact, if we compare a long-stroke low-speed diesel engine and a typical one of equal cylinder displacement, in the first case it is necessary to lubricate the surface that is by 15…25% larger. The increase of maximum pressures (up to 130…140 bar) and temperatures in the upper part of the cylinder (up to 200…220°C) leads to enhanced requirements for the oil to prevent deposit formation and wear.

Stainge Hypotheses and Their Correspondence to Research Design

A lot of research was devoted to ensuring high-quality lubrication of the cylinder-piston group in marine diesel engines (MER, 2010; Bogach *et al*., 2005; Rozhdestvenskii *et al*., 2010). Typical problems associated with the use of cylinder oils in long-stroke slow-speed diesel engines and their possible solutions have been presented in Table 1.

According to the analysis of current developmental trends for slow-speed diesel engines, special requirements are imposed on the cylinder oil, which are far stricter than those for slow-speed diesel engines of previous models for the purpose of ensuring the necessary life time and reliability of modern engines. In particular, the requirements for ensuring oil fluidity and metal wettability now have a new meaning with view to the fact that less than 1 g of the oil is fed into the engine cylinder per crankshaft revolution; at the same time the lubricated surface area is up to 10 m^2 and piston stroke is up to 4.5 m. These properties must ensure equal oil spread across the cylinder bushing. Oil film persistence, until it is replaced on the bushing surface, was increased in long-stroke low-speed diesel engines, as compared to the typical ones. As a result, the oil must endure higher thermal load, while performing the necessary functions. Provision for the thickness and durability of the lubricating film in the conditions of low speed of the piston, i.e., energy-conserving ship propulsion, which is quite popular in navigation today, is one of the most important tasks (Patrakhaltsev *et al*., 2013).

High power values per cylinder capacity unit of modern slow-speed diesel engines produce much heat and a great share of such heat is absorbed by the oil film. In case of insufficient thermal and oxidative oil stability, preconditions occur for increased carbon deposit in the piston ring area leading to less life time between cylinder-piston group overhauls. Therefore, the oil must be of a certain degree of detergency (washing property) and high thermal oxidative stability. Thus, a recent quality leap in the marine diesel engine development affected directly the change of requirements for cylinder oils and presented a task of developing oils of a new generation that would satisfy such requirements.

The quality of fuels is of no less importance than the development progress for slow-speed diesel engines for evaluating operating conditions of the cylinder oil (Voznitskii, 2005). For the last 10…15 years the specifics of using fuels in ship power plants underwent significant changes, i.e., consumption rates for fuels produced using secondary processes, such as thermal and catalytic cracking, viscosity breaking, etc., decreased. Intensified oil processing resulted in weighting residual and distillate components.

Fuels that are traditionally divided into heavy and light (diesel) fuels are used for internal combustion engines of ship power plants. This classification is based on a specific gravity or fuel density to be more precise, which is in the range of 840…860 kg/m^3 for diesel fuels and makes 980 kg/m^3 for heavy fuels at 20°C.

Marine diesel engine fuels are complex compounds of flammable materials with their exact molecular structure still unknown and they contain mineral impurities and moist. Elementary chemical analysis of such fuels does not discover the chemical nature of their component compounds and, therefore, cannot give us a good picture of their properties, but allows calculating a thermal and material balance of fuel burning. The element chemical composition of fuel is expressed in the relation:

$$C^p + H^p + O^p + N^p + S^p + A^p + W^p = 100\,\%$$

and consists of flammable substances, such as: C, H, S, as well as O and N in complex high-molecular weight compounds. Moreover, fuel contains inflammable mineral additives that are transformed into ash A and moist W, if burned (Agabekov and Kosiakov, 2014).

Carbon is the main flammable component of fuel and carbon burning produces the greatest share of heat. Carbon content in fuel makes 85…88%. Hydrogen is a second important element of the combustible matter of fuel and hydrogen content in the combustible matter of liquid fuels amounts to 10...11%. Oxygen and nitrogen are organic ballast in the fuel, as long as presence of such substances reduces the content of flammable elements in fuel. Moreover, being in combination with hydrogen or carbon of fuel, oxygen transfers a certain share of flammable components into an oxidized condition and decreases fuel heat value. Nitrogen is not oxidized during fuel combustion in the atmospheric air, but converts into combustion products in a free form (Safieva, 2004).

Sulfur is a part of inorganic compounds in fuel. Sulfur content may be up to 3.5%. Sulfur compounds containing in fuel are divided into active and non-active components. Active sulfur compounds (free sulfur, hydrogen sulfide, mercaptans) cause corrosion in contact with metal. Non-active sulfur compounds (sulfides, disulfides, etc.) do not cause metal corrosion in normal conditions (Bolshakov, 1986).

All sulfur contained in various compounds (neutral and aggressive compounds) is burned in the process of combustion. Moreover, a great excess of combustion air in the marine diesel engine cylinder, which totals up to 2.4...2.7 for low-speed diesel engines, facilitates combustion.

Table 1. Use of oils for lubricating a cylinder-piston group of long-stroke low-speed diesel engines

Trouble	Solution approach	Solution means
Increased lubricating area	Improved oil spread; or better metal wettability	Basic oils and additives
Increased pressure on piston ring	Increased durability and thickness of oil film	Basic oils and additives
Long contact with flame and gases during combustion	High thermal stability	Basic oils and additives
Tendency towards corrosive wear	Higher acid neutralization speed	Additives
Tendency towards increased carbon deposits	High level of detergents (detergency)	Additives

Under the operating conditions in the diesel cylinder the effect of active and non-active sulfur compounds changes. Both categories of additives convert to active components. This is due to the fact that sulfur dioxide SO_2 and sulphuric anhydride SO_3 are generated in the process of combustion and react with the condensed water, thus forming H_2SO_3 and H_2SO_4 acids. These acids cause severe corrosion of parts of the diesel engine cylinder-piston group (Nadkarni, 2000).

The process of sulfur transformation into sulfuric and sulfurous acids is as follows:

$$\begin{gathered} S + O_2 = SO_2, \\ 2SO_2 + O_2 = 2SO_3, \\ SO_2 + H_2O \leftrightarrow H_2SO_3, \\ SO_3 + H_2O \leftrightarrow H_2SO_4. \end{gathered}$$

Enhanced wear of engine parts running on sulfur fuels is principally conditioned by electrochemical (wet) corrosion. Gaseous sulfuric acid anhydride in the cylinder combines with water vapors, which are always present in the cylinder and produces sulfuric acid vapors. Increasing temperatures facilitate dissociation of sulfuric acid vapors; therefore, the most favorable conditions for vapor formation are at the end of combustion product expansion and at release. The amount of sulfuric acid that is condensed on the cylinder bushing face increases with lowered temperatures of bushing walls and raised dew point of H_2SO_4 vapors. Thus, gaseous corrosion and liquid-phase corrosion may occur in the diesel, depending on temperatures of cylinder-piston group parts and dew point of sulfur fuel combustion products. The corrosive effect of sulfuric acid solutions forming on the cylinder walls are defined by their concentration and temperature. Sulfuric acid having strength more than 93% does not affect ferrous metals, while diluted acid causes their corrosion easily. Acid with strength ranging from 3 up to 20% is the most active with regard to cast iron.

Materials and Methods

Marine slow-speed diesel engines typically run on heavy-grade fuels in their steady state. The temperature of air charge in the diesel engine cylinder at fuel injection and its long ignition time allow for safe use of fuel with degraded structural and functional composition in diesel engines of all these types. In-service time of slows-speed diesel engines running on light fuel and light and heavy fuel mixture is defined by their operation in start-up conditions and depends on the ship application. Naturally, in case of operation in near-shore regions and frequent port calls when the main engine is switched to start-up and reverse operation, in-service time of a light-fuel diesel engine increases along with fuel consumption rates. In case of long sails, the main engine runs exclusively on heavy-grade fuels and the time of such operation may be up to tens of days, which reduces light fuel consumption significantly.

Identifying Subsections

Marine slow-speed diesel engines and fuel handling systems of modern ships are modified for use of super-heavy fuels having viscosity up to 750 cSt @ 50°C and density up to 1010 kg/m^3. Operating specifics of the cylinder oil on the surface of cylinder-piston group parts, in case high-viscosity and high-density fuels are used, are defined by a longer fuel combustion on the expansion line, high degree of the thermal effect on the oil film, ingress of a relatively large amount of ash onto the film surface due to incomplete combustion and ingress of unburned fuel drops into the film due to an increased spraying rate of the high-density fuel. Such mixing process of the particles located on the cylinder surface affects adversely oil lubricating properties and contributes to reducing thermal and thermal oxidative stability of oil.

The use of heavy and super-heavy fuels in crosshead diesel engines predetermines tougher requirements for a number of the cylinder oil properties (Shabanov *et al*., 2011).

First of all, this concerns ensuring the neutralization capacity of high thermal oxidative stability and anti-carbonization oil properties (Tsvetkov *et al*., 2010). Structural improvement of slow-speed diesel engines and more severe operating conditions of such engines determine the basic requirements for the new generation cylinder oils. Oil must fulfill the following functions:

- Possess a proper viscosity to ensure a sufficient lubricating capacity at high operating temperatures and fast spreading across the friction surfaces at the same time
- Create an effective seal of piston rings and cylinder bushing

- Minimize friction of motion and ensure high anti-friction properties
- Neutralize strong mineral acids that are produced as a result of sulfur-containing fuel combustion
- Prevent carbon deposition in the piston ring area, cylinder bushing gaps, gas distribution valves and ensure ring mobility in the process of long-term operation
- Burn in the cylinder, while leaving minimum carbon deposition, possible of softer consistency

Leading companies produce one or two grades of cylinder oils at the moment. These are usually oils of viscosity class SAE50, less often SAE60 with basicity of 70…100 mgKOH/g, which are highly alkaline third generation oils in terms of their quality and properties. These include oils manufactured by the following companies: Mobil oil (Mobilgard 570 class SAE50, basicity 70 mgKOH/g); ESSO (Exxmar X70 and X90, viscosity classes accordingly SAE50 and SAE60, basicity 70 and 90 mgKOH/g; Shell (Alexia50 и Alexia X, viscosity class of both grades SAE50, basicity 70 and 100 mgKOH/g accordingly); Castrol (S/D Z65 and Cyltech80, viscosity class of both grades SAE50; basicity 65 and 80 mgKOH/g accordingly), British Petroleum (Energol CLO50M viscosity class SAE50, basicity 70 mgKOH/g); Teboil (Ward Heavy SAE50, basicity 70 mgKOH/g), etc.

Subject Characteristics

The cylinder-piston group of diesel engines is subject to ongoing condition monitoring. Frequent visual inspections of cylinder bushing are not always possible in the modern operating conditions of marine diesel engines. This is primarily due to a long uninterrupted operation of main engines of sea ships (e.g., the duration of ocean sails may be 20...30 days) and high labor costs for such operations. Therefore, indirect techniques are used for cylinder group diagnosis. Determination of basicity and amount of metallic impurities in the oil sampled from the under-piston spaces of the diesel engines is the most popular and easy for the sea ship conditions. Ship laboratories, such as Cylinder Scrape-Down Oil Analysis, Unimarine Cylinder Scrape-Down Oil Analysis, Shell Analex Alert, Signum onboard test kit of ExxonMobil, Parker Kittiwake Cold Corrosion Test Kit, Digi TBN Test Kit and some other are used for this purpose.

Oil that is fed into the cylinder bushing gap is constantly undergoing oxidation by combustion products; therefore, sulfuric acid neutralization before the corrosion of cylinder bushings starts is a top priority task for internal combustion engine operation. Formation of a sulfuric acid environment in the diesel engine cylinder contributes to enhanced wear of the bushing, piston and piston rings and reduces life time and reliability of such parts (Sagin and Solodovnikov, 2015; Solodovnikov, 2015).

Modern diagnosis techniques analyze the corrosion degree of marine diesel engine cylinder bushings, based on determining the residual basicity (base number-BN) of the oil sampled from the under-piston spaces. At the same time, cylinder-piston group condition may be evaluated using the BN value. Corrosion conditions of cylinder bushings are divided into three main groups, such as:

- BN = 17…45-cylinder bushings are operated in the acceptable conditions and their wear does not exceed the acceptable value
- BN = 10…16-cylinder bushings are subjected to increased corrosion effect, which may contribute to wearing intensification
- BN < 10-sulfuric corrosion takes place in the diesel cylinder that contributes to excessive wear of the cylinder-piston group

If the diesel engine is operated in the first group conditions (BN = 17…45), the cylinder oil system is not subjected to any adjustment and specific cylinder oil consumption is considered optimum for these operating conditions.

Second group conditions (BN = 10…16) are indicative of insufficient oil that is spread onto the cylinder bushing surface and cylinder oil feed rate must be adjusted to restore the required BN value.

Diesel engine operation in the third group conditions (with BN < 10) is considered an emergency, it is indicative of an excessive wear of the cylinder group and it is not acceptable. In this case it is required not only to adjust cylinder oil feed rate, but also to set the intensity of cylinder bushing cooling and to switch the diesel engine to reduced load.

Sampling Procedures

Adaptive Cylinder Oil Control (ACC) factor and oil Feed Rate (FR) are the basic indicators of cylinder oil feed. ACC value is taken according to the empirical data depending on the values of Particle Quantity Index (PQI) and BN in the analysis of the oil sampled from the under-piston space. ACC = 0.2…0.35 for marine slow-speed diesel engines.

Recommended oil feed rate is calculated by formula, g/(kW·Hr):

$$FR = ACC \times S$$

where, S (sulfur) is sulfur content in fuel, %.

At the same time, it must be born in mind that recommended oil feed rate must not be less than 0.6

g/(kW·Hr). Automatic control systems (LUBECS in particular) are installed on modern sea ships that are equipped with slow-rate diesel engines, which maintain minimum cylinder oil feed rate at 0.6 g/(kW·Hr), regardless of diesel engine operating conditions.

12K98ME-C7 marine diesel engine by DOOSAN-MAN-B&W, installed on the APL Salalah ship, was used for cylinder group diagnosis, based on the analysis of the oil sampled from the under-piston space. The diesel engine has the following basic characteristics:

- Nominal power-54,120 kW
- Nominal speed-97 rpm
- Number of cylinders-12
- Cylinder diameter-980 mm

During the experimental research, the diesel engine run on RMK 700 fuel of the same grade having the following properties:

- Density at 15°C, kg/m^3-1010
- Viscosity, cSt, at 50°C-700
- Flash Point (min), °C-60
- Sulfur content, %-2.4…3.0

Diesel engine cylinders were lubricated with Mobilgard 570 having the following properties:

- Specific Gravity ft 15°C-0.937
- Flash Point, °C-256
- Viscosity, cSt, at 40°C-229
- Viscosity, cSt, at 100°C-21
- TBN, mgKOH/g-70

This study is aimed at determining the optimum cylinder oil consumption rate, including diesel engine cylinder-piston group diagnosis.

Results

Determining Optimum Cylinder Oil Consumption Rate

Studies to determine optimum cylinder oil feed rate were done exclusively in the steady state of the diesel engine. Constant load on the diesel engine was determined by invariant crank shaft speed of the crank shaft and cyclic fuel injection.

An individual cylinder oil injection value was established for each diesel engine cylinder. Variations for all cylinders did not exceed 5% of the average value. Samples of the used oil were collected from the under-piston space of each cylinder and BN and PQI values were further determined at the marine technical laboratory. The experiments were done for ten cycles with 24 h sampling frequency. Averaged experience findings are shown in Fig. 1.

Based on the correlations in Fig. 1, oil level that was set up for the eleventh cylinder ensures the largest BN value against minimum PQI. According to the test, optimum ACC factor value was determined and further recommended FR oil consumption rate was calculated (with view to sulfur content in fuel).

Determining Diesel Engine Operating Parameters

A number of other parameters were monitored during the experiment using 12K98ME-C7 marine slow-speed diesel engine by DOOSAN-MAN-B&W; a dynamic pattern for such parameters has been provided in Table 2. The Table indicates findings exemplified by the eleventh cylinder of the main engine, which was characterized by optimum BN and PQI values. Similar findings were obtained for all twelve diesel engine cylinders; however, the eleventh cylinder only was used as an example for the purpose of reducing the paper volume.

Based on the data presented in Table 2, special focus should be on ACC-factor, Feed Rate and Min Feed Rate.

According to the study, optimum cylinder oil feed rate for the diesel running on high-sulfur fuel is achieved by finding the optimum ACC factor value. This value is determined for each engine individually and depends on engine condition and cylinder lubricating system specifics. ACC value is constant and Feed Rate of the cylinder oil in case of switching to various types of fuel depends exclusively on sulfur content in the fuel.

Min Feed Rate means calculated minimum oil feed rate for lubricating the engine cylinder. It is limited by minimum acceptable feed rate established by the manufacturer. In case of diesel engine operation under ultralow loads (53...66 rpm in the experiment), a limited quantity of cylinder oil is fed into the diesel engine cylinder at each injection. Calculated FR value is 0.46...0.55 g/(kW·Hr) for these operating conditions, which leads to forced oil feeding at each 12th piston stroke for achieving 0.6 g/(kW·Hr). Ship crew can change Feed Rate upwards only in these operating conditions to increase oil feed rate.

Determining Cylinder Oil Specifications

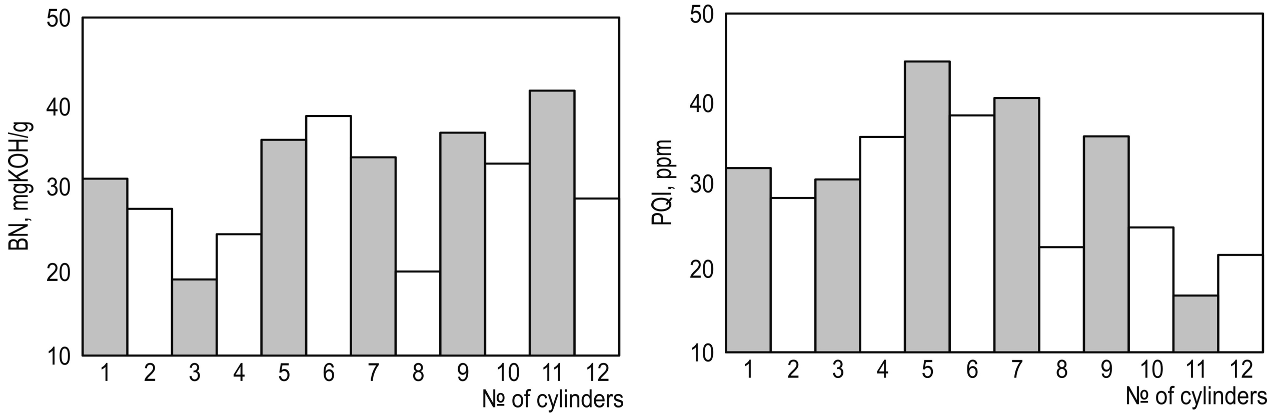
For further follow-up and due to regular inspections of the cylinder-piston group by the ship owner, used oil samples were presented for analysis at a third-party onshore research laboratory. For this purpose, run time of the engine and cylinder bushings was 9,124 and 11,364 h in operation and corresponded to the following dates: 30/09/14 and 17/02/15 (Table 2). Values that correlated with ship studies were obtained, which proved that the suggested technique was correct and adequate and that the cylinder oil feeding system was set up properly. These data are given in Table 3.

Table 2. Determining optimum cylinder oil feed rate for 12K98ME-C7 diesel engine by DOOSAN–MAN-B&W

Date (dd/mm /yy)	Operation time of main the engine	TBN of cylinder oil (ExMob570), mgKOH/g	Operation time of cylinder bushings	Sulfur content in the fuel, %	Diesel engine power, kW	Shaft speed, rpm	Cylinder oil consum ption rate, L/24 Hr	Specific cylinder oil consumption, g/(kW·Hr)	PQ-Index	BN of used oil, mg KOH/g	ACC factor	Feed rate (calculated value), g/(kW·Hr)	Feed rate (minimum possible value), g/(kW·Hr)
25/04/15	12035	70	12035	2.84	24090	78	344	0.56	10	32	0.27	0.767	0.767
20/04/15	11976	70	11976	2.84	23930	78	388	0.63	5	42	0.27	0.767	0.767
18/03/15	11960	70	11960	2.84	22196	78	336	0.59	5	45	0.28	0.795	0.795
10/03/15	11824	70	11824	2.84	27023	78	413	0.60	10	24	0.28	0.795	0.795
27/02/15	11593	70	11593	2.84	23305	78	435	0.73	15	23	0.28	0.795	0.795
17/02/15	11364	70	11364	2.84	24517	78	401	0.64	20	36	0.30	0.852	0.852
25/01/15	11056	70	11056	2.73	21413	73	683	1.24	45	29	0.30	0.819	0.819
15/01/15	10820	70	10820	2.73	18601	73	577	1.21	55	26	0.30	0.819	0.819
12/01/15	10767	70	10767	2.73	19154	73	599	1.22	55	30	0.33	0.901	0.901
07/01/15	10634	70	10634	2.73	12928	74	544	1.64	80	21	0.20	0.550	0.750
25/12/14	10446	70	10446	2.73	7402	53	126	0.66	80	25	0.20	0.550	0.700
20/11/14	10104	70	10104	2.41	10392	61	317	1.19	40	28	0.20	0.480	0.600
31/10/14	9763	70	9763	2.53	18153	73	480	1.03	80	10	0.20	0.510	0.600
30/09/14	9124	70	9124	2.29	22746	74	490	0.84	65	13	0.20	0.460	0.600
29/08/14	8450	70	8450	2.87	13846	66	260	0.73	50	35	0.20	0.570	0.600

Table 3. Data by the onshore laboratory for analysis of cylinder oil sampled from the under-piston space of the main engine

	Lubricant data			Wear Elements-ppm (mg/kg)	
	11,364 Hr	9,124 Hr		11,364 Hr	9,124 Hr
Contamination	Normal	Normal	Ag (Silver)	0	0
Equipment Rating	Normal		Al (Aluminum)	13	7
Oil Rating	Normal		Cr (Chromium)	1	4
Viscosity 40°C, cSt	67.4	34.5	Cu (Copper)	2	31
PQ Index	16	26	Fe (Iron)	32	357
TBN, mgKOH/gm	42	13.4	Mo (Molybdenum)	7	5
Contaminant Elements-ppm (mg/kg)			Ni (Nickel)	33	61
	11,364 Hr	9,124 Hr	Pb (Lead)	0	0
B (Boron)	0	0	Additive Elements-ppm (mg/kg)		
K (Potassium)	0	12		11,364 Hr	9,124 Hr
Na (Sodium)	11	14	Ba (Barium)	0	0
P (Phosphorus)	23	25	Ca (Calcium)	16,420	19,980
Si (Silicon)	42	10	Mg (Magnesium)	63	66
V (Vanadium)	66	201	Zn (Zinc)	103	14



(a) (b)

Fig. 1. Determining optimum cylinder oil feed rate acc. to BN (a) and PQI (b) values

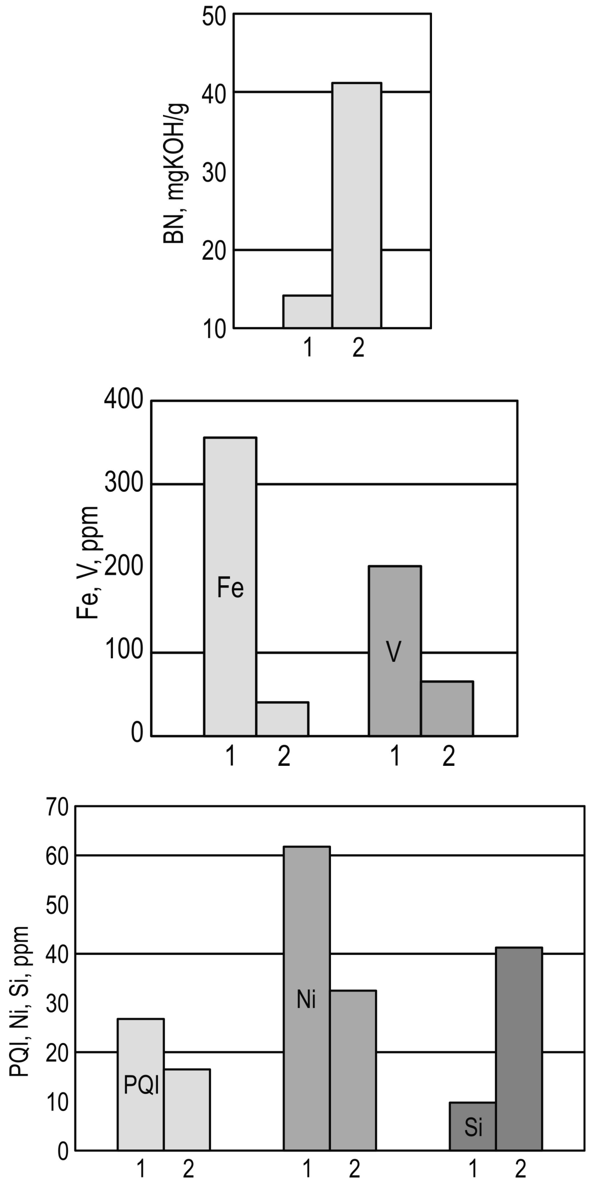


Fig. 2. Values, such as Base Number (BN), Fe (Iron), V (Vanadium), Particle Quantity Index (PQI), Ni (Nickel), Si (Silicon) in oil samples taken from the under-piston space of 12K98ME-C7 marine diesel engine by DOOSAN-MAN-B&W: 1- after 9,124 h in operation; 2- after 11,364 h in operation

According to the studies performed by the onshore laboratory, diagrams in Fig. 2 were also plotted to reflect the values of basic properties of the used oil.

Findings of the onshore laboratory revealed changes in control data, such as an increase in BN, decrease in PQI and Fe in under-piston oil tests, while proving the correct oil feed adjustment in the ship conditions. Changes in Ni, Si and V values are indicative of fuel degradation.

Discussion

The results of cylinder oil optimization studies allowed determining optimum ACC factor for a definite 12K98ME-C7 engine by DOOSAN-MAN-B&W, which is taken as 0.27. This enabled to operate safely the diesel engine cylinder-piston group when running on a fuel with up to 3% sulfur content and to determine optimum cylinder oil feed rate. These factors ensured efficient diesel engine operating conditions against minimum corrosion wear of cylinder bushings.

It should also be pointed out that correct diesel engine diagnosis, based on performance of the oil taken from the under-piston area, ensured safe diesel engine operation. BN and PQI changes define the nature of diesel engine cylinder-piston group operation (Fig. 3).

The following is shown in Fig. 3:

- I-dangerous zone (it is strongly advised to refrain from operating the diesel engine)
- II-zone of increased attention (immediate cylinder oil feeding adjustment required)
- III-safety zone
- 1-cat fines zone (catalytic cracking or “cat cracking”)-high risk area for cylinder bushing damaging due to abrasive deposits of aluminum and silicon particles with further mechanical damage to the bushings
- 2-liner polish zone ore bore polishing-an area characterized by ‘mirror’ polishing of the cylinder bushing surface, leading to critical bushing wear due to enhanced abrasive particle spread across the bushing face surface. Distortion of optimum alignment of piston rings and cylinder bushing face surface with oil film refers to carry-over of abrasive particles from micro-cracks in areas of higher wear factor and thinner oil film across the entire bushing surface

The cylinder group often operates in marine slow-speed diesel engines in the II zone with TBN 50…70 and metal level less than 300 mg kg^{-1}. This zone is dangerous not only in terms of possible transition into the zone of ‘mirror’ polishing of the cylinder bushing surface, but also possible damage to the oil film, as a result of deposits from the upper part of piston head onto the cylinder bushing surface. This possibility is a result of more alkaline environment in the cylinder bushing, contributing to step-like washout of acidic deposits. However, correct diagnosis of the cylinder-piston group and prompt adjustment of lubricating conditions or diesel engine load allows for safe engine operation in any operating conditions.

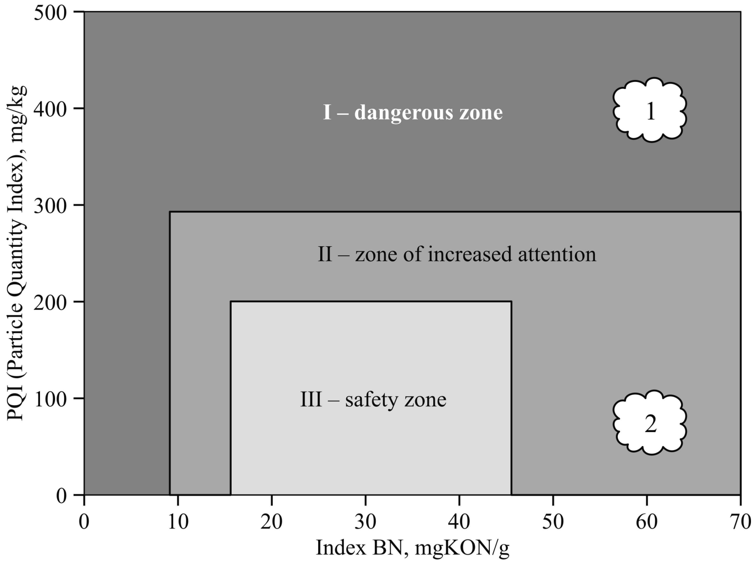


Fig. 3. Metal level dependence on BN residual base number and Operating zones of the cylinder-piston group of a marine diesel engine subject to BN and PQI values

Conclusion

One of the criteria enabling to diagnose the technical condition of the cylinder group of marine slow-speed diesel engines is parameters of oil taken from the under-piston spaces of diesel.

Taking into account the unequal conditions of the operation process progress in different cylinders of a diesel engine, the performance of this oil for each cylinder has own values.

The main indicator of the oil amount supplied to the diesel engine cylinder is an adaptive cylinder oil control factor (ACC-factor). Its magnitude has an optimal value for each diesel engine and is determined by the characteristics of the fuel used (in particular by sulfur content) and a load of the diesel. For marine slow-speed diesel engines recommended range of the ACC-factor is within ACC = 0.2 ... 0.35.

Qualitative indicators of the technical state of slow-speed diesel engine cylinder group include values of Particle Quantity Index (PQI)-the amount of metal particles and residual oil Base Number (BN), taken from the under-piston spaces.

Decrease in ACC-factor magnitude is provided by a proportional reduction of oil supply to the diesel engine cylinder. However, it is economically justified only in case of ensuring the maximum possible values of PQI and minimum permissible values of BN.

Safe operation of marine slow-speed diesel engines is ensured based on the synthesis of solving problems concerning determination of the optimal values of ACC, PQI and BN, as well as the maintenance of the effective power of the diesel engine.

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Author’s Contributions

Sergey Victorovich Sagin: Organized theoretical description of lubrication processes, experimental researches in the scientific laboratory, results analysis and finalization.

Oleksandr Vladymyrovich Semenov: Contributed to the experimental research at the marine diesel engine in sea-craft conditions, results analysis and finalization.

Ethics

The authors have no conflicts of interest in the development of the research and publication of this article.

References

Agabekov, V.E. and V.K. Kosiakov, 2014. Oil and gas: Technology and products. Rostov-on-Don, Feniks.

Bogach, V.M., A.A. Zandorozhnyi and I.D. Koliev, 2005. The specifics of oil flowage into MAN-B&W marine diesel engines. Odessa, 14: 116-125.

Bolshakov, G.F., 1986. Sulfur organic compounds of oil. Novosibirsk, Nauka.

Kamkin, S.V. and I.V. Voznitskii, 1996. Operating marine diesel engine power plants. Transport, Moscow.

Kicha, G.P., B.N. Perminov and A.V. Nadezhkin, 2011. Resource-efficient oil use in marine diesel engines. Maritime State University Press, Vladivostok.

Konks, G.A. and V.A. Lashko 2005. Global marine diesel engine engineering: design concepts, international experience analysis. Mashinostroienie, Moscow.

Matskevich, D.V., 2013. Regenerating anisotropic behavior of hydrocarbon fluids in operation. Eng. Prob., 1: 63-71.

Nadkarni, K., 2000. Determination of sulfur in petroleum products and lubricants: A critical review of test performance. American Laboratory.

MER, 2010. Optimizing lubricators for two-stroke diesels. MER.

Pakhomov, Y.A., 2007. Marine power instalaltion, including internal combustion engines. Trans Lit, Moscow.

Patrakhaltsev, N.N., I.S. Melnik and I.A. Petrunia 2013. Increasing efficiency of low loads of a marine diesel engine running on running on a variable pitch propeller. Engine Eng., 1: 38-42.

Rozhdestvenskii, Y.V., K.V. Gavrilov and I.V. Mukhorotov, 2010. The effect of viscosity and temperature properties of engine oils of hydromechanical properties of piston-cylinder tribocoupling. Engine Eng., 2: 23-26.

Safieva, R.Z., 2004. Oil and gas chemistry. Oil disperse systems: Composition and properties (part 1). Study guide. Gubkin Russian State University of Oil and Gas, Moscow.

Sagin, S.V. and D.V. Matskevich, 2011. The specifics of preparing an oil system of marine diesel engines running on a variable pitch propeller at the time of exiting drydock. Eng. Prob., 3: 50-56.

Sagin, S.V. and V.G. Solodovnikov, 2015. Cavitation treatment of high-viscosity marine fuels for medium-speed diesel engines. Modern Applied Sci., 9: 269-278. DOI: 10.5539/mas.v9n5p269

Shabanov, A.A., A.B. Zaitsev and I.S. Kudinov, 2011. The effect of certain physical and chemical parameters of engine oils on technical and economic and life-time resources of piston oil engines. Engine Eng., 1: 24-28.

Sizykh, V.A., 2002. Marine power plants. RKonsult, Moscow.

Solodovnikov, V.G., 2015. Ultrasound fuel treatment for reducing sulfur corrosion in marine medium-speed diesel engines. Marine Hardware Automation: Sci. Tech. Digest, 20: 84-91.

Tsvetkov, Y.N., D.A. Krylov and A.A. Tatulian, 2010. Correlation between friction losses for marginal and fluid-dynamic lubricating conditions in internal combustion engines. Engine Eng., 1: 13-20.

Vaskevich, F.A., 2009. Internal combustion engines: Theory, operation and maintenance. MGA, Novorossiisk.

Voznitskii, I.V., 2005. The practice of using marine fuels on ships. Morkniga, Saint-Petersburg.

Voznitskii, I.V., 2007. Practial recommendations on lubricating marine diesel engines. Morkniga, Saint-Petersburg.