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Experimental Investigation into the Effects of Fuel Dilution on the Change in Chemical Properties of Lubricating Oil Used in Fuel Injection Pump of Pielstick PA4 V185 Marine Diesel Engine

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Abstract: The engine oil contamination caused by various chemical elements and fuel is an important problem. As a consequence, the engine oil loses its tribological properties, engine lubrication worsens and may lead to potential problems such as excessive wear, corrosion, etc. For that reason, the study of oil degradation and contamination due to the replacement strategies is of special interest to the engine operators and engine manufacturers. In this paper, the chemical elements and fuel dilution of engine oil are analyzed under real engine operating conditions. This research is focused on the fundamental question: how is the chemical performance of lubricant components impacted by diesel dilution? Various tribological tests were performed on regularly collected samples from the fuel injection pump of a Pielstick PA4 V185 marine diesel engine. These tests assessed the influence of fuel on the lubricating oil chemistry performance and useful residual life. Tests included variations in lubricant density, viscosity, flash point temperature and chemical components for 10 samples taken in the following hours of engine operation. Results suggest that diesel dilution only slightly affects chemical additive performance. Most of the examined chemical elements remained at a negligible level (below 1 ppm) in the case of elements whose content was greater, and the changes were either negligible (Al, Fe, MG, Si) in the grits from 1 to 5 ppm or higher (Ca, P, Zn, C), ranging from tens to several hundred ppm. On the other hand, the kinematic viscosity changed significantly from 89.8 to 12.0 cSt at 40 °C or from 9.8 to 2.9 cSt at 100 °C. The change in flash point, although significant from 236 (for fresh oil) to a value below 100, does not exceed the limit values. To sum up, the study concluded that the reduction in oil change intervals for this engine is worth considering under the given operating conditions.

Keywords: engine lubrication; oil properties; oil fuel dilution; oil analysis; viscosity; lubricity

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1. Introduction

The specificity of the economic development of the world means that more and more industrial devices are produced in the world causing, among other things, rapid technological development in all areas. Such a phenomenon is also observed in heavy industry, the maritime industry, such as shipbuilding, and the mining industry, including the subsea oil and gas industry. However, high investment costs and variable profitability operation conditions incurred by ship-owners in the construction of ships as well as drilling and production oil rigs mean that facilities of this type are operated as long as possible. Despite this, the average service time of these devices has decreased in recent years due to economic and petrol crises (i.e., 2009, 2020, and 2022). Many ships of various types, due to the lack of charter, were temporarily withdrawn from service, and some of them never returned to operation. The situation was similar in the case of oil rigs. The economic crisis caused a drop in crude oil prices on the world markets, which drastically reduced the profitability of crude oil exploration, production and, consequently, decreased profitability of construction and operation of drilling and production oil rigs. This forced the shipowners, especially the smaller ones, to use the equipment they already had.

It seems crucial to seek opportunities to reduce operating and maintenance costs as well as operating areas that were previously not taken into account or seek even greater savings in the areas of regular operations.

One possibility for an oil rig owner is the assessment of operation and maintenance of diesel engines driving AC generators on one of the platforms. The operating costs of this equipment determine a significant part of the rig platform operating costs, so any, even small, savings in this area may be vital for the organization in the long term. In the case of diesel engines, methods of increasing their energy efficiency and reducing their operating costs are still being sought. The areas of marine engine operation where the opportunities of cost reduction are expected include, among others, the fuel system and lubrication system. The research presented in this paper is focused on these areas, that is, on the lubricating oil used to lubricate the diesel engine fuel injection pump.

The analysis of the auxiliary systems of piston engines demonstrated that the fuel injection system is characterized by the greatest energy losses. Indeed, these losses double those obtained in the lubrication and cooling systems. The energy losses of the fuel injection system, lubrication system, and cooling system are equal to 0.61%, 0.30%, and 0.31% of the total chemical energy of the injected fuel, respectively. As far as energy losses due to friction processes are concerned, it was observed that the main losses are located in the piston and reach the maximum value [1].

Lubricating oil is a complex substance of hydrocarbon molecules consisting of numerous atoms of carbon, hydrogen, oxygen and others. The atoms in each hydrocarbon molecule are firmly chemically bonded together, and the energy required to break a hydrocarbon molecule apart is much higher than the energy needed to change it from a liquid state to a gaseous state. The oil film offers resistance to flow due to its adhesion to the moistened surfaces. Oil that is running by gravity or is being pumped through a pipe shows resistance to flow due to its adhesion to the surface as well as its viscosity. Viscosity is an important indicator of the oil condition because it changes abruptly when there is a lubricant breakdown [2]. The lower the viscosity, the less energy it takes to shear the oil and to cool the oil, but conversely, the lower the viscosity, the thinner the oil film. It is important to have a good understanding of engine oil viscosity because viscosity is the most important characteristic of oil. Another important indicator of the condition of the lubricating oil is the content of contaminants that the oil washes away as it flows through the engine.

The two most common contaminants in engine oils are fuel and water. Unburned fuel is deposited on the cylinder wall, leaking through the interface with the piston ring and into the crankcase. It has been reported that the fuel content can be as high as 9% in turbocharged gasoline direct injection engines, which consequently resulted in a 30% reduction in the oil viscosity [3]. The fuel concentration at the interface between the piston ring and cylinder wall near the combustion chamber could be much higher than that of the oil sump, even amounting to 22% [4].

In car diesel engines, unfinished cycles of filter regeneration lead to the penetration of the excess of unburned fuel into the engine oil, which results in a significant deterioration of its physical, chemical and functional properties. In a marine diesel engine, fuel oil is diluted in lubricating oil mainly by improper work of the fuel injectors (leaks and improper atomization). The viscosity of the lubricating oil is systematically lowered as a result of diluting it with fuel and the leaching of elements included in the additives package. This contributes to the reduction in the base number, with the simultaneous increase in the acid number of the lubricating oil, which, in turn, influences the durability of engine oils and loss of the functional properties of lubricating systems. The first functional property is degradation—thermal and oxidative degradation resulting from a decrease in the efficiency of anti-oxidant, anti-abrasive and detergent additives owing to the destruction of polymer viscosity modifiers. Another one is contamination with combustion products due to the presence of solid particles such as dust, outer contaminants, abrasive metals, water and cooling liquid, as well as diluting the oil with unburned fuel. [5,6].

Diluting engine oil with fuel can cause really dangerous problems to the engine, including the occurrence of boundary lubrication, accelerated wear of cylinder liners, piston rings, bearings and crank pins, reduction in lubricating oil pressure, reduction in engine performance or, ultimately, the decrease in engine lifetime [7].

The dilution of lubricating oil with fuel is normal in the trunk piston engines, provided that the amount of fuel does not exceed several percentage points. However, it is not easy or unambiguous to determine this value due to different oils used in engines as well as different operating conditions (different loads). As to the impact of fuel dilution on the engine oil lubricity, there is a lack of consensus in the literature. Some researchers [8] reported that the fuel content reached 6% in certain marine engine operating conditions with a start-and-stop cycle protocol; however, the fuel-diluted engine oil showed a minimal effect on friction and an inconclusive impact on wear compared with fresh oil. In contrast, the load-carrying capacity was reported to be lowered by the fuel content with the hypothesis that the effectiveness of extreme pressure additives in the engine oil was reduced [9]. According to another study, when 6% gasoline was added to an SAE 5W-50 engine oil, friction and wear were increased by 3–16% and 2–10%, respectively, under various loading conditions [10]. Others [11] reported that the addition of 15% diesel fuel significantly reduced the engine oil viscosity but did not cause any noticeable wear on a 2700 cc, 5-cylinder engine. This study intended to separate the impacts of fuel on the base oil and on the anti-wear additive.

The aim of this article is to analyze changes in selected physical, chemical and functional properties of lubricating oil used in the crankcase of the fuel injection pump of diesel engines in marine applications, which drive the AC generator. In this pump, lubricating oil has no contact with combustion products, such as unburned fuel, exhaust gases, etc., but with absorbed fuel leaking inside the pump. The following physical and chemical properties have changed during the research: diluted fuel level in engine oil, viscosity (kinematic, dynamic HTHS—High Temperature High Shear and structural viscosity CCS), total base number and acid number, as well as the degree of oxidation, nitration and sulphonation, and water content. Such high changes in viscosity make the oil film less able to handle large loads that can occur at certain points, e.g., in the main bearings and those of the crankshaft [12].

In order to determine the optimum oil change interval reliably, it is necessary to monitor the actual physical and chemical condition of oil [13].

2. Materials and Methods

2.1. Choice of the Tested Oil Properties

General capabilities expected from engine lubricants are the following:

- Dispersivity or capacity to keep the cold parts of an engine clean;
- Detergency or capacity to keep hot parts of an engine clean;
- Thermal strength or capacity to withstand temperature changes;
- Anti-oxidation or capacity to resist the action of oxygen;
- Anti-wear or capacity to contain wear;
- Anti-scuffing or capacity to preserve oil film even in the presence of high pressures;
- Alkalinity reserve or capacity to neutralize acids formed during combustion or other sources, thereby preventing corrosive wear;
- Demulsibility or capacity to separate contaminant;
- Resistance to hydrolysis or capacity to withstand the action of water, which can affect the additive's pumpability;
- Centrifugibility and filterability or capacity to separate insoluble elements;
- Anti-rust, anti-corrosive property and anti-foaming are some of the other properties that protect the metallic object from wear.

As the tested oil does not participate in the lubrication of the cylinder liner, it does not come into contact with the products of fuel combustion, and thus, not all of the listed properties are important. Therefore, the following properties were selected for the analysis of this oil:

- Viscosity—viscosity is the most important property of the lubricating oil, minimizing frictional losses and measured as a fluid resistance to flow. Viscosity of oil may drop due to fuel dilution when running on diesel and may rise when running on heavy diesel fuel. Likewise, the aging of the oil due to oxidation and thermal degradation increases the viscosity. Too low a viscosity of the lubricant results in the fact that the oil film cannot be maintained between the moving surfaces, which leads to excessive wear. Too high a viscosity of the liquid causes excessive resistance to the flow.
- Metal particle content—metals, non-metals and chemicals alike can be present in a huge variety, and they can belong to one of three major oil element categories—wear metals, contaminants and additives. Table 1 presents the limits for the metallic content normally accepted in the industry for diesel engines, independent of the brand and without considering kilometers or hours of operation [14,15].

Table 1. Limits of chemical components normally accepted in industry for diesel engines [14].

Metal Component	Normal (ppm)	Abnormal (ppm)	Critical (ppm)
Aluminium Al	<20	20–30	>30
Chrome Cr	<10	10–25	>25
Copper Cu	<30	30–75	>75
Nickel Ni	<10	10–20	>20
Iron Fe	<100	100–200	>200
Sodium Na	<50	50–200	>200
Lead Pb	<30	30–75	>75
Tin Sn	<20	20–30	>30
Silicon Si	<20	20–50	>50

- Water content—water presence in oil systems deteriorates the rheological properties of the working fluid used, reducing its lubricating and insulating abilities. Water in oil reduces the possibility of bearing load transfer, accelerates the oil oxidation processes, rinses out improvers and increases the amount of sediment formed and causes corrosion. Limits are laid down by the regulations of many manufacturers; the limit of 0.2% should cause an investigation into the source, while remedial action is needed at 0.5%. The presence of Na and Mg in oil indicates contamination with salt water.
- Flash point—the "lowest liquid temperature at which, under certain standardized conditions, a liquid gives off vapors in a quantity such as to be capable of forming an ignitable vapors/air mixture". Commercial products must adhere to specific flash points that have been set by regulating authorities, especially for safety reasons.

2.2. Research Object

The experimental materials included Marionol RG1240 oil, which is TPEO (Trunk Piston Engine Oil) and meets the requirements of API (American Petroleum Institute). It is intended for lubrication of marine piston engines working on light fuel (MGO—Marine Gas Oil). Marinol RG1240 oils contain a properly selected set of additives with such properties as washing and dispersing, anti-oxidant, anti-corrosive, anti-rust and anti-wear. The basic technical specifications of this oil are presented in Table 2.

Table 2. Oil Marinol RG1240 technical specification [16].

Properties	Test Methods	Unit	RG1240
Kinematic viscosity at 100 °C	ASTM D 445	mm^2/s	14.3
Pour point	ASTM D 5950	°C	−21
Ignition temperature	PN-EN ISO 2592	min	255
TBN base number	PN-ISO 3771	mg KOH/g	12
Viscosity index	ASTM D 2270	(-)	98
Corroding action Cu, 100 °C/24 h	PN-EN ISO 2160	degree	1

The level of changes in the properties of oil used as an engine lubricant and to lubricate the fuel injection pump was assessed on the basis of the Pielstick PA4 V185 marine engine. This engine was produced in the late 1970s in the French Societé d'Etudes de Machines Thermiques (SEMT) and manufactured on the German license (the company is now part of the MTU-MAN group). This is a 16-cylinder V-type engine with two charge air coolers powered by two turbochargers. The engine drives a 1.2 MW AC generator (Figure 1).

The fuel amount was controlled on the fuel injection pump by an electronic Woodward governor with a hydraulic actuator. The engine was powered by light fuel (MGO) through one injection pump located centrally on the engine block between the cylinder heads and turbochargers. The fuel pump was a Bosch type with 16 pistons, also in the V type arrangement (Figure 2), and derived by a toothed gear from the crankshaft. The capacity of the fuel injection pump crankcase was 1.8 L of lubricating oil. According to the manufactures, manual lubricating oil in the fuel injection pump has to be replaced every 100 working hours [17].

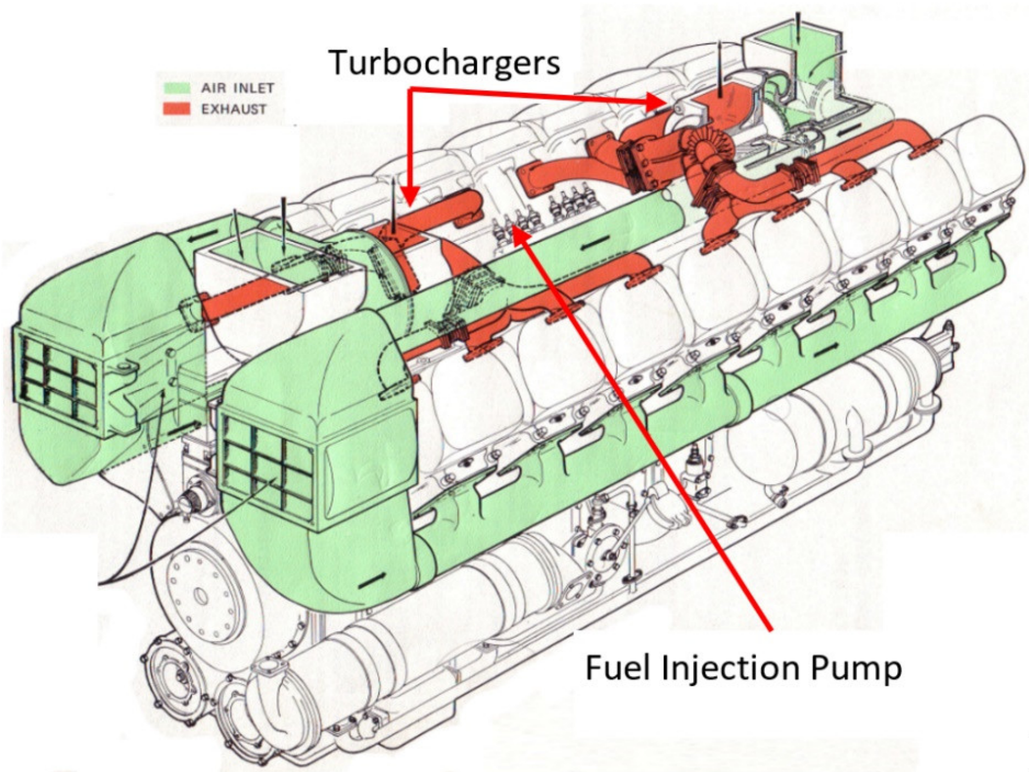


Figure 1. General view of the Pielstick PA4 V185 engine [18].

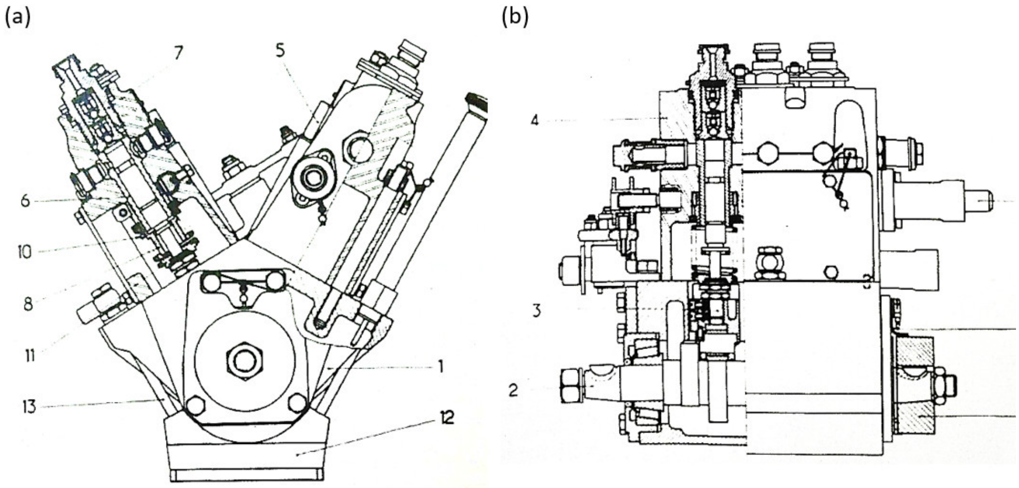


Figure 2. Fuel injection pump of the Pielstick PA4 V18 engine: (**a**) cross-section, (**b**) longitudinal section [17].

2.3. Oil Samples

Oil samples were placed into 100 mL plastic containers from the pump crankcase with a syringe (20 mL) through the dipstick socket (element 5 in Figure 3).

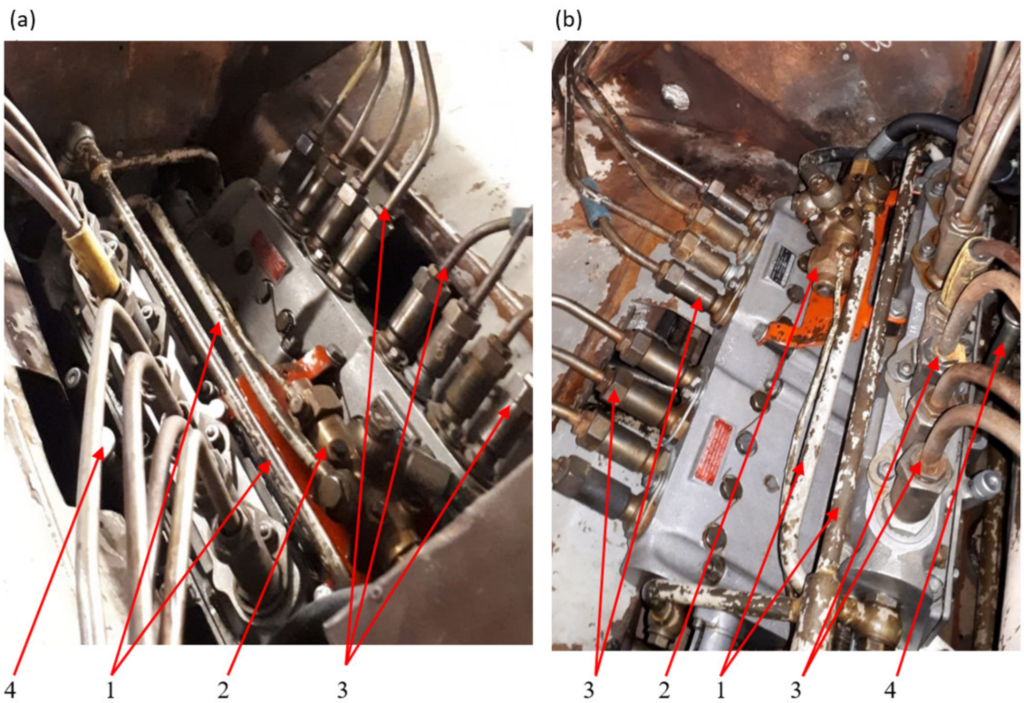


Figure 3. Fuel injection pump of the Pielstick PA4 V18 engine: (**a**,**b**) photo of real pump: 1—fuel overflow pipe, 2—engine emergency stop safety valve, 3—high pressure pipe supplying fuel to 16 injectors, 4—deep stick.

The sampling was performed every several hours while the engine was operating under load, according to Table 3. The engine working hours counter indicated 66,001 h and 67 h after general repair when sampling began. Due to the relatively small capacity of the crankcase, samples were taken at specified intervals, always after engine start-up and complete oil change.

Table 3. Oil samples interval schedule in hours (0—fresh oil).

Samples No.	1	2	3	4	5	6	7	8	9	10	11
Engine working time after start-up and oil change (h)	0	1	2	4	6	8	10	12	18	24	36
Engine working hours counter after last general repair (h)	-	67	s93	187	203	229	255	281	313	345	371

2.4. Laboratory Equipment Used for Oil Test

2.4.1. Density—Density/Specific Gravity Meter DA-640

The DA 640 oscillating density meter was used to measure the lubricating oil density. This device allows for the smooth control of changes in the frequency of resonance vibrations and enables the measurement of the density of the tested liquid in the temperature range from 0 to 93 °C. The device meets the ISO 12185, 15212 standards, as well as the ASTM D1250, D1465 and D5002 standards [19]. It is one of the most accurate measuring devices of this type, as the obtained result reaches an accuracy of $+/-$ 10 g/cm^3.

2.4.2. Chemical Composition—Spectroil Q100

The SpectrOil Q100 Rotating Disc Electrode Optical Emission Spectrometer (RDE-OES) technology is a robust, proven spectroscopic technique designed to simultaneously analyze wear, additives and contaminants in mineral or synthetic petroleum-based products, compliant with ASTM D6595 and D6728. It is widely used in commercial oil laboratories as a proven means of precisely determining elemental composition in lubricating oil, coolant, light or heavy fuels, grease, and process water. The quality and stability of the Q100's solid state optics provide reliable trending and have other features such as no sample dilution, usage of only 2 mL of tested fluid, simultaneous measurement of up to 31 elements in 30 s test time, etc. [20].

2.4.3. Viscosity—MARS Rheometer

HAAKE MARS Rheometer is a highly flexible Modular Advanced Rheometer System (MARS) that provides accuracy, easy handling, and many application-oriented solutions for comprehensive material characterization. It is equipped with application-specific accessories for different fields such as polymers, petrochemical, pharmaceuticals, cosmetics, paints, inks, coatings, food, construction and building materials. For this research, the important feature is the temperature module (with high-performance Peltier temperature control units for precise temperature control from -150 to 600 °C) as well as application-focused measuring cells measuring geometries, etc. [21].

2.4.4. Flash Point—ERAFLASH

ERAFLASH is the Continuously Closed Cup flash point testing methods device, measuring according to ASTM D6450 and ASTM D7094 standards as well as the IP620 European standard equivalent [22]. The sample volume is only 2 mL. During measurements, an electric arc ignites the sample vapor, and the analyzer determines the flash point by the pressure change inside the closed cup.

3. Results and Discussion

3.1. Density and Fuel Content in Oil

Due to the oil sampling taken during normal engine operation, it was impossible to precisely measure the volume of lubricating fluid (oil-fuel mixture) in the pump crankcase. For the same reason, in order to maintain analogous conditions of oil dilution by fuel in time, each of the samples was taken consistently after oil change in the crankcase and after working for a certain period of time (specified in Table 3). For greater readability of the results, an estimation of the amount of fuel that leaked into the pump crankcase during engine operation was made. This was achieved by comparing the fresh oil mass quantity (determined from the change in density) with the used oil mass quantity (determined in the same way). The results of measures of oil density are presented in Table 4.

Table 4. Oil density for samples at different operation times (Fresh oil = 0 h).

Oil Working Period	at 15 °C	at 40 °C	at 60 °C	Fuel Oil Quantity		
	(g/cm³)	(g/cm³)	(g/cm³)	(kg)	(l)	(%)
Fresh oil	0.8886	0.8736	0.8616	0	0	0
after 1 h	0.8749	0.8658	0.8538	0.5708	0.6525	27
after 2 h	0.8744	0.8647	0.8523	0.5986	0.6846	28
after 4 h	0.8723	0.8643	0.852	0.7227	0.8285	32
after 6 h	0.8708	0.8639	0.8517	0.8194	0.9410	34
after 8 h	0.8689	0.8627	0.8504	0.9532	1.0970	38
after 10 h	0.8645	0.8611	0.8489	1.3226	1.5299	46
after 18 h	0.8625	0.8611	0.8489	1.5253	1.7685	50
after 24 h	0.8614	0.8528	0.8405	1.6485	1.9137	52
after 32 h	0.8577	0.8427	0.8307	2.1392	2.4941	58

The mass of used oil is the sum of masses of fresh oil and fuel (Equation (1)), where the density of the fuel was assumed to be 0.8317 g/cm^3 (according to BDN—Bunker Delivery Note of 21 December 2021), the density of fresh oil was assumed to be 0.8886 g/cm^3 measured in the laboratory, and the density of the used oil was measured in the laboratory as well. After the transformation, the following Equation (2) was obtained:

$$LO \times \rho_{LO} + FO \times \rho_{FO} = UO \times \rho_{UO} \quad \text{(kg)} \tag{1}$$

$$FO = 1.8\frac{\rho_{LO} - \rho_{UO}}{\rho_{UO} - \rho_{FO}} \quad \text{(liters)} \tag{2}$$

where:

LO—Lubrication Oil (Fresh Oil) = 1.8 in liters,
FO—Fuel Oil in litres,
UO—Used Oil in litres,
ρ_{LO}—Lubrication Oil density = 0.8886 g/cm^3,
ρ_{FO}—Fuel Oil density = 0.8317 g/cm^3,
ρ_{UO}—Used Oil density.

Based on the value of the fuel density given as the standard at 15 °C, the calculations were made for this temperature. The results of calculations of the amount of fuel that leaked into the lubricating oil are also presented in Table 4.

As can be seen from the calculating results of the fuel content in the oil with the time of oil operation, these values increase (Figure 4).

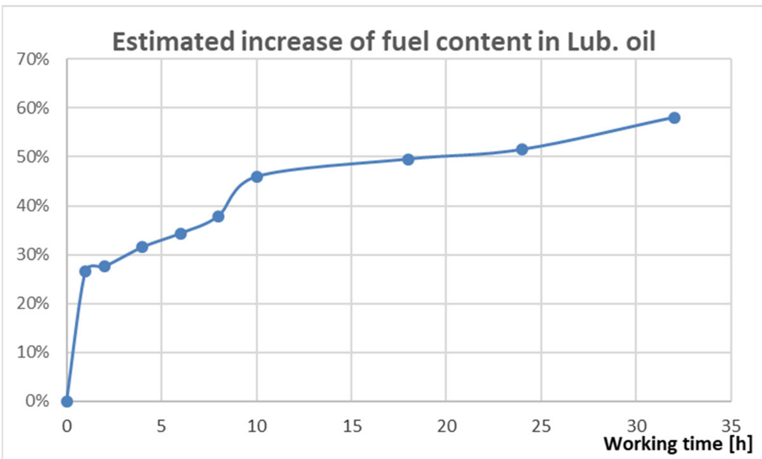


Figure 4. Calculation results of fuel oil quantity in lubrication fluid in the fuel injection pump.

3.2. Spectroscopy

Spectroscopy is a useful method for assessing the condition of engine oils. The results of the tested samples are presented in Tables 5 and 6. The tables show the mean values measured three times for a given number of oil samples. However, only the components whose content in fresh and used oil exceeded 2 ppm or the change in relation to that in clean oil that reached more than 5% are presented in the table. The other components of the content or the change that did not exceed the adopted values are as follows: Ag, B, Ba, Cd, Cu, Cr, K, Mn, Mo, Ni, Pb, Sn, Ti, V, H.

Table 5. Oil components measured by spectroscope in fresh and used oil (samples of 2–10 working hours).

Chemical Element	Critical Level	Fresh Oil	Oil Samples Elemental Composition after Specified Working Time (h)—Mean Values of 3 Samples							
	—	0	1	2	3	4	6	8	9	10
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Al	>30	3.40	2.68	2.83	2.42	2.75	2.30	2.46	2.54	2.35
Ca		6278	6181	6131	4995	5037	4904	5089	4867	4649
Fe	>200	7.69	4.82	2.37	1.86	2.77	1.84	1.73	2.83	1.37
Mg		24.57	16.64	17.07	17	16	16	15	16	14
Na	>200	63.71	67.00	72.00	83	76	69	71	82	81
P		1230	819	836	759	776	651	598	599	631
Si	>50	5.89	10.62	9.69	10	9	10	8	10	7
Zn		1420	448	480	545	471	541	406	507	354
C		200	206	207	226	186	237	194	208	184
Ag, B, Ba, Cd, Cu, Cr, K, Mn, Mo, Ni, Pb, Sn, Ti, V, H	Less than 1 ppm									

Table 6. Oil components measured by spectroscope in fresh and used oil (samples of 12–36 working hours).

Chemical Element	Oil Samples Elemental Composition after Specified Working Time (h)—Mean Values of 3 Samples					Maximum and Minimum Value		Specific Max and Min (Deviation)	
	12	15	18	24	36	max	min	max/Fresh	min/Fresh
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(-)	(-)
Al	2.72	2.39	2.54	2.99	3.00	3.00	2.30	−12%	−32%
Ca	5135	4920	4874	4401	3862	6181	3862	−2%	−38%
Fe	3.11	3.33	3.12	1.20	1.03	4.82	1.03	−37%	−87%
Mg	17	17	16	14	12	17	12	−31%	−53%
Na	86	80	82	82	5	86	65	35%	2%
P	717	707	680	499	435	836	435	−32%	−65%
Si	9.78	10.59	10.23	8.17	9.27	11	10	80%	13%
Zn	500	502	490	467	424	545	354	−62%	−75%
C	201	220	214	228	225	237	184	18%	−8%
Ag, B, Ba, Cd, Cu, Cr, K, Mn, Mo, Ni, Pb, Sn, Ti, V, H	Less than 1 ppm					——-		Less than 5%	

Two similar courses of changes in the quantity of specific chemical elements can be seen in Figure 5a–e. One of them presents some elements that do not change quantitatively with the working time, especially those whose content in pure oil is low or very low (e.g., Mg, Mo, Pb, Al, Mn). The second one, showing their decrease in the content in subsequent samples, can be observed with increasing working time (e.g., Na, P, Zn, Ca). These elements are components of engine oil alkaline additives, and the visible decrease in the quantity of those elements is most likely the result of oil dilution with fuel, not oil degradation from working conditions (this oil does not participate in the neutralization of acid fuel combustion products).

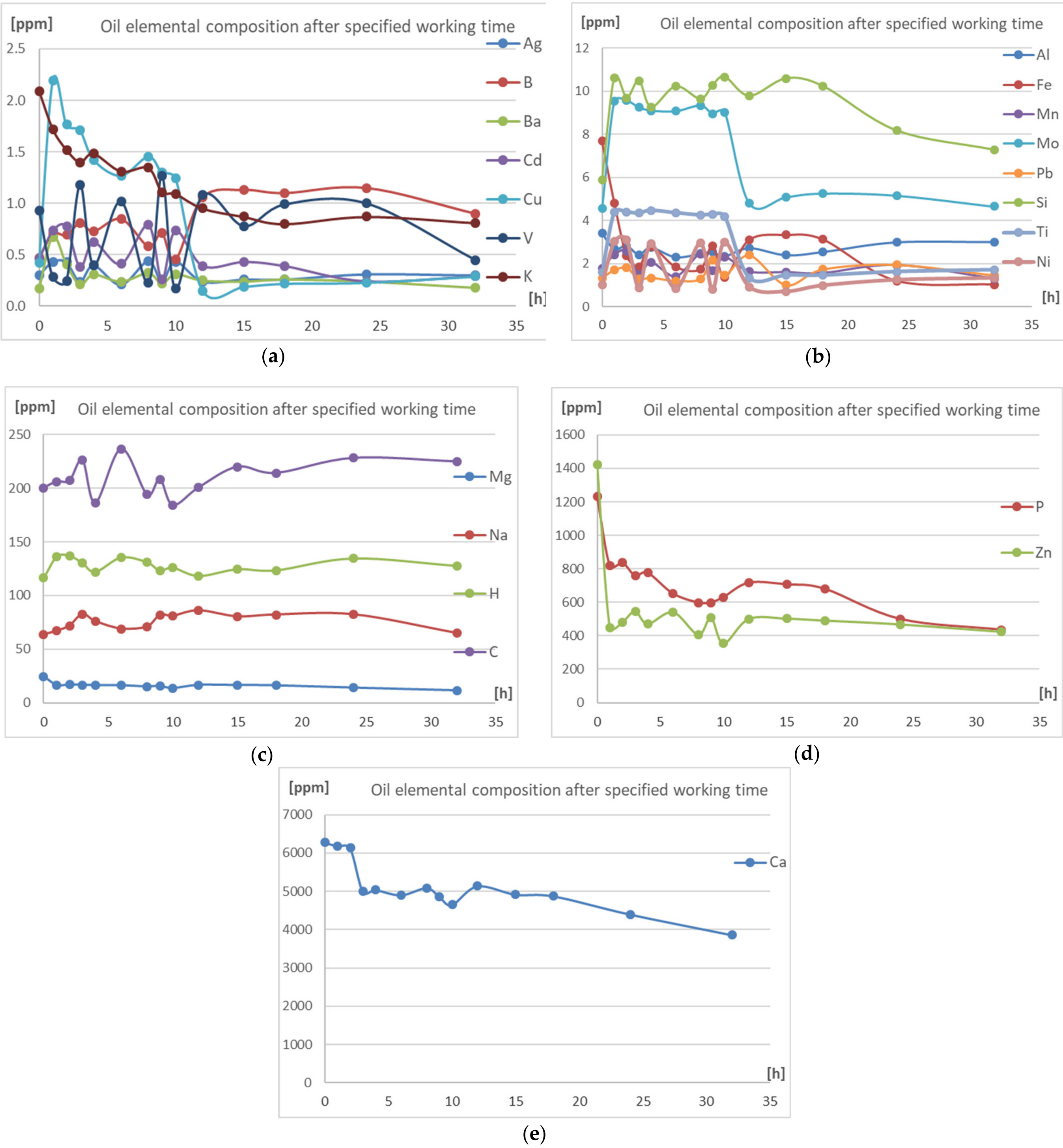


Figure 5. The course of changes in chemical element content in the injection pump lubricating oil during operation time, because the content of individual elements is different, they have been presented in several graphs grouping elements with similar content: (**a**) presents Ag, B, Ba, Cd, Cu, V, K; (**b**) presents Al, Fe, Mn, Mo, Pb, Si, Ti, Ni; (**c**) presents Mg, Na, H, C; (**d**) presents P, Zn; (**e**) presents Ca.

The presented graphs show several different types of changes in the course of their content in the used oil.

Only two chemical elements (Silicon and Bismuth) show an incomprehensible change in the content with the working time. Figure 5 shows that there are the only elements that increase their concentration in the tested oil (the maximum measured change in relation to fresh oil is almost double). However, with the operating time of the oil, the content of this element drops to a value close to that in the fresh oil. Moreover, despite such a large change in the silicon content, the measured values were far from the maximum values of the oil for use (Table 1).

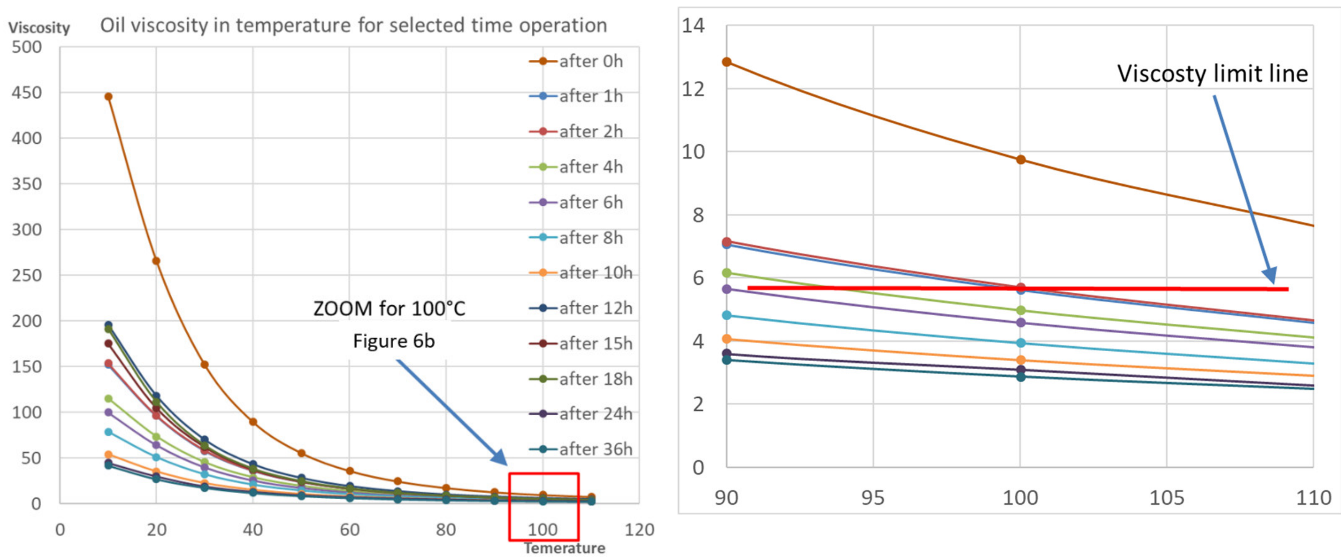
For a few elements (copper, molybdenum, titan), a visible increase can be observed in the initial stage of oil operation; however, after several hours, the content of these elements drops to a value close to that of fresh oil. It is difficult to clearly define what is responsible for such a course of changes in these elements.

In the case of three other elements (phosphorus, zinc and calcium), a downward trend can be observed in the samples taken along with the engine and oil operation time. In this case, the decrease in content can be interpreted as a dilution of the oil additives contained in the fresh oil.

However, all these changes are relatively small and, apart from the elements in which a decrease is observed (P, Zn, Ca), it is difficult to determine the cause of the change in their content in the tested oil.

3.3. Viscosity

Viscosity tests were performed five times for each oil sample, and the mean value of these measurements was taken in further analysis. The trends of kinematic viscosity change in oil working time can be observed in Figure 6. The reduction in the kinematic viscosity of the tested oil is already significant after the first hour of operation. This fact confirmed a significant fuel leak and oil dilution. The oil saturation speed with fuel and thus the speed of viscosity change decrease slower with the oil working time. The difference in viscosity between the samples of the 24 and 36 h of working time (Table 7) is relatively small. However, the viscosity values determined for the samples of 8 h and more of working time are below the limit values determined, i.e., by SAE (Society of Automotive Engineers) [23]. These values, determined in accordance with the ASTM TEST D445 standard, assume the permissible lowest kinematic viscosity value ranges from 3.8 to 21.9 cSt at 100 °C (Figure 6b)—where the highest value 21.9 applies to oils with the highest kinematic viscosity [24].



(**a**) (**b**)

Figure 6. Oil viscosity change in relation to time operation of the fuel injection pump: (**a**) in a wide range of temperatures, (**b**) at 100 °C with limits according to the ASTM TEST D445 standard.

Table 7. Kinematic viscosity measured for samples of oil in different operation times for temperatures of 40 and 100 °C.

Engine Oil Working Time (h)	0	1	2	4	6	8	10	12	18	24	36
Oil kinematc viscosity (cSt at 40 °C)	89.8	38.8	36.3	28.9	25.7	20.9	15.4	14.5	13.8	13.0	12.0
Oil kinematc viscosity (cSt at 100 °C)	9.8	5.6	5.7	5.0	4.6	3.9	3.4	3.3	3.2	3.1	2.9

According to another classification of oils proposed by ISO (International Standard Organization), ISO Viscosity Grades (ISO VG), the minimum value of the kinematic viscosity at 40 °C is 9 cSt for the lowest viscosity oils (ISO VG = 10); however, if the ISO VG for the tested oil is taken into account, then the limit value for that oil is 80 cSt at 40 °C. It can be observed (Table 7), that the tested oil exceeded the defined minimum values 80 cSt just after the first hour of operation, reaching the kinematic viscosity of 38.8 cSt measured during the tests.

Each ship engine manufacturer has adopted its own minimum viscosity limits for lubricating oils that can be used in given engines. As can be seen in Table 8, some manufacturers report absolute values (in cSt) and others as percentage decrease in viscosity.

Table 8. Limiting values of lubricating oil viscosity provided by the main manufacturers of marine engines.

Marine Engine Manufacture	Max	Min	Min Determined for Tested Oil at 100 °C
	(cSt) or (%)	(cSt) or (%)	(cSt)
Daihatsu	+30%	−20%	11.6
Deutz-MWM	11 or +25%	9.0	9.0
Krupp MaK	130 at 40 °C	80 at 40 °C	5.6
MAN B&W	26.0 SAE *	3.8–21.9 SAE *	5.6
S.E.M.T. Pielstick	26.0 SAE *	3.8–21.9 SAE *	5.6
MTU	+25%	9.0 (SAE 30)	9.0
Wartsila	19	11.5	11.5
Sulzer	+30%	−20%	11.6
Yanmar	+30%	−20%	11.6

* MAN B&W, S.E.M.T. Pielstick—kinematic viscosity limits adopted from SAE.

The last column in Table 8 shows the viscosity absolute values for selected manufacturers, and the minimum value is 5.6 cSt at 100 °C. Assuming this value "optimistically" as the general limit value of the viscosity of lubricating oil in marine engines, it can be seen that the viscosity limit value in tested oil is transcended just after the first working hour (Table 7) and decreases even more with the oil working time.

3.4. Flash Point

Each sample was tested five times, and the trend of change in the ignition temperature during engine operation is presented in Figure 7. The flash point temperature drops sharply from about 250 to 105 °C during the first hour of operation, suggesting a relatively large leakage of fuel into the lubricating oil. At the same time, a relatively small decrease and stabilization of this temperature at the level of 105 ÷ 88 °C in the following hours of engine operation is observed. A similar drop in the value between the pure oil and the oil from sample 1 (after 1 h of operation) is observed in the diagram in Figure 4 (which represents diluted fuel quantity and density of used oil). The obtained flash point temperature, even after many hours of oil operation, does not exceed the value considered as dangerous (38 °C), at which the liquid from combustion becomes flammable.

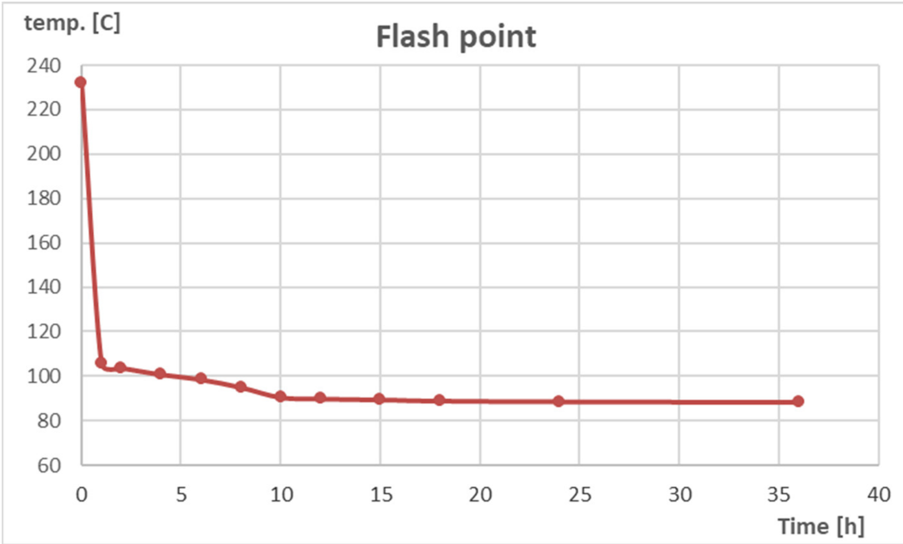


Figure 7. Change in the value of the lube oil flash point temperature during the operation time of the injection pump.

4. Summary

The results obtained were analyzed for potential side effects that could have occurred during prolonged engine operation by assessing the content of trace elements in the samples taken. In the literature on the subject, many scientists have investigated the changes in the properties of engine oils under real operating conditions, but no papers have been found that take into account the changes in the properties of the lubricating oil used only for lubrication of the fuel injection pump.

Lubricating oil in internal combustion engines is exposed to various factors depending on the operating conditions, the fuel quality, the ambient conditions and operating parameters. The rate of deterioration strongly depends on these factors. In order to avoid an engine failure, the oil must be changed before it loses its protective properties. At the same time, an unnecessary oil change should be avoided for environmental and economic reasons. In order to determine the optimum oil change interval reliably, it is necessary to monitor the actual physical and chemical condition of oil.

This paper experimentally investigates how the diesel dilution affects engine lubricating oil chemical performance. Thus, accurate estimations of engine oil lifetime could be essential. To ensure economical operation and correct lubrication during engine working time, an appropriate strategy of oil change intervals is required.

Results suggest that diesel dilution only slightly affects chemical additive performance, water content and flash point but does reduce viscosity and, hence, oil film thickness. In summary, the study concluded that the reduction in oil change intervals for this engine is worth considering under the given operating conditions.

Taking into account the oil viscosity and density obtained from the tested samples, it is necessary to pay attention to the following issues:

- The problem of the technical condition of the fuel injection pump,
- The change in the oil replacement strategy from 100 working hours (according to manufacturer recommendation) to a more frequent period (i.e., every 24 h),
- The change of the used oil into oil with a respectively higher viscosity.

In selecting the correct oil change strategy, further tests may be helpful, for example, on such oil properties as lubricity/rheology.

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