Evaluation of Tribological Properties of Hydraulic Oils by Four-ball Tester Based On Orthogonal Experiment Method

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Abstract—In order to effectively evaluate anti-wear performance of hydraulic oil, four-ball tester method is used to design an orthogonal test program with 4 factors and 3 levels based on orthogonal test method, and a test method for evaluating tribological properties of hydraulic oils is established. Considering industry standards and combining with actual working conditions of hydraulic system of construction machinery, four factors of load, speed, temperature, and time have been investigated. Evaluating tribological properties of hydraulic oils by wear scar diameters, mean friction coefficient and instant friction coefficient, oil temperature and abnormal noise. The results show that under the selected factors and levels, the significant factors affecting the wear scar diameter are load, speed, temperature and time in order, the optimal test condition is load of 588 N, speed of 600 r/min, temperature of 96 °C, during time of 90 min which can effectively distinguish hydraulic oils with different quality grades. This evaluation method can provide a basis for the selection of hydraulic system oils.

1.Introduction
As is known, hydraulic system of construction machinery is developing towards high precision, miniaturization, and long oil exchange period, the requirements for anti-wear and anti-friction performance of hydraulic oils are becoming more and more urgent. At present, the nominal pressure of hydraulic system of construction machinery can reach 31.5 MPa, or even more than 40 MPa [1-2]. Therefore, evaluation of friction performance of hydraulic oil effectively is a key technology for oil development and improvement of the reliability of construction machinery [3-4].

Nowadays, there are two main types of hydraulic oil friction performance testing methods, one is the test machine method and the other is bench evaluation method. Among them, test machine method is easy to operate in laboratory, and bench test cycle is much longer in comparison. In laboratory, four-ball tester is used to evaluate anti-wear performance of hydraulic oil usually [5-7]. The standard method is relatively weak in distinguishing anti-wear performance of construction machinery hydraulic oil. Therefore, this article optimized the experimental conditions. A distinguishable evaluation method for hydraulic oil tribological properties is selected by comprehensive analysing of the wear scar diameters, mean and instant friction coefficient, oil temperature, and abnormal noise during the test [8-9].
2. Experimental Details

2.1. Materials
The ball specimen of diameter 12.7 mm are made of GCr15 steel balls. Market-available hydraulic transmission oil A with good anti-wear performance, high-pressure hydraulic oil B commonly used in China, and hydraulic oil B-1 for loaders developed. Oil B-1 is developed based on hydraulic oil B which enhances anti-wear performance.

2.2. Tribological Tester
A four-ball tester is used to evaluate the friction performance of hydraulic oils. Three fixed steel balls are submerged by lubricating oil, and the fourth steel ball is above the center of the three steel balls and rotated in a point contact mode. The test is performed under a certain load, speed, temperature, and during time. By designing orthogonal experiments, 4 factors and 3 levels are investigated, shown in Table 1 and the friction performance of hydraulic oils under each factor and level are analysed.

| Sequence | Time /min | Speed /r/min | Temperature /°C | Load /N |
|----------|-----------|--------------|-----------------|--------|
| 1        | 60        | 600          | 54              | 196    |
| 2        | 60        | 1200         | 75              | 392    |
| 3        | 60        | 1800         | 96              | 588    |
| 4        | 90        | 600          | 75              | 588    |
| 5        | 90        | 1200         | 96              | 196    |
| 6        | 90        | 1800         | 54              | 392    |
| 7        | 120       | 600          | 96              | 392    |
| 8        | 120       | 1200         | 54              | 588    |
| 9        | 120       | 1800         | 75              | 196    |

3. RESULTS AND DISCUSSION

3.1. Determination of Optimal Test Conditions
In order to choose a better test method, selected hydraulic oil A and hydraulic oil B are taken as 4 factors and 3 levels, and tested according to the orthogonal test design table. The difference between wear scar diameters of test oils is used to judge the distinguishing performance of the test conditions. When lubricating oil film is not broken, the larger the difference in wear scar diameters between tow test indicates that the condition has better distinguishing performance for the two test oils, and vice versa.

As shown in Fig. 1, friction coefficient increased suddenly, abnormal noise occurred and the oil temperature increased obviously during the test lubricated by the two oils which indicated that the protective tribofilms of the two oils are ruptured during the 3rd, 6th and 8th test. At the same time, wear scar diameters of the steel balls (fig. 2) are larger than that of the other six groups. From the analysis of the above phenomena, we can see that the test conditions for the 3rd, 6th and 8th groups are relatively harsh. Therefore, the other 6 groups of conditions are focused on.

Fig. 2 and Fig. 3 shown the wear scar diameters and mean friction coefficient under different test conditions. Fig. 4 shows instant friction coefficient under different test conditions. When condition 4 is
used, that is, 90 min, 600 r/min, 75 ℃, and 588 N, the difference between the wear scar diameters and average friction coefficient is 0.14 mm and 0.026 respectively. The friction coefficient of oil A is lower than that of oil B. The friction coefficient of oil A is relatively stable within 90 minutes, and the friction coefficient of hydraulic oil B fluctuates greatly in the first 30 minutes; when the standard test conditions is used for condition 2, the friction coefficient is relatively close. Therefore, in terms of anti-wear and anti-friction, condition 4 shows a stronger distinction in oil evaluation than the other eight test sequences.

Further, calculation of range value of the orthogonal experiment is carried out, as shown in Table 2. It can be seen that the significance of the influence on the wear scar diameter is in order of load, test speed, test temperature and test time. When the test conditions are 90 min, 1200 r/min, 96 ℃, 588 N and 120 min, 1200 r/min, 96 ℃, 588 N, the two oils can be distinguished well.

When the during time (90 min) and load (588 N) are fixed, the test temperature and rotating speed in the above two test conditions are cross-tested (table 3). Combining the change of oil temperature, abnormal noise during the process, when test load under 588 N and test speed 1200 r/min for number 2 and number 4 conditions, the wear scar diameters are large, oil temperature increases obviously and the oil film has broken. This indicates that these conditions are too harsh, as shown in table 3.

At rotation speed of 600 r/min, when the temperature is 75 ℃ and 96 ℃, the difference between the wear scar diameters are both 0.14 mm; Fig. 5 shows that the instant friction coefficient of hydraulic oil A, which is stable and always lower than Oil B. The friction coefficient of the two oils at 96 ℃ are lower than 75 ℃, which indicates that the hydraulic oil shows better anti-friction performance at higher temperature. The above data shows that the test conditions of 1 and 3 can distinguish tribological performance of hydraulic oils effectively.

However, considering common temperature of hydraulic oil in hydraulic system and maximum allowable working temperature, first group of test conditions (588 N, 90 min, 75 ℃, 600 r/min) is selected as the final evaluation test condition.
3.2. Verification of test conditions
The tribological properties of hydraulic oil A, hydraulic oil B and hydraulic oil B-1 are evaluated under load of 588 N, during time of 90 min, temperature of 75 °C and speed of 600 r/min. The test results are shown in table 4 and Fig. 6. It can be seen that the anti-wear performance of the three oils is clearly distinguished, and the anti-friction performance of oil A is better than that of oil B and B-1. This condition is suitable for selecting hydraulic oils.
TABLE 4 Friction performance of the three hydraulic oils

| Lubricant | Wear scar diameter/mm | Oil temperature variation range/°C | Mean friction |
|-----------|---------------|----------------------------------|--------------|
|           |               |                                  |              |
| A         | 0.48          | 75-78                            | 0.117        |
| B         | 0.62          | 75-78                            | 0.121        |
| B-1       | 0.57          | 75-77                            | 0.124        |

Fig. 6 Instant friction coefficient under different test conditions

4.Conclusions

Based on the experimental and analytical investigations presented in this paper, the following conclusions have been drawn:

1) The optimal test condition is load of 588 N, rotation speed of 600 r/min, temperature of 96 ℃, during time of 90 min, which can distinguish hydraulic oil of different quality grades, and can be used to evaluate the friction performance of hydraulic oil in construction machinery.

2) Under the selected factors and levels, the significant factors affecting the wear scar diameters are in order of test load, test speed, test temperature and test time.

3) The tribological properties of hydraulic oils can be comprehensively judged and distinguished through wear scar diameter, mean and instant friction coefficient, combined with oil temperature changes and abnormal noise during the process.

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