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Research on the correlation application of marine lubricating oil technical indicators.

Peibo Shi [a], Fanghao Li [b], Haodong Yin [c], Yeli Yan [d], Zhibin Wang [e]

School of Maritime, Shandong Jiaotong University, Weihai 264200, China.

[a]1014418900@qq.com, [b]772749373@qq.com, [c]1290450002@qq.com, [d]Lyer1210@126.com, [e]wzb1786297922@163.com

Abstract

In order to timely grasp the running state of ship equipment lubricating oil, reduce serious or sudden equipment failure caused by lubrication problems. The ship lubricating oil was monitored to analyze the correlation between the pollution degree of lubricating oil and the content of wear particles, the correlation between the content of ferromagnetic particles and the ferrography analysis technology, and the correlation between additives and physicochemical indexes. The results show that the rate correlation between the wear intensity index of lubricating oil and the pollution degree is as high as 0.993. The correlation coefficient between the PQ index of lubricating oil and ferromagnetic substances was as high as 0.995, and the contents of the two were approximately equal. The correlation was very obvious, and the standard deviation was only 0.32, with little difference. Ammonium thiophsphonate has a significant positive impact on the Four-ball PB value of the lubricating oil, Oil sludge quantity and the phosphorus retention of the oil after oxidation. Sulfurized olefin has a significant positive impact on copper corrosion. Amine sulfuric-phosphoric diester has a significant positive impact on the kinematic viscosity of the lubricating oil at 100°C. This method allows the relevant personnel to obtain a few test results, so as to analyze the pros and cons of ship lubricating oil and mechanical equipment wear, in order to have a more comprehensive grasp of the equipment, timely arrangements for maintenance, reduce equipment sudden failure.

Keywords

Marine diesel engine, Marine lubricating oil, Mechanical failure, Oil detection, Monitoring index.

1. Introduction

The ship with diesel engine as the main power device has a complex structure and high equipment maintenance cost. Once a failure occurs, it will bring huge economic losses to the ship owner. The operation of marine equipment is inseparable from lubricating oil, and lubricating oil plays a "heart" role in the operation of marine diesel engines and other mechanical equipment [1, 2]. Moreover, it can take away the heat generated by friction between some mechanical parts, and can effectively prevent the corrosion of parts [3], reduce the occurrence of mechanical failure, and prolong the service life of mechanical parts [4, 5]. Therefore, it is of great significance to ensure the good operation of marine equipment by adopting advanced monitoring methods for marine lubricating oil, monitoring lubricating oil well, predicting repair and maintenance, and keeping the equipment in a good operating state [6, 7].

Deng Yong et al. [8] analyzed the correlation between oil pollution degree and wear state, concluded that the pollution degree analysis method can replace the direct reading ferrography analysis to a certain extent. When analyzing marine diesel engine lubricating oil, it is found that there is a certain correlation between various detection indicators such as pollution degree detection, ferrography analysis, spectral element analysis, kinematic viscosity and copper corrosion. There is a regular understanding of the physical and chemical properties of oil, which can significantly improve the accuracy and comprehensiveness of oil analysis and judgment [9]. Therefore, the experiment selects a number of relevant technical indicators as the research object according to the testing experience, through the grey correlation analysis method, the overall average value, the standard deviation and the uniform design mathematical statistics method, etc. The correlation of abrasive particles, PQ index, spectral element index, conventional physical and chemical index, four-ball index and additive index was systematically studied, to find the correlation between the technical indexes of each lubricating oil.

2. Correlation analysis between pollution degree and ferrography detection

Lubricating oil pollution refers to the degree of lubricating oil ,"dirty", so-called "dirty" refers to the number of mechanical impurities in lubricating oil, that is, the number of insoluble particles in lubricating oil. Ferrography analysis is a technology that separates metal particles from oil by magnetic force and analyzes these particles. The pollution degree index can directly reflect the pollution state of the lubricating oil [10], and the The data of ferrography detection can reflect the wear status of the ship equipment through the wear particle state [11]. According to the relationship, the correlation analysis between the pollution degree and the ferrography detection data was carried out.

2.1. Experimental data

Oil samples were taken from the oil pan of the diesel engine crankcase of a ship. In order to reduce the experimental error, 6 groups of oil samples were randomly selected and analyzed by different instruments. The content of metal abrasive particles was analyzed by YTF-8 analytical ferrography and JXM metallographic microscope. To facilitate the analysis, the wear particles are divided into two categories, one is large wear particles, the other is small wear particles. Large wear particles in lubricating oil are represented by D_L and small wear particles in lubricating oil are represented by D_S.

The pollution degree of the oil was analyzed by the LAP2 type pollution degree detector. The marine lubricating oil of the crankcase of the marine diesel engine generally reflects the pollution degree of the oil by the number of abrasive particles of 60~300 μm. The experimental data are listed in Table 1.

Table 1 Contamination degree of oil sample and test data of ferro-spectral detection

Project	1 group	2 group	3 group	4 group	5 group	6 group
Pollution degree/(mg·L^{-1})	14	14.2	14.1	14	14.1	14.2
D_L/μm^2	926.2	925.2	927.2	924.2	925.2	926.2
D_S/μm^2	103.1	101.1	104.1	102.1	103.1	101.1

Using the mass fraction of abrasive particles (W_{PC}), the wear intensity index (I_S) and the percentage of large abrasive particles (P), a comprehensive analysis of the parameter changes of the measured oil contamination, large wear particles and small wear particles is carried out to find oil The relationship between the contamination degree of the sample and the wear data detected by ferrography detector, the experimental data is shown in Table 2.

Particle mass fraction (W_{PC}) represents the total wear amount per milliliter of undiluted marine lubricating oil sample, and its formula is (1):

$$W_{PC}=(D_L+D_S)/\text{sample size} \tag{1}$$

Wear severity index (I_S) is expressed as the product of the total wear amount and the wear severity, and its formula is shown in (2):

$$I_S = (D_L + D_S)(D_L - D_S) = D_L^2 - D_S^2 \tag{2}$$

The percentage of large abrasive grains (P) is expressed as the ratio of the large abrasive grain reading to the sum of the large abrasive grain reading and the small abrasive grain reading, and its formula is shown in (3):

$$P = \frac{D_L}{D_L + D_S} \tag{3}$$

where, D_L is the reading of large abrasive particles, and the size of large particles is greater than 35 μm; Ds is the reading of small abrasive particles, and the size of small particles is less than 35 μm.

Table 2 Preprocessed test data

Project	1 group	2 group	3 group	4 group	5 group	6 group
Pollution degree/(mg·L^{-1})	14.000	14.200	14.100	14.000	14.100	14.200
W_{PC}	1029.300	1026.300	1031.300	1026.300	1028.300	1027.300
IS	847216.83	845773.83	848863.03	843721.230	845365.430	847625.230
P	0.900	0.901	0.899	0.901	0.900	0.902

2.2. Correlation degree calculation

The grey correlation analysis method is used to analyze the pollution degree and wear particle content of ship lubricating oil, so as to find out the relationship between pollution degree and wear particle content, and find out the ranking of influencing factors.

2.2.1 Data processing

Taking W_{PC}, I_S and P as the comparison sequence and the contamination degree as the reference sequence, the dimensionless processing of the data is carried out, and the obtained experimental data are shown in Table 3.

Table 3 Calculated values of oil contamination degree and correlation degree

Project	1 group	2 group	3 group	4 group	5 group	6 group
Pollution degree/(mg·L^{-1})	1.000	1.014	1.007	1.000	1.007	1.014
W_{PC}	1.000	0.997	1.002	0.997	0.999	0.998
I_S	1.000	0.998	1.002	0.996	0.998	1.000
P	1.000	1.002	0.999	1.001	1.000	1.002

2.2.2 Correlation analysis

Correlation coefficient is used to calculate the correlation coefficient between each comparison sequence and the reference sequence respectively. The specific calculation method and steps are as follows:

(1) Let X0 be the pollution degree as the reference sequence, Xi be WPC, IS, P as the comparison sequence, and obtain the absolute difference between the reference sequence and the corresponding element of the comparison sequence $\Delta_i = |X_O(K) - X_i(K)|$ (i=1, 2, 3..., m, K= 1, 2, 3..., n, n is the number of objects to be evaluated), and the absolute difference is calculated Δi as shown in Table 4.

Table 4. Calculated value of difference between reference sequence and comparison sequence

Δ_i	1 group	2 group	3 group	4 group	5 group	6 group
X_0 -X_1	0	0.017	0.005	0.003	0.008	0.016
X_0 -X_2	0	0.016	0.005	0.004	0.009	0.014
X_0 -X_3	0	0.013	0.008	-0.001	0.007	0.013

(2) The formula of the minimum difference of two levels is shown in (4), and the formula of the maximum difference of two levels is shown in (5):

$$\frac{\min}{i}\frac{\min}{K}\left|X_0(K)\text{-}X_i(K)\right| \tag{4}$$

$$\frac{\max}{i}\frac{\max}{K}\left|X_0(K)\text{-}X_i(K)\right| \tag{5}$$

where, $\left|X_0(K)\text{-}X_i(K)\right|$ denote the absolute value of the difference between the two evaluated objects (i=1, 2, 3..., m, K=1, 2, 3..., n, n is the number of evaluated objects).

According to formulas (4) and (5), the minimum difference between the two levels is 0.001 and the maximum difference between the two levels is 0.017

(3) The formula of the correlation coefficient ξ (K) is shown in (6):

$$\xi（K）=\frac{\frac{\min}{i}\frac{\min}{K}\left|X_0(K)\text{-}X_i(K)\right|+\rho\times\frac{\max}{i}\frac{\max}{K}\left|X_0(K)\text{-}X_i(K)\right|}{\left|X_0(K)\text{-}X_i(K)\right|+\rho\times\frac{\max}{i}\frac{\max}{K}\left|X_0(K)\text{-}X_i(K)\right|} \tag{6}$$

where, ρ is the resolution coefficient, which takes a value within (0, 1). The smaller ρ is, the greater the difference between the correlation coefficients and the stronger the distinguishing ability. For the convenience of calculation, it is taken in this study ρ=0.5.

Correlation coefficients calculated ξ (1) by formula (6) are shown in Table 5.

Table 5 correlation coefficient

Correlation coefficient	1 group	2 group	3 group	4 group	5 group	6 group
ξ (1)	1.118	0.370	0.693	0.832	0.572	0.384
ξ (2)	1.118	0.388	0.693	0.752	0.533	0.426
ξ (3)	1.118	0.450	0.569	1.199	0.596	0.452

(4) The correlation coefficient only describes the degree of correlation between the reference sequence and each time sequence point of the comparison sequence. If you want to know the overall correlation degree between each sequence, you also need to calculate the average value of the correlation coefficient between each sequence (r_i), its calculation formula is shown in (7):

$$r_i=\frac{1}{n}\sum_{K=1}^{n}X（K） \tag{7}$$

where, ξ (K) is the correlation coefficient (K=1, 2, 3…, n, n is the number of objects to be evaluated), n is the number of oil samples of marine lubricating oil.

According to formula (7), we get: r_1=0.661, r_2=0.652 and r_3=0.661.

2.2.3 Rate correlation

Rate correlation is the correlation degree that reflects the relative change rate of things in the process of development. If the relative change rate of two things in the development process is basically the same, it is considered that the two have a strong degree of correlation, and if their rate of change is inconsistent, the degree of correlation between the two is weak.

The calculation formula of the rate correlation degree (J_{io}) is shown in (8); the correlation coefficient of the kth item of the rate correlation degree ($X_{io}(K)$) is the formula (9):

$$J_{i0} = \frac{1}{n-1} \sum_{K=1}^{n-1} X_{io}(K) \tag{8}$$

$$X_{io}(K) = \frac{1}{1 + \left| \frac{DX_i(K)}{X_i(K)\,D_k} - \frac{DX_0(K)}{X_0(K)\,D_k} \right|} \tag{9}$$

where, $\frac{\Delta X_0(K)}{X_0(K)\Delta K}$ and $\frac{\Delta X_i(K)}{X_i(K)\Delta K}$ are the relative rate of change, which $X_0(K)$ represents the degree of pollution, is the reference sequence (K=1, 2, 3... , n, n is the number of lubricating oil samples to be tested), $X_i(K)$ is the comparison sequence, respectively W_{PC}, I_S, P, (i=1, 2, 3... , m , m is the number of comparison sequences; K=1, 2, 3... , n, n is the number of lubricating oil samples to be tested).

The rate correlations calculated from formula (8) are as follows: J_1 =0.991, J_2 =0.993 and J_3 =0.992.

Rate correlation degree can be calculated, and the rate correlation strength is in the following order: wear intensity index > percentage of large abrasive particles > abrasive particle mass fraction.

2.3. Analysis of results

The correlation analysis shows that the rate correlation between the wear intensity index and the pollution degree of the oil is the strongest, which is 0.993. In the absence of the detection of the pollution degree of the oil, it can be used to characterize the lubricating oil of the main engine of the ship. pollution degree. Similarly, in the absence of ferrographic abrasive particles to detect oil, the pollution degree of marine lubricating oil can be evaluated by ferrographic abrasive particles, which can timely understand the pollution degree of marine lubricating oil and the situation of ferrographic abrasive particles.

3. Correlation between PQ index and element measurement

The PQ index is usually used to detect the content of trace ferromagnetic abrasive particles in lubricating oils such as engine oil, gear oil and hydraulic oil [12]. Although the oil element spectrometer can detect up to 20 elements [13], the main concern of ship owners or maintenance personnel is the content of ferromagnetic particles. If the correlation between the PQ index of lubricating oil and the content of ferromagnetic particles can be found, It can reduce the detection cost of lubricating oil, and use the analysis methods such as gray correlation, overall average and standard deviation to seek the relationship between the two, and theoretically explore the data relationship between the PQ index and the content of ferromagnetic particles.

3.1. Oil sample experiment

Experimental oil sample is shown in Table 6; the experimental reagent is tetrachloroethylene (Shenyang Chemical Reagent Factory); the measuring instruments are TTL-3 iron meter, YTF-8 analytical ferrometer and Spectroil Q^{100} oil element spectrum analyzer. The oil samples were heated in a vacuum drying oven at 60℃ for 30 min, and then diluted with tetrachloroethylene. The TTL-3 iron meter was used to determine the PQ index in the sample, the spectrometer was used to determine the element composition and content of the sample, the correlation between the PQ index and the element composition was analyzed, an appropriate mathematical model was established, and the relationship between each index was analyzed.

Table 6. Information of test oil sample

Lubricant brand	Lubricant model	Sampling location
Great Wall	4012	Marine main engine system lubricating oil
Great Wall	L-M46	Right Rudder Propeller Lubricant
Great Wall	L-HV100	Right clutch oil
Great Wall	L-HM100	Left rudder propeller oil
MEROPA	100	oil purifier lubricating oil
PRESLIA	68	Marine steering gear oil

3.2. Experimental analysis

3.2.1 Correlation of the mass fraction of ferromagnetic abrasive particles

PQ index and element measurement data of lubricating oil samples are listed in Table 7 and Table 8.

Table 7 PQ index and element measurement data of samples

Project	1 group	2 group	3 group	4 group	5 group	6 group
PQ Index	29.81	5.96	3.55	13.72	9.89	5.06
Fe/(mg/kg)	29	5.6	3.0	13	9.4	4.6
Cu/(mg/kg)	35	8.5	1.8	1.2	11	0.2
Al/(mg/kg)	1.2	2.3	1.0	2.1	2.1	1.9
Pb/(mg/kg)	0.1	1.0	1.4	1.1	3.8	2.0
Cr/(mg/kg)	0.1	0.6	0	1.6	0.7	0.4
Ni/(mg/kg)	1.0	0.6	0.6	0.8	0.8	0.5
Sn/(mg/kg)	3.7	0	0.1	0	0	0
Sb/(mg/kg)	1.9	7.1	0.3	0	3.4	2.8
Mn/(mg/kg)	0.1	0	0	0	0	0
Ti/(mg/kg)	0	0	0	0	0	0
Mo/(mg/kg)	1.6	1.9	1.2	1.3	2.1	1.1
Fe+Ni/(mg/kg)	30	6.2	3.6	13.8	10.2	5.1

Table 8 PQ index and element measurement data of samples

Project	7 group	8 group	9 group	10 group	11 group	12 group
PQ Index	23.51	13.7	13.44	6.93	38.76	1.50
Fe/(mg/kg)	23	13	13	6.4	38	1
Cu/(mg/kg)	6.9	15	1.6	6.3	8.7	3.2
Al/(mg/kg)	1.2	1.3	0.8	1.4	1.8	1.2
Pb/(mg/kg)	2.4	2.9	0.7	2	3.1	1.3
Cr/(mg/kg)	0.1	0.1	0	0.1	0.6	0
Ni/(mg/kg)	0.6	0.7	0.5	0.6	0.8	0.6
Sn/(mg/kg)	2.5	3.2	0	0	0	0.1
Sb/(mg/kg)	1.1	0.9	1.6	2.2	1.2	1.2
Mn/(mg/kg)	0.1	0	0	0	0	0
Ti/(mg/kg)	0	0	0	0	0	0
Mo/(mg/kg)	0.9	0.9	1.5	1.4	1.5	1.1
Fe+Ni/(mg/kg)	23.6	13.7	13.5	7	38.8	1.6

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The PQ index of the sample and the measured data of each element are plotted according to table 7 and table 8. As shown in Figure 1, from the line graph, it can be seen that the PQ index is related to the elements of Fe, Ni and Fe+Ni. The change trend of the content is relatively consistent, and the mass fraction of Cu changes greatly, but it is inconsistent with the change of the PQ index. The mass fractions of Al, Pb, Cr, Ni, Sn, Sb, Mn, Ti, Mo have little change, and the influence on the PQ index is small and can be ignored. However, further data analysis is needed to find a more accurate and consistent trend's element.

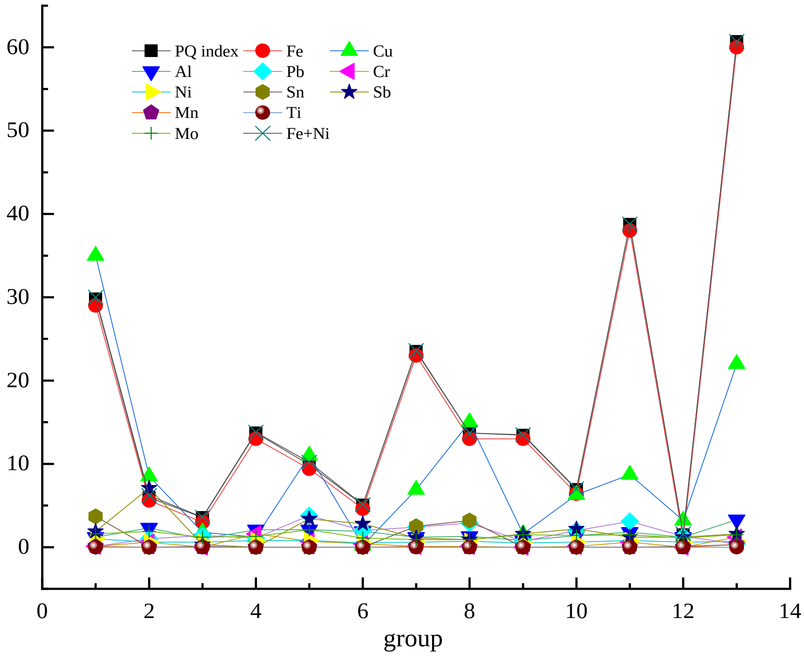

Fig.1 PQ index and element measurement data of sample

3.2.2 Relationship between PQ index and mass fraction of Fe and Ni elements

From Figure 3.1 that the PQ index corresponds to the mass fraction of Fe, Ni, Fe+Ni elements measured by the rotating disk electrode emission spectrometer, showing a certain correlation. The correlation coefficient can be calculated by formula (7):

$$r_{Fe}=0.984,\ r_{Ni}=0.667 \text{ and } r_{Fe+Ni}=0.995$$

Set the absolute error of the PQ index analysis as Ea and the relative error as Er, the obtained data are listed in Table 9.

The absolute error Ea of the PQ index analysis can be tested by the Pau Ta Criterion to check whether there is abnormal data. When $-0.86 \le X_i \le 1.06$, it means that the data of X_i is not abnormal, then Ea has no abnormal data, and the absolute error Ea number The set is {0.19; 0.24; 0.05; 0.08; 0.31; 0.04; 0.09; 0.00; 0.06; 0.07; 0.04; 0.10; 0.00}, which conforms to the normal distribution law.

Let $\overline{X}$ represent the population mean, and its formula is (10) as shown:

$$\overline{X}=\frac{1}{n}(X_1+X_2+\cdots+X_n) \tag{10}$$

σ represents the standard deviation, and its formula is shown in (11):

$$\sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i-\overline{X})} \tag{11}$$

where, X_1, X_2, $X_3\cdots$, X_n respectively represent the values of different samples used.

Calculate the overall mean and standard deviation of the absolute error separately: $\overline{X}=0.10$, σ=0.32.

Table 9. Difference analysis between PQ index and total amount of Fe and Ni elements

PQ Index	Fe+Ni (mg/kg)	Ea	Er
29.81	30.00	0.19	0.01
5.96	6.20	0.24	0.04
3.55	3.60	0.05	0.01
13.72	13.80	0.08	0.01
9.89	10.20	0.31	0.03
5.06	5.10	0.04	0.01
23.51	23.60	0.09	0.00
13.70	13.70	0.00	0.00
13.44	13.50	0.06	0.00
6.93	7.00	0.07	0.01
38.76	38.80	0.04	0.00
1.50 _	1.60	0.10	0.07
60.70	60.70	0.000	0.000

3.3. Analysis of results

During the operation of ship equipment, more ferromagnetic substances will be produced in the lubricating oil. After the analysis of the PQ index and the content of each element, it is found that the PQ index is approximately equal to the content of the ferromagnetic substances in the sample, and the error is small, but when Fe, When the Ni mass fraction is low ($\leq 1.6\times10^{-7}$), the error between the PQ index and the content of ferromagnetic substances will be slightly larger.

4. Research on the correlation of physical and chemical indicators

In order to provide better lubrication for mechanical equipment, various additives are added to the lubricating oil [14, 15], therefore, it is very necessary to study the correlation between marine lube oil additives and physical, chemical properties such as four-ball PB value, copper corrosion performance, kinematic viscosity and sludge production [16], using uniform design mathematical statistics The method explores the relationship between the two theoretically.

4.1. Physical and chemical experiments

Table 10. Main properties of oil sample additives and base oil

Item	Main property
Sulfurized olefin	Sulfur 42.40%, open flash point 120℃, moisture trace
Amine sulfuric-phosphoric diester	Sulfur 11.28%, Phosphorus 9.13%, Nitrogen 1.61%
Ammonium thiophosphate	Sulfur 5.91%, Phosphorus 5.68%
Anti-corrosion agent	Nitrogen 2.81%
Oiliness additive	Nitrogen 2.81%
Metal deactivator	Sulfur 32.52%, Nitrogen 6.29%
SAE90 base oil	Kinematic viscosity (100℃) 20.62 m^2/s, flash point (open) 258℃

Add 100 mL of experimental lubricating oil to a 150 mL centrifuge tube, place the centrifuge tube in a constant temperature drying box at 131℃ for 72 h, and take it out. Centrifuge at 10,000 r/min for 15 min to measure the viscosity change and phosphorus change of the oil sample, sludge changes and oil changes. In order to ensure the accuracy of the experiment, the oil operation in this experiment was carried out as much as possible in the sterile workbench to avoid the influence of external factors on the experiment. The properties of the additives and base oils used in the experiments are listed in Table 10.

4.2. Additive correlation research

The uniform design method was used to analyze the correlation between the base oil and the additive, and the results are listed in Table 11 and Table 12.

Table 11 Uniform design

SAE90	Sulfurized olefin (X_1)	Amine sulfuric-phosphoric diester (X_2)	Ammonium thiophosphate (X_3)	Anti-corrosion agent (X_4)	Oiliness additive (X_5)	Metal deactivator (X_6)
97.84	0.10	0.20	0.40	0.20	0.19	0.19
95.76	1.10	0.50	1.00	0.45	0.06	0.16
94.94	2.00	1.00	1.50	0.25	0.27	0.15
94.92	3.00	1.40	0.00	0.40	0.15	0.12
93.37	4.00	1.80	0.60	0.20	0.03	0.10
92.13	5.00	0.00	1.20	0.35	0.24	0.08
91.57	6.00	0.40	1.90	0.05	0.12	0.07
92.66	7.00	0.90	0.20	0.30	0.00	0.04
97.67	8.00	1.20	0.80	0.00	0.21	0.02
87.67	9.10	1.70	1.50	0.25	0.10	0.01

Table 12 Uniform design test results

Four-ball PB value Y_1/N	Copper corrosion (100℃×3h) Y_2	Oven oxidation experiment			
		100℃ kinematic viscosity Y_3/%	Phosphorus retention Y_4/%	Oil loss Y_5/%	Oil sludge quantity Y_6/%
1028.0	2a	2.16	55.57	0.50	1.2
1275.0	2a	0.48	30.43	0.60	3.4
1302.4	2a	0.00	25.00	1.10	6.1
930.0	2a	0.18	29.64	1.20	0.8
1273.0	2a	-1.75	85.00	1.20	1.7
1077.0	2b	4.06	35.71	2.20	2.7
1175.0	2b	-0.61	37.50	2.10	5.6
881.0	3b	-1.47	50.00	1.10	1.3
1028.0	3b	-1.89	64.28	1.80	2.3
1233.8	4a	-3.52	43.47	1.80	3.0

Note: (1) Corrosion score of copper sheet: 2=2a, 2.5=2b, 3.5=3b, 4=4a; (2) Phosphorus retention = (phosphorus content in oil after oxidation/phosphorus content in oil before oxidation) ×100%.

Some conclusions can be drawn from table 12. There is a certain corresponding relationship between sulfurized olefin and copper corrosion. There is a certain corresponding relationship between sulfurized olefin, the 100℃ kinematic viscosity and amine sulfuric-phosphoric diester. There is a certain corresponding relationship between Ammonium thiophosphate, four-ball PB value and oil sludge quantity. There is a certain corresponding relationship between anti-

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corrosion agent, oiliness additive and phosphorus retention. There is a certain corresponding relationship between Metal deactivator and oil loss.

After the design is completed, the independent variables and dependent variables acting as various factors are gradually screened. The screening process and results are listed in Tables 13, 14 and 15.

Table 13 Data filtering process

Independent variable	Dependent variable					
	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
variable 1	X_3	X_1X_1	X_1X_2	X_4X_5	X_6X_6	X_3X_3
variable 2	X_2X_6	X_1X_3	X_4X_5	X_3X_3	X_5	X_3X_6
variable 3	X_3X_3	X_2X_6	X_2X_4	X_4X_4	X_1X_3	X_1X_2
variable 4	X_1X_5	X_2X_3	X_3X_5	X_4X_5	X_6	X_1X_5
variable 5	X_3X_6	X_1X_4	X_2X_2	X_5X_6	X_3X_3	X_1X_5
variable 6	X_6X_6	X_2X_2	X_1X_3	X_3	X_4X_4	X_1X_5
variable 7	X_6	X_1X_2	X_2X_6	X_1X_1	X_2	X_1X_5
variable 8	X_4X_6	X_2X_4	X_4X_6	X_3X_6	X_2X_4	X_1X_5

Table 14. Regression equation

Dependent variable	Y_1	Y_2	Y_3
regression equation	$Y_1=716.608+740.568X_3+1465.404*X_2*X_6-228.030*X_3*X_3-87.795*X_1*X_5-845.833*X_3*X_6+5015.783*X_6*X_6-596.856*X_6+144.949*X_4*X_6$	$Y_2=1.066+0.028*X_1*X_1-0.029*X_1*X_3-1.714*X_2*X_6+0.144*X_2*X_3+0.231*X_1*X_4-0.244*X_2*X_2+0.060*X_1*X_2-0.144*X_2*X_4$	$Y_3=0.927-0.216*X_1*X_2+51.034*X_4*X_5-4.541*X_2*X_4-3.131*X_3*X_5+0.112*X_2*X_2-0.045*X_1*X_3-3.707*X_2*X_6+1.105*X_4*X_6$

Table 15. Regression equation

Dependent variable	Y_4	Y_5	Y_6
regression equation	$Y_4=62.908-37.103*X_4*X_4-538.370*X_4*X_5+440.427*X_5*X_6+86.020*X_3-0.604*X_1*X_1-348.438*X_3*X_6$	$Y_5=0.432-99.213*X_6*X_6+1.970*X_5+0.141*X_1*X_3+15.785*X_6-0.200*X_3*X_3+0.910*X_4*X_4-0.080*X_2-0.050*X_2*X_4$	$Y_6=0.068+1.186*X_3*X_3+10.102*X_3*X_6+0.243*X_1*X_2-0.764*X_2*X_2+7.433*X_2*X_6-0.058*X_1*X_5+0.550*X_4*X_5-0.952*X_4*X_6$

4.3. Analysis of results

The correlation between base oil and additives can be obtained by studying Tables 13 to 15.

(1) Ammonium thiophsphonate (X_3) will have a significant positive influence on the four-ball PB value (Y_1) of the four-sphere, that is, it will help to improve the PB value of the four-sphere. Amine sulfuric-phosphoric diester (X_2) and metal deactivator (X_6), sulfurized olefin (X_1) and oiliness additive (X_5), ammonium thiophsphonate (X_3) and metal deactivator (X_6) has an interaction.

(2) From the point of view of copper sheet corrosion, the main factor affecting copper sheet corrosion is sulfurized olefins, sulfurized olefins (X_1) will have a significant positive impact on

copper corrosion (Y_2), that is, copper sheet corrosion becomes corrosion resistance with the increase of sulfurized olefins content, and amine sulfuric-phosphoric diester (X_2) will have a significant negative impact on copper corrosion (Y_2), that is, the corrosion resistance of copper sheet decreases with the increase of thiophosphoric acid ester amine salt content. Interactions exist between amine sulfuric-phosphoric diester (X_2) and thiophosphate ester amine salt (X_3), sulfurized olefins (X_1) and anti-corrosion agent (X_4), sulfurized olefins (X_1) and amine sulfuric-phosphoric diester (X_2), sulfurized olefins (X_1) and thiophosphate ester amine salt (X_3), amine sulfuric-phosphoric diester (X_2) and metal deactivator (X_6), amine sulfuric-phosphoric diester (X_2) and anti-corrosion agent (X_4).

(3) From the influence on the increase of 100°C kinematic viscosity of oil after oxidation, it can be seen that amine sulfuric-phosphoric diester (X_2) has a significant positive effect on 100°C kinematic viscosity (Y_3), that is, the addition of amine sulfuric-phosphoric diester (X_2) helps to improve the increase of 100°C kinematic viscosity of oil after oxidation. There is an interaction between anti-corrosion agent (X_4) and oiliness additive (X_5), anti-corrosion agent (X_4) and metal deactivator (X_6), sulfurized olefins (X_1) and amine sulfuric-phosphoric diester (X_2).

(4) From the perspective of phosphorus retention after oil oxidation, ammonium thiophsphonate (X_3) will have a significantly positive impact on phosphorus retention (Y_4), that is, the increase of ammonium thiophsphonate (X_3) will help improve the phosphorus retention ability of oil after oxidation. Sulfurized olefins (X_1) and anti-corrosion agent (X_4) will have a significantly negative impact on phosphorus retention (Y_4). There is an interaction between anti-corrosion agent (X_4) and oiliness additive (X_5), oiliness additive (X_5) and metal deactivator (X_6), ammonium thiophsphonate (X_3) and metal deactivator (X_6).

(5) It can be seen from the oil loss after oxidation that oiliness additive (X_5) and anti-corrosion agent (X_4) have a significantly positive impact on oil loss (Y_5). Metal deactivator (X_6), ammonium thiophsphonate (X_3) and amine sulfuric-phosphoric diester (X_2) have a significantly negative impact on oil loss (Y_5) after oxidation, and there is an interaction between sulfurized olefin (X_1) and thiophosphate ester amine salt (X_3).

(6) From the perspective of oil sludge generated after oil oxidation, ammonium thiophsphonate (X_3) has a significantly positive impact on the amount of oil sludge quantity (Y_6), and amine sulfuric-phosphoric diester (X_2) has a significantly negative impact on the amount of oil sludge quantity (Y_6). There is an interaction between ammonium thiophsphonate (X_3) and metal deactivator (X_6), sulfurized olefin (X_1) and amine sulfuric-phosphoric diester (X_2), amine sulfuric-phosphoric diester (X_2) and metal deactivator (X_6).

5. Conclusion

By studying the correlation of oil detection indexes, the pollution level of oil can be used as an intuitive understanding of the pollution status of oil used in equipment. When there are ferromagnetic substances in lubricating oil, PQ index can be approximately equal to the content of ferromagnetic substances iron and nickel in the sample. When the lubricating oil contains additives, additives can be used to judge the change trend of oil physical and chemical indexes, so as to realize the wear condition evaluation of ship machinery equipment based on multi-index parameter fusion. In some special cases, ferromagnetic abrasive particles can also be used as the judgment of the pollution status of the oil used for equipment, which undoubtedly provides a temporary but simple and effective method for the condition monitoring and fault diagnosis of equipment based on oil analysis, improves the accuracy and scientificity of the condition monitoring and fault diagnosis of ship machinery and equipment, and provides theoretical support for further exploring the correlation application of ship lubricating oil.

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