Bench experimental research of cylinder oil on large marine diesel engines

J H Lin¹, B X Wang¹ and L D Wei² *

¹CNOOC Energy Technology & Services-Oil Production Services Co., Tianjin 300452, China
²Merchant Marine College, Shanghai Maritime University, Shanghai 201306, China
Email: weilidui@163.com

Abstract. To lower the risks of the real ship test of the cylinder oil of large marine low-speed two-stroke marine diesel engine, a 6S50ME marine diesel engine was selected to do bench test about cylinder oil. In the calibration condition, the test cylinder oil and the reference cylinder oil were compared. The test results show that the wear amount of cylinder liners, piston rings and piston-ring-grooves is consistent with the wear condition judged by the metal element content detected by the residual oil of the cylinder. At the same time, combined with the evaluation result of the detergency and dispersibility of the cylinder oil, it can effectively judge whether the oil product can be tested on the ship. Since wear volume of element Cr and Fe tends to the stabilization after 60 hours, so it is feasible to set the diesel engine bench test at 100 hours. In addition, special attention should be paid to the control of water outlet temperature and exhaust gas temperature in the test. The cylinder oil evaluated in the above way meets the requirements of OEM after the actual ship test. Thus, the assessment method of cylinder oil based on the bench test is feasible, and can greatly shorten the test time and reduce the test cost.

1. Introduction
The large low-speed, crosshead, two-stroke, diesel engine, which dominates the main propulsion power plant on the merchant ships, is developing in the direction of large cylinder diameter, long-stroke, high power, high detonation pressure, low energy consumption and low emission, which will put forward new and higher requirements for cylinder oil and require cylinder oil that can adapt to various working conditions [1-2]. The marine lubricant is different from vehicle-use lubricant which has a general specification and convenient test methods [3-6]. Although the marine lubricant can be tested on the text bench described in the literatures [7-9] which is very different from the actual operating condition. Therefore, OEMs (original equipment manufacturer) such as MAN, WARTSILA, WinGD and Mitsubishi) require that the test time on the vessels shall not be less than 4000 hours, which will bring huge risk for the marine lubricant manufactures. In general, the test time of 4000 hours is equivalent of at least 8 natural months considering the actual ship operating conditions; also, the staff of the OEMs don’t follow the experiments on aboard ship while the ship crew has no desire to do the job due to the extra work, so the accurate experimental data cannot be obtained or gotten on time; certainly, besides the normal testing costs, the OEMs will have to pay additional charge if the experiments affect the ship operation or bring the accidental damage about the engine. As a result, the bench test becomes critical. In the past, Bolnes 3DNL 170/600HF three-cylinder engine was mostly used for bench test [10]. However, due to its small cylinder diameter (170mm) and lower power, etc., it was quite different from
the actual marine diesel engine, and the test time often exceeded 600 hours which is recognized by the industry. Thus, this approach was limited due to the low correlation degree and poor test economy. On the contrary, the correlation degree is higher when the full-size marine diesel engine widely used on the real ship is put into use for the bench test [11], and the determination of the time of the bench test and the key indicators which shows that the test satisfies the requirements, are the key. However, the truth is that there is very little public research on the subject. The assessment about the cylinder oil in the paper is based on the MAN 6S35ME diesel engine mass-produced by the MAN Corporation.

2. Experiment method
The MAN 6S35ME is a large low-speed two-stroke, direct-scavenging, crosshead, electronically controlled direct-injection fuel injection and direct-reversing marine diesel engine (Figure 1), whose parameters are shown in Table 1. The engine output end is connected with NCK2000 hydraulic dynamometer on the bench.

![Figure 1. Test marine engine (6S35ME).](image1)

![Figure 2. The connection diagram of cylinder oil.](image2)

| Parameters                  | Values          |
|------------------------------|-----------------|
| Type                         | 6S35ME-9        |
| Rated power/ kW              | 3570            |
| Number of cylinders          | 6               |
| Stroke number                | 2               |
| Bore/ mm                     | 350             |
| Stroke/ mm                   | 1550            |
| Rated speed rev/min          | 142             |
| Maximum cylinder pressure/MPa| 18.0            |

The engine has six cylinders. Cylinder oil system of the engine is divided into three groups: cylinder 1 and cylinder 2 use test oil A; cylinder 3 and cylinder 4 use reference oil C; cylinder 5 and cylinder 6 use test oil B (Figure 2). Marine heavy oil is used for the engine, and the cylinder oil feed rate is about 0.8g/kWh. The residual cylinder oil dripping from the cylinder wall was taken as samples for oil analysis every 10 hours, and the internal combustion chamber and piston ring conditions are checked every 25 hours to ensure no abnormal wear and to determine whether the operation is normal. The engine runs at full load until the Fe and Cr content in residual cylinder oil tend to be stable. During the test, the working
conditions and parameters of the diesel engine must be controlled within the range specified in Table 2. Table 3 shows the general physical and chemical indexes of the test cylinder oil and the reference cylinder oil.

### Table 2. Operating parameters of the marine diesel engine.

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Revolution speed /(r/min)         | 142±1        |
| Power/kW                          | 3170±30      |
| Specific fuel oil consumption / (g/kWh) | 171±8.5  |
| Sulfur of the fuel oil /%         | 3.5          |
| Consumption of cylinder oil / (g/kWh) | 0.8        |
| Consumption of system oil / (kg/cyl./24h) | 3-4       |
| Input pressure of cylinder cooling water /MPa | 0.26±0.02 |
| Output temperature of cylinder cooling water /°C | 67±2        |
| Cylinder exhaust gas temperature /°C | 260±10     |
| Scavenging pressure/MPa           | 0.235±0.005  |
| Scavenging temperature /°C        | 40±3         |

### Table 3. The physical and chemical indexes of the test cylinder oil and the reference cylinder oil.

| Item                                      | Test oil A | Test oil B | Reference oil C | SAE5040TBN |
|-------------------------------------------|------------|------------|-----------------|------------|
| Kinematic viscosity (100°C) / (mm²/s)     | 20.17      | 20.23      | 20.46           | 16.3-21.9  |
| Density (20°C) / (kg/m³)                  | 915        | 918        | 921             | -          |
| Base number/(mgKOH/g)                     | 69         | 70         | 69              | ≥40        |
| Water /%                                  | 0.05       | 0.03       | 0.05            | -          |
| Flash point (open) /°C                    | 254        | 258        | 250             | ≥220       |

### 3. Experimental results

#### 3.1. Estimation of experiment process

During the test, the cylinder combustion chamber was inspected at the 25th, 50th, 75th, and 100th hours respectively, and no abnormal wear was found in the cylinder liners, piston rings, piston ring grooves, etc. At the same time, there were no abrupt changes of the main parameters during the operation, indicating that it could operate under the calibration condition when the diesel engine was controlled according to the parameters in Table 2 and the test process was normal.

#### 3.2. Clean dispersion Estimation of cylinder oils

Before the test, the cylinder liner and piston components were cleaned, as shown in Figure 3(a). Figure 3(b)-(d) shows the carbon accumulation of piston after the test. Obviously, the carbon accumulation areas of the piston surface are mainly concentrated in the piston heads and piston skirts, while the piston ring grooves have very little carbon. After test the cylinder oil residues in piston ring groove parts of all cylinders can be easily erased, and also surface scratch or scuff of the cylinder liners, pistons, piston rings are not be seen. All of these indicated that combustion, lubrication and sealing of each cylinder of the engine are normal and the entire test process is good. According to the internationally authoritative
CRC (Coordinating Research Council, USA) scores for pistons, 25 is classified as mild carbon deposition, 50 is classified as moderate carbon deposition, and 100 is classified as severe carbon deposition. In the test, the piston was divided into five parts: piston head, piston skirt, piston ring, piston groove and piston platform, so the full score is 500. Figure 4 shows the CRC carbon scores on the piston surface after the test. The carbon on the surface areas of the six pistons is less. Compared with the reference pistons of 3# and 4#, the cleanliness of the pistons of 1# and 2# is slightly better, while that of the piston of 5# and 6# is slightly worse.

![Figure 3. The piston deposit carbon before and after the test (100 hours).](image1)

![Figure 4. CRC scores of the piston surface carbon.](image2)

3.3. Wear resistance estimation of the test cylinder

3.3.1. Wear results of the cylinder liners and the piston rings. Figure 5 shows the wear of the cylinder liner in the front-after direction (F-A) and exhaust-maneuver (E-M) directions with 11 measuring points in the axial direction, where No.1 measuring point is close to the top of the cylinder liner, and No. 11 measuring point is close to the bottom of the cylinder liner. The maximum amount of wear occurs in the upper part of the cylinder liner, and the lower part of the cylinder liner has less wear, which conforms to the general law. The maximum wear of 1# and 2# cylinder liners is 0.050mm/kh, while 3# and 4# are 0.050mm/kh and 0.070mm/kh, respectively; 5# and 6# are 0.080mm/kh and 0.160mm/kh, respectively. It can be seen that cylinder 1#-4# are normal, while the wear of cylinder 5# is beyond recommended value of about 0.050mm/kh and close to the limit value of 0.100mm/kh beyond the given by MAN Corporation as well as that of cylinder 6# beyond the limit value. In figure 6, the radial wear of piston ring of cylinder 1#-4# is small, while piston ring 5# and 6# are large. The wear trend of each cylinder with time is consistent with the wear of cylinder liner; the height wear difference among the piston rings of each cylinder is small and close to the recommended value of MAN corporation[12]; the condition of the gap between the piston ring-groove on each piston similar to the height wear of the rings. It shows that lubricating oil is the main cause of the wear difference of each cylinder. It was judged that, compared with reference oil C, test oil A had better wear resistance, while test oil B was worse.
3.3.2. **Wear results of the cylinder liners and the piston rings.** The test cylinder oil is residual oil that drips along the cylinder wall and falls into the scavenging chamber. Figure 7 shows the ICP measurement results of important elements in cylinder oil. The change of content can be divided into two stages: rapid rise stage and stable stage. The wear of the cylinders using the test oils A and the reference oils C entered the stable stage from the rising stage after 55 hours, and the contents of Fe and Cr in the two oils were close to each other. However, the wear of cylinders with the test oil B slowly entered the stabilization stage after 65 hours, and also the content of the two elements was higher than that of the reference oil, indicating that the lubrication performance was slightly worse. All these indirect measurements results were consistent with the direct measurement results of the cylinder liner.

![Figure 7. Fe and Cr content in cylinder oil.](image)

3.3.3. **Figure 8 shows the change of oil base value.** The base values of the three cylinder oils have little difference in the test, and the residual TBN (total base number) of the cylinder oil is between 20-30mgKOH/g, indicating that the three cylinder oils all have sufficient base-number reserves, which can meet the requirements of common marine fuel oil at present. The two indexes of Fe and Cr both entered the stable stage between 55 and 65 hours, and the change of TBN was also relatively gentle. This
indicates that the lubricating performance of oil could be reflected within 100 hours on the test bench, for even if the test time is greatly extended, the wear number of cylinders will not change greatly. Considering that the lube oil should have a large safety margin and the test cost, it is appropriate to choose a time period with a large amount of wear. Thus, the test was stopped at 108 hours. Compared with Bolnes 3DNL 170/600HF diesel engine bench test, the time is greatly shortened, and two kinds of oil can be tested at the same time. Thus, the test cost is significantly reduced.

3.4. Typical parameters analysis about the marine diesel engine
When other parameters change within the control scope of diesel engine and while the cylinder liner cooling water outlet temperature and exhaust temperature become too high or too low, this will indicate that cylinder oil did not work in the calibration mode, one side it may be due to the bad lubrication or the bad seal between the cylinder and the piston components, which effects the normal combustion and emissions in the cylinder; on the other hand, it may also be due to abnormal combustion emission in cylinder of diesel engine, which will affect the normal cylinder oil lubrication. On the contrary, it indicates that the diesel engine is working normally. Therefore, these two parameters must be concerned.

Figure 9 shows that the temperature at the outlet of liner cooling water and the average temperature of exhaust smoke change little before and after the test, and the difference between the two indexes of each cylinder is also small during the test, indicating that the influence of the two test oils on the operation of diesel engine is similar to that of the reference oil. At the same time, combining with the surface carbon deposition and wear of the cylinder liners and the piston components, all show that the test process is reliable, and the test method is feasible.

Figure 8. TBN content in residual oil of cylinder oil.

Figure 9. The average outlet temperature of the cylinder cooling water and the average exhaust temperature.
3.5. Ship fields test verification

After bench test, according to the specifications of MAN Corporation, a 48,000 GT bulk carrier with a marine main engine model of 6S50MC-C was selected for 4217 hours of real ship test. During the test, heavy oil with sulfur content of 2.5-3.5% was mainly used, and the average feed rate of cylinder oil was 1.16g/kWh. Throughout the process, cylinders 1#-4# use test oil A tested on the bench, cylinders 5#-6# use reference oil. Figure 10 shows the measured average wear of each cylinder liner and piston rings each 1000 hours. The results indicate that the wear change of cylinder 5#-6# is very small, while that of cylinder 1#-3# using test oil increases slightly and that of the cylinder 4# increases greatly but without beyond the recommended value. At the same time, comparing to the bench test results, the wear is also increased a little. Considering the fuel types and the change of working conditions as well as the differences in engine models, increase in wear is acceptable. The detergency and dispersibility of the test oil also meet the requirements. Later, similar results were verified on two other container ships again. Therefore, the certification from MAN Corporation was passed. The results show that the test method on the bench test is feasible, reliable and economical.

4. Conclusions

After the test, based on the wear of cylinder liner and piston components, the detergency and dispersibility of the test oil, and the comparison of Fe, Cr element content in residual oil of the reference oil and the test oil, the conclusion can be drawn that whether the test oil is fit to be tested on the real ships.

The wear amount of cylinder liners, piston rings and grooves and the content of important elements in cylinder oil are consistent for the result judgment. The wear amount measurement can only be used for the result judgment, while the oil analysis can intermittently judge the wear process of cylinder liners and piston rings under cylinder oil lubrication. Therefore, basing on the content of Fe and Cr elements of the residual oil in the test process tends to stabilization after 60 hours and other factors are taken into account, the bench test time can be determined as 100 hours, which can save the test cost.

In addition, the outlet temperature of cooling water and exhaust temperature of diesel cylinder liners can also indirectly reflect the sealing, lubrication, friction and wear conditions between cylinder liners and piston components. Therefore, in the process of the test these parameters also need to pay attention.

To sum up, the evaluation method of cylinder oil based on the bench test is feasible and can be used as an important reference for the bench test of this type of diesel engine.

References
[1] COSCO Group 2014 Effects of oil quality on ship cost reduction and countermeasures J. Tech. Adv. 99 1-10
[2] Liu H 2010 The development of marine engine and the require of lubricant for large marine Lubr. Eng. 35 121-5
[3] Yang J and Zhai Y 2008 High-power engine lubricants during the past 30 years J. Trans. CSICE 26 47-52
[4] Ma Y 2006 Study on 5070 marine cylinder oil J. Lubricating Oil 17 28-32
[5] Wei H, Yin F and Sun P 2006 Study of running-in oil effect on process of vehicle diesel running-in J. Chinese Internal Combust. Engine Eng. 27 74-76
[6] Bao C, Wang B and Yang Z 2008 Experimental study on monitoring lubricating oil of automotive engine J. Trans. CSICE 26 457-62
[7] Maekawa K, Akizuki Y and Matsumoto S 2001 Experimental estimation for behavior of cylinder oil on cylinder liner surface J. Bull. JIME 29 21-7
[8] Truhan J J, Qu J and Blau P J 2005 A rig test to measure friction and wear of heavy duty diesel engine piston rings and cylinder liners using realistic lubricants J. Tribol. Int. 38 211-8
[9] Johansson S, Nilsson P H and Ohlsson R 2011 Experimental friction evaluation of cylinder liner/piston ring contact J. Wear 271 625-33
[10] Pevzner L A 1993 Engine test method for qualification of oils for low-speed marine diesels J. Chem. Tech. Fuels Oils 29 89-92
[11] Huang S, Zhao X, Zhai Y 2010 Technical progress of two-stroke low speed marine engine and marine engine oil evaluation J. Lbr. 25 31-6
[12] MAN B&W 2008 6S35ME-B9 Main Engine Manual Copenhagen 151-214