Study on Optimization of Operating Parameters of Contact Mechanical Seal Based on Orthogonal Test

LuLing Dai1, a*

1 Intelligent manufacturing College of Nanjing vocational college of science and technology, Nanjing, Jiangsu, China
a@email: dailuling@njpi.edu.cn
* Corresponding author: a@email: dailuling@njpi.edu.cn, postal address: 210048 No. 188, Xinle Road, chemical industrial park, Nanjing, Jiangsu, Telephone 13951071326

Abstract: The working condition parameters of common contact mechanical seals are experimentally studied by orthogonal experimental design. The effects of working condition parameters on mechanical seal performance are compared by variance and range analysis, and the optimal sealing working condition is put forward. The results show that the spring specific pressure has a great influence on the leakage of mechanical seal, and the leakage decreases rapidly with the increase of spring specific pressure; with the increase of spring specific pressure, the friction power consumption increases. According to the test results, considering the requirements of mechanical seal performance and service life, the optimal spring specific pressure is 0.028 MPa under the condition of medium pressure \( p_s = 0.60 \) MPa and motor speed \( n = 2960 \) r/min. At this time, the leakage is 6.120 ml/h and the friction power consumption is 0.648 kW.

1. Introduction
Mechanical seal is a widely used dynamic seal for rotating shaft, which plays a very important role in the safe production process of process industry[1]. Among them, B104 (also known as GY70) mechanical seal is widely used in centrifugal pump because of its simple structure and low manufacturing cost. Weilong et al[2] conducted single factor experimental research on the basic performance of GY70 mechanical seal, obtained the influence law of spring specific pressure, rotating speed and medium pressure on mechanical seal leakage and friction power consumption, and obtained the best sealing working point of mechanical seal.

Although the single factor test is simple and clear, it is difficult to find the internal relationship of the interaction of various factors for multi factor problems, and it is often lack of global. Among various experimental optimization technologies, orthogonal experimental design is very effective in solving multi factor optimization problems[3]. There are many factors that affect the sealing quality and service performance of mechanical seal in service, and these factors affect and restrict each other. By using the advantages of orthogonal experimental design method and analyzing the significance of the influence of various factors on sealing performance, satisfactory experimental results can be obtained with relatively few test times, short test time and low test cost, which lays the foundation for further optimization[4]. In this study, a three factor and four level orthogonal test scheme is designed, the orthogonal test optimization of working condition parameters of mechanical seal is carried out, the effects of working condition parameters of spring specific pressure, rotating speed and medium pressure...
on the performance of contact mechanical seal are analyzed and compared, and the preliminary optimized working condition is put forward.

2. Test conditions and multi factor orthogonal test

2.1. Test conditions

B104 mechanical seal commonly used in centrifugal water pump is selected for the test, and its main structure and material are shown in Table 1. The test medium is 20°C clean water.

| B104 mechanical seal | structural style | Built in, Single spring, Drive sleeve drive, Balanced type |
|----------------------|------------------|----------------------------------------------------------|
| Material Science     | Rotating ring    | Cemented carbide YG8                                      |
|                      | Stationary ring  | Carbon graphite                                           |
|                      | Auxiliary sealing ring material/form | Fluororubber O-ring |
| Main dimensional parameters | Inner diameter of sealing cavity (mm) | 131.58 |
|                       | Outer diameter of sealing face (mm) | 76.850 |
|                       | Inner diameter of sealing face (mm) | 66.850 |
|                       | Seal mounting shaft diameter (mm)    | 70 |
|                       | Equilibrium coefficient $\beta$     | 0.9 |

2.2. Orthogonal test

The experimental optimization technology is applied to the optimization of working condition parameters of mechanical seal. A three factor four level orthogonal test (see Table 2 for the level of orthogonal test factors) is designed to compare the influence of the changes of medium pressure $p_s$, motor speed $n$ and spring specific pressure $p_{sp}$ on the target characteristic value - leakage $Q$ and end face friction power consumption $N_f$. The statistical analysis software "orthogonal design assistant" is used to complete the construction of orthogonal table. 16 groups of mechanical seal performance tests are carried out according to each group of parameters, and the corresponding performance indexes are obtained (see Table 3).

| Level | Factor |
|-------|--------|
|       | A      | B      | C      |
| 1     | 0.15   | 1160   | 0.03   |
| 2     | 0.30   | 1760   | 0.06   |
| 3     | 0.45   | 2360   | 0.09   |
| 4     | 0.60   | 2960   | 0.12   |

| Experiment number | $p_s$ (MPa) | $n$ (r/min) | $p_{sp}$ (MPa) | Leakage $Q$ (ml/h) | End friction power consumption $N_f$ (kW) |
|-------------------|-------------|-------------|----------------|--------------------|------------------------------------------|
| 1                 | 0.15        | 1160        | 0.03           | 6.718              | 0.050                                    |
| 2                 | 0.15        | 1760        | 0.06           | 2.549              | 0.140                                    |
| 3                 | 0.15        | 2360        | 0.09           | 0                  | 0.310                                    |
| 4                 | 0.15        | 2960        | 0.12           | 0                  | 0.456                                    |
| 5                 | 0.30        | 1160        | 0.06           | 1.318              | 0.116                                    |
| 6                 | 0.30        | 1760        | 0.03           | 6.629              | 0.168                                    |
3. Analysis of orthogonal test results

3.1. Friction power consumption of seal face
Analyze the variance of the test data to calculate the $F$ ratio. The larger the $F$ value, the greater the influence relationship between the target characteristic value and this factor. See Table 4 for variance analysis of friction power consumption of sealing face.

Table 4 Variance analysis of friction power consumption of B104 mechanical seal end face

| Factor                | Sum of squares of deviations | Freedom | $F$ ratio | $F$ critical value | Significance |
|-----------------------|------------------------------|---------|-----------|--------------------|--------------|
| Medium pressure       | 0.159                        | 3       | 0.052     | 4.760              |              |
| Motor speed           | 0.333                        | 3       | 0.109     | 4.760              |              |
| Spring specific pressure | 0.037                      | 3       | 0.012     | 4.760              |              |
| Error                 | 6.10                         | 6       |           |                    |              |

It can be seen from table 4 that the primary and secondary relationships of the three parameters on the friction power consumption of the seal face are: motor speed, medium pressure and spring specific pressure. For mechanical seals with certain structure, constant medium pressure and constant working speed, the spring specific pressure is an important part of the end face specific pressure. The greater the spring specific pressure, the greater the end face specific pressure and the greater the friction power consumption. Large spring specific pressure means that the end faces of the mechanical seal fit tightly, and the micro convex contact pressure between the sealing end faces of the dynamic and static rings of the mechanical seal is large, with high friction and high friction power consumption. With the increase of rotating speed, the influence of spring specific pressure on friction power consumption of mechanical seal increases accordingly. The increase of rotating speed means that the friction distance of mechanical seal increases correspondingly in the same working time[5]; Mechanical seals with the same spring pressure will also consume more power due to the increase of rotating speed. The increase of spring specific pressure increases the difference of friction power consumption of mechanical seal at different speeds.

Fig. 1 is a range diagram of the variation of end face friction power consumption of B104 mechanical seal with medium pressure, motor speed and spring specific pressure.
As can be seen from Figure 1, the friction power consumption of the sealing face increases with the increase of medium pressure, motor speed and spring specific pressure, but almost linearly increases with the increase of motor speed. In production, the commonly used motor speed of centrifugal pump is 3000 r/min. When the medium pressure is in the range of 0.15-0.45 MPa, the end face friction power consumption increases obviously. After reaching 0.45 MPa, the seal end face friction power consumption increases and slows down. When the motor speed is 2960 r/min and the sealing medium pressure is 0.60 MPa, the service performance of mechanical seal is better.

3.2. Leakage

See Table 5 for variance analysis of leakage. Figure 2 is the range diagram of B104 mechanical seal leakage varying with three parameters.

Table 5 Variance analysis of leakage of B104 mechanical seal

| Factor                | Sum of squares of deviations | Freedom | F ratio | F critical value | Significance |
|-----------------------|------------------------------|---------|---------|-----------------|--------------|
| Medium pressure       | 4.625                        | 3       | 0.306   | 4.760           |              |
| Motor speed           | 3.231                        | 3       | 0.214   | 4.760           |              |
| Spring specific pressure | 79.982                      | 3       | 5.299   | 4.760           | *            |
| Error                 | 30.19                        | 6       |         |                 |              |

It can be seen from Table 5 that the primary and secondary relationships of the three parameters on the seal leakage are: Spring specific pressure, medium pressure and motor speed, and the spring specific pressure has a significant impact on the leakage. The leakage of mechanical seal is caused by many reasons. Practice has proved that excessive specific pressure of face seal is the main cause of thermal and mechanical damage of mechanical seal, and too small specific pressure of face seal will lead to excessive leakage rate. Theoretical analysis and experimental results show that[5], Although the change of spring specific pressure is sometimes not enough to change the end face friction state of mechanical seal, with the increase of spring specific pressure, the lubricating medium between friction pairs has been relatively reduced, and the end face friction characteristics have gradually deteriorated, resulting
in excessive leakage and failure of mechanical seal. Therefore, the mechanical seal has an optimal spring specific pressure. Under this specific pressure, not only its leakage rate does not exceed the standard, but also has good end friction characteristics.

Figure 2 Range diagram of relationship between leakage and operating parameters of B104 mechanical seal

As can be seen from Figure 2, with the increase of motor speed, the leakage of mechanical seal is gradually increasing. This is because the higher the speed, the stronger the hydrodynamic pressure between seal end faces and the increase of end face clearance, resulting in the increase of leakage. When the speed increased to 1760 r/min, the leakage began to decrease significantly until the speed reached 2360 r/min. This is because with the increase of spring specific pressure and medium pressure, the dynamic pressure caused by the increase of rotating speed is very small compared with the compression effect caused by spring and medium pressure, so the impact on the leakage becomes very small. The leakage decreases obviously with the increase of spring specific pressure, and decreases rapidly when it is greater than 0.06 MPa. This is consistent with the analysis results of literature [2].

4. Single factor optimization test

According to the previous orthogonal test results, the non main factors of curing B104 mechanical seal are: motor speed \( n = 2960 \text{ r/min} \), medium pressure \( p_m = 0.60 \text{ MPa} \), and the single factor test of the change of target characteristic value leakage \( Q \) and end friction power consumption \( N_f \) with spring specific pressure \( p_{sp} \) is conducted. See Table 6 for the results of single factor test of leakage \( Q \) of B104 mechanical seal, and see Figure 3 for the change trend; The results of single factor test data of end friction power consumption \( N_f \) are shown in Table 7, and the change trend is shown in Figure 4.

| Spring specific pressure \( p_{sp} \) (MPa) | 0.004 | 0.010 | 0.020 | 0.030 | 0.040 | 0.050 | 0.060 | 0.070 | 0.080 |
|------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Leakage \( Q \) (ml/h)                  | 14.251| 12.037| 8.977 | 5.414 | 3.294 | 1.341 | 0.225 | 0.046 | 0 |
The spring specific pressure is one of the important factors affecting the leakage of mechanical seal under certain medium pressure and speed, especially the balanced mechanical seal. When the pressure and speed of sealing medium are constant, the influence of spring specific pressure on leakage is shown in Figure 3. The relationship curve in the figure shows that the leakage of mechanical seal decreases rapidly with the increase of spring specific pressure. Under the experimental conditions, when the spring specific pressure reaches 0.080 MPa, the leakage has been reduced to zero. However, mechanical seal is a relative seal, and it is impossible to achieve absolute zero leakage. The reason why the leakage can not be measured in the test is that the leakage liquid is heated and vaporized due to the friction heating of the sealing end face.

Table 7 Single factor test results of end face friction power consumption of B104 mechanical seal

| Spring specific pressure $P_{sp}$ (MPa) | 0.004 | 0.010 | 0.020 | 0.030 | 0.040 | 0.050 | 0.060 | 0.070 | 0.080 |
|----------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| End friction power consumption $N_f$ (kW) | 0.601 | 0.617 | 0.638 | 0.6521 | 0.656 | 0.697 | 0.703 | 0.754 | 0.781 |

When the rotating speed and sealing medium pressure are constant, the influence of spring specific pressure on friction power consumption is shown in Figure 4. The relationship curve in the figure shows that the friction power consumption increases with the increase of spring specific pressure, which is just opposite to the change of leakage.

The theoretical analysis and test results show that there is an optimal spring specific pressure objectively. Under this specific pressure, not only the leakage rate does not exceed the standard, but also has good end face friction characteristics. The optimum spring specific pressure is different under different working conditions. Correct selection of spring specific pressure is the key to realize long service life and low leakage rate of mechanical seal. In the service stage of mechanical seal, its use effect and life extension must be comprehensively considered in order to give full play to its function and meet the needs of production. From the above experimental results, considering the requirements of mechanical seal performance and service life, it can be concluded that the optimal spring specific pressure is 0.028 MPa under the conditions of medium pressure $P_s$ =0.60 MPa and motor speed $n$ = 2960 r/min. At this time, the leakage is 6.120 ml/h and the friction power consumption is 0.648 kW (see Fig. 5).
5. Conclusion

(1) Theory and practice show that the operating condition of mechanical seal is closely related to medium pressure, rotating speed, spring specific pressure and other factors. The operating conditions of mechanical seal will directly affect its performance and service life. In the daily equipment management work, the site conditions shall be reasonably used, the operating conditions of mechanical seal shall be optimized, and the performance and service life of mechanical seal shall be improved, so as to stabilize production and reduce equipment maintenance and repair costs.

(2) From the orthogonal test results of B104 mechanical seal, the influence order of the three parameters on the friction power consumption of the seal face is motor speed, medium pressure and spring specific pressure. The spring specific pressure has a significant impact on the leakage.

(3) The comprehensive test results show that the optimal operating conditions after the orthogonal test of operating parameters of B104 mechanical seal are as follows: When the medium pressure is 0.60 MPa and the motor speed is 2960 r/min, the spring specific pressure is 0.06 MPa.

(4) From the single factor test of spring specific pressure leakage of B104 mechanical seal, it can be seen that the leakage of mechanical seal decreases rapidly with the increase of spring specific pressure. Under the test conditions, when the spring specific pressure reaches 0.080 MPa, the leakage has been reduced to zero.

(5) From the single factor test of spring specific pressure end friction power consumption of B104 mechanical seal, it can be seen that the friction power consumption increases with the increase of spring specific pressure.

(6) Considering the requirements of mechanical seal performance and service life, and realizing the best working state of mechanical seal, it can be concluded that under the conditions of medium pressure $p_s=0.60$ MPa and motor speed $n=2960$ r/min, the best spring specific pressure is 0.028 MPa. At this time, the leakage is 6.120 ml/h and the friction power consumption is 0.648 kW.

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