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Test Results of the Mechanical Face Seal for a Turbopump

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Abstract: The mechanical face seal has been tested in Korea Aerospace Research Institute (KARI) for turbopump applications. In the turbopump under current development, the mechanical face seal is installed between fuel pump and turbine to prevent a mixture of fuel and combustion gas. Generally the mechanical face seal in turbopump is exposed to severe environment because of great rotational speed, high temperature of combustion gas and high level of pressure difference. Thus a series of tests were performed to guarantee the reliability of mechanical face seal by means of simulating the practical operating conditions. The tests were conducted up to 20,000 rpm with pressure difference of 800 kPa and temperature of 620 K. In addition several carbon materials for mechanical face seal were conducted to the tests to compare the life time. During the tests, the performance against leakage was monitored and the carbon wear was also measured to estimate the life of a mechanical face seal. The results show that the leakage flow rates of mechanical face seal is ignorable compared to an overall flow rate of fuel pump. The carbon material which has the finest wear resistance was found during the tests. Lastly no critical failure of mechanical face seal was found during the tests and the reliability of mechanical face seal for turbopump was successfully proved.

Keywords: Turbopump, mechanical face seal, reliability, leakage, wear

1. Introduction

A turbopump [1] feeds oxidizer and fuel into a combustion chamber in a liquid rocket engine. Two pumps and a turbine are united in one axis as shown in Fig. 1. Considering cavitation performances and fuel rich gas on turbine side, LOX pump is located at one end of the shaft and the fuel pump in the middle connecting by a spline between pumps. The open cycle of the engine leads the turbine to employ single stage impulse type. Between two pumps, inter-propellant seal [2] is adopted to avoid any interaction between propellants. Also a mechanical face seal is installed between the fuel pump and the turbine, which provides the sealing between fuel and fuel rich gas.

Unlike mechanical face seal for industrial pump, the mechanical face seal in the turbopump is generally exposed to severe operating conditions. The mechanical face seal in this paper runs up to the linear velocity of 70 m/s with the pressure and temperature difference of 400 kPa and 300 K, respectively. Thus reliability of the mechanical face seal becomes an important matter during the development procedure of the turbopump. If any failure occurs in the mechanical face seal, a whole rocket engine system could fail. Thus an acceptance test of mechanical face seal is crucial. With this background, KARI built the test facility [3] which can simulate practical operating conditions of mechanical face seal. The acceptance test of mechanical face seal was performed with this test facility. The acceptance test consists of the performance test and the endurance test and the results of both tests are given in this paper.

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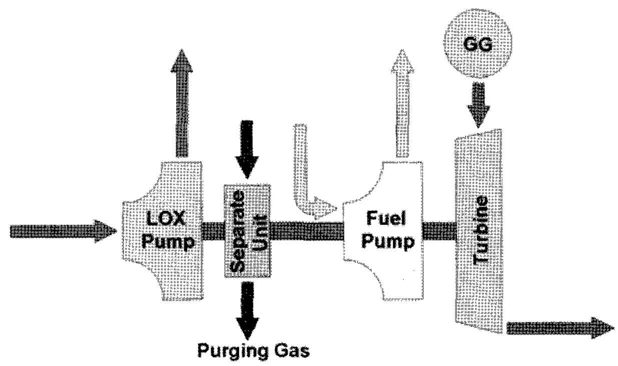

Fig. 1. Schematics of turbopump.

2. Mechanical Face Seal

Figure 2 shows the structural arrangement of mechanical face seal. The mechanical face seal is mainly composed of a bellows seal assembly and a mating ring. The bellows seal assembly, which is installed in a pump casing, includes housing, metal bellows, holder and carbon. The carbon in bellows seal assembly and the mating ring are in sliding-contact each other during operation, which provide the sealing between fuel and gas.

The operating conditions of mechanical face seal are determined by the operating conditions of turbopump and they are listed in Table 1. The working fluid on fuel pump side of mechanical face seal is kerosene with the pressure up to 800 kPa. On turbine side, the mechanical face seal is exposed to fuel rich combustion gas. The temperature of combustion gas reaches up to 620 K and the maximum pressure is around 400 kPa. Thus the mechanical face seal experiences the pressure

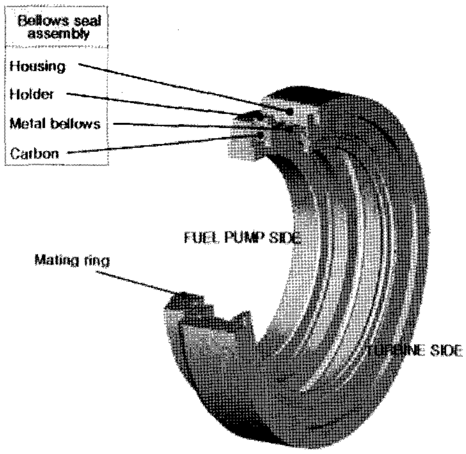

Fig. 2. Structural arrangement of mechanical face seal.

Table 1. Operating conditions of mechanical face seal

Fuel pump side	
Media	Kerosene
Pressure	400~800 kPa
Temperature	300 K
Turbine side	
Media	Combustion gas
Pressure	400 kPa
Temperature	620 K
Rotational speed: 20000 RPM	
Duration for single operation: 120 sec	
Overall life time: 1200 sec	

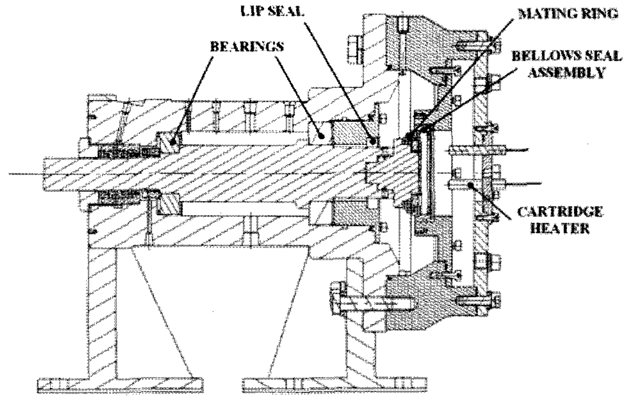

Fig. 3. Cross-sectional view of mechanical face seal test rig.

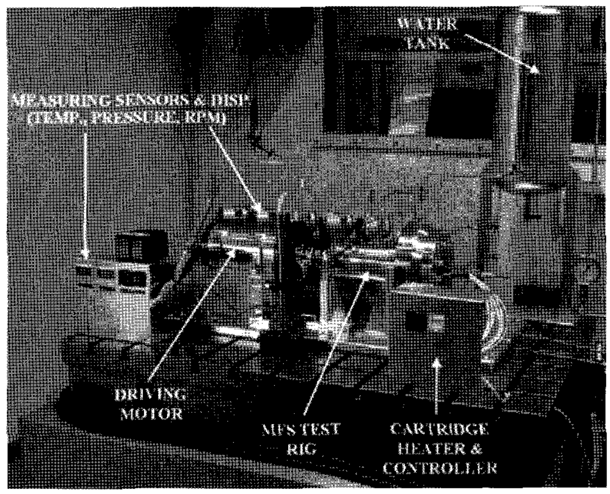

Fig. 4. Overview of mechanical face seal test rig.

difference of 400 kPa at nominal operating conditions. The linear velocity on the sealing surface is 70 m/s. According to the requirements, the mission time of turbopump for single operation is 120 seconds and 10 times of operation should be available. Thus the mechanical face seal should survive for 10 times of 120 seconds operation. The acceptance test was performed based on this life time requirement, 1200 seconds.

3. Acceptance Test

Generally a manufacturer of mechanical face seal strictly controls the quality to ensure reliability of mechanical face seal. A series of tests such as flatness check, spring rate check and vacuum leak test are performed before delivery to KARI. However considering the role of mechanical face seal in turbopump, the acceptance test simulating the practical operating conditions is necessary before the mechanical face seal is installed to turbopump. The acceptance test is composed of water leak test, performance test and endurance test. The water leak test is performed to check whether any leakage occurs under the practical installation condition. Normally a special test rig which has same dimensions and tolerances with the turbopump is manufactured and the mechanical face seal is installed into the test rig to perform the water leak test. The performance test is carried out by simulating the operating conditions including nominal rotational speed and pressure difference. Through the performance test, the amount of carbon wear and the leakage flow rate of working fluid are measured and evaluated. Finally the mechanical face seal undergoes the endurance test. During the endurance test, all operating conditions of the mechanical face seal including temperature difference are simulated.

Figure 3 provides the cross-sectional view of mechanical face seal test rig. A shaft with the mating ring is connected to motor and rotates during test. The bellows seal assembly is installed to the stationary casing of test rig and it is in contact with the mating ring during test. A cartridge heater is located at rear side of the bellows seal assembly to simulate the combustion gas from turbine. The actual working fluid in fuel pump is kerosene. Thus it is desirable to use kerosene for tests of the mechanical face seal. However instead of kerosene, water is used for the acceptance test owing to limitation of test facility. Nevertheless it is expected to obtain more conservative test results because lubrication characteristic of water is worse than one of kerosene.

Figure 4 shows the test facility for the acceptance test of mechanical face seal. The fuel pump side of mechanical face seal in the test rig is filled with water and connected to the water tank. During the test, the top of water tank is pressurized

Table 2. Operating conditions of mechanical face seal

No.	Event	Note
1	Measure the carbon thickness	Check initial carbon thickness before test
2	Assemble the test seal	
3	Measure the weight of water tank	To check the leakage during test
4	Drive motor	Up to test rpm
5	Pressurize	Up to test ÄP
6	Perform the test	
7	Stop motor	
8	De-pressurize	
9	Measure the weight of water tank	Check the leakage during test
10	Disassemble the test seal	
11	Measure the carbon thickness	Check the wear of carbon
12	Inspect	Check the seal failure

Table 3. Operating conditions of mechanical face seal

No.	Event	Note
1	Measure the carbon thickness	Check initial carbon thickness before test
2	Assemble the test seal	
3	Run the cartridge heater	Up to test temperature
4	Drive motor	Up to test rpm
5	Pressurize	Up to test ÄP
6	Perform the test	
7	Stop motor	
8	De-pressurize	
9	Stop the cartridge heater	
10	Disassemble the test seal	
11	Measure the carbon thickness	Check the wear of carbon
12	Inspect	Check the seal failure

with nitrogen gas to provide the pressure difference between the fuel pump side and the turbine side. A permanent magnet synchronous motor (PMSM) of 100 kW power is used to drive the test rig. The PID control is applied to temperature control of the cartridge heater.

As mentioned previously, the acceptance test includes water leak test, performance test and endurance test. In this paper the results of performance and endurance test are given. Table 2 gives the procedure of performance test of mechanical face seal. After step 5 in Table 2, the mechanical face seal reaches the test pressure and rotational speed. The test pressure and rotational speed are maintained constantly during single test period. The single test duration is adjusted from 120 seconds to 300 seconds conditionally by monitoring a vibration level of test rig. These tests are repeated until the elapsed test time reaches up to the required life time of mechanical face seal, 1200 seconds. Additionally the amount of carbon wear and the leakage flow rate of water are measured after every single test.

After the performance test, the endurance test is carried out and the procedure of endurance test is described in Table 3. Unlike the performance test, the high temperature atmosphere in turbine side is simulated by the cartridge heater instead of measuring the leakage flow rate. The single test duration is adjusted from 120 seconds to 300 seconds. After every single test the amount of carbon wear is measured. Also the seal failure is carefully examined.

4. Test Results

4.1. Performance test result

Figure 5 shows the one of results in performance test. Although the nominal rotational speed is 20000 RPM, the test was performed at 9911 RPM to find out an effect of rotational speed on carbon wear. Nominal test duration is 240 seconds. However the test duration is adjusted based on vibration level because the test speed exceeds the maximum speed of ball bearing in the test rig. The pressure difference was 820 kPa, which is more severe condition compared to the actual pressure difference of 400 kPa. Elapsed test duration is 1690 seconds.

In Fig. 5, it is found that the carbon thickness decreases with the lapse of time until 600 second. Then there is no change of carbon thickness. This means that the carbon wear does not occur after the specific stage of test although it is observed in the early stage. It is believed that, at the beginning of test, the mating ring and the bellows seal assembly is not in contact homogenously due to manufacturing tolerances. As carbon wear progress with the lapse of test time, the sealing surface between the mating ring and the bellows seal assembly is polished homogenously. Finally the sealing surface reaches to the steady-state without any carbon wear. A tendency of leakage flow rate supports this phenomenon, which converges on specific value with the test time. The average leakage is 0.05 gram/sec and this is ignorable compared to the flow rate of fuel pump.

Figure 6 shows the performance test result with the rotational speed of 19200 RPM. The pressure difference is 820 kPa and elapsed test time is 1800 seconds. Unlike the previous test result in Fig. 5, the carbon wear occurs constantly in a specific slope. This means that the life time of mechanical face seal is determined by the amount of carbon wear in a range of higher

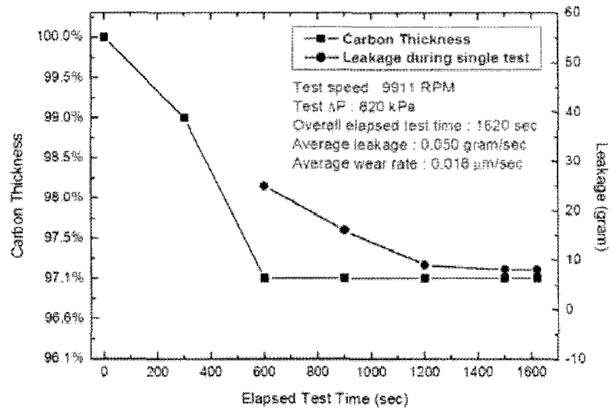

Fig. 5. Performance test result at 9911 RPM with ΔP = 820 kPa.

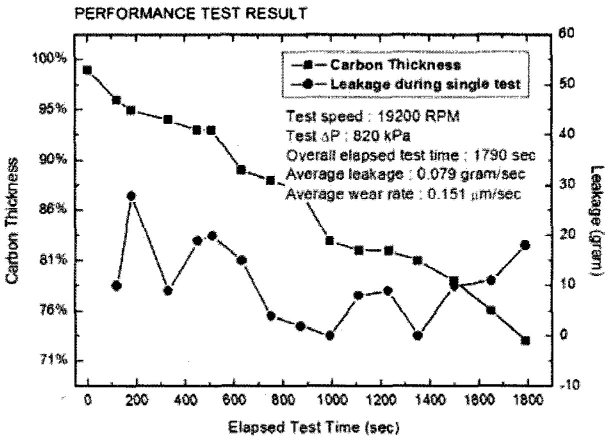

Fig. 6. Performance test result at 19200 RPM with ΔP = 820 kPa.

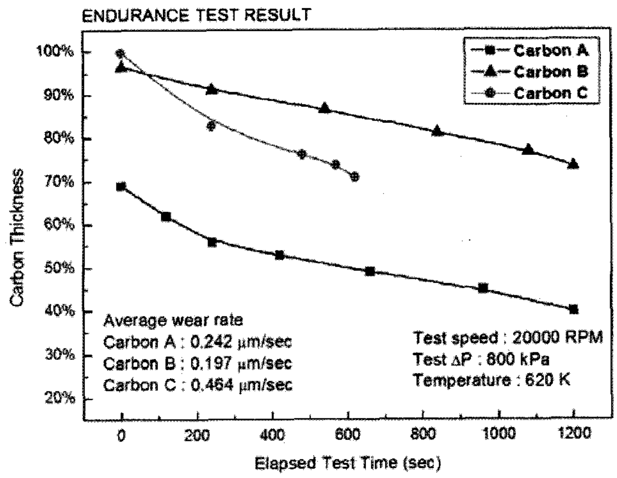

Fig. 7. Endurance test result at 20000 RPM with ΔP = 800 kPa, turbine side temperature of 620 K.

rotational speed. Considering the overall test time, the average wear rate of carbon is 0.151 μm/sec. The leakage varies from 2 grams to 28 grams. Likewise this is ignorable compared to the flow rate of fuel pump. From the standpoint of leakage and carbon wear, the mechanical face seal showed reasonable performance. Moreover any critical failure on mechanical face seal was not observed during the overall performance test.

4.2. Endurance test result

In the performance test, it is found that the life time of mechanical face seal mainly depends on the carbon wear. Thus the method of reducing the carbon wear is a key in enhancing the endurance of mechanical face seal. It is thought that many factors such as rotational speed, pressure difference and temperature have an effect on the carbon wear. However these factors are given as the operating conditions of mechanical face seal, so it is not possible to change for the durability enhancement of mechanical face seal. Practically only one option is possible: carbon material. Thus several carbon materials are conducted to the endurance test and listed in Table 4. The carbon A is the material used during performance test.

Figure 7 gives the result of endurance test according to the carbon materials. The rotational speed is up to 20000 RPM. The pressure difference is 800 kPa, which is two times higher than the design value of 400 kPa. The temperature of turbine side is 620 K. After every single test, the mechanical face seal is disassembled from the test rig and inspected. The thickness of carbon A in Fig. 7 is about 70% of initial thickness and this

Table 4. Carbon materials conducted to endurance test

	Carbon A	Carbon B	Carbon C
Impregnation	Salt	Salt	Salt
Density (g/cm^3)	1.84	1.78	1.85
Flexural strength (MPa)	70	40	58
Compressive strength (MPa)	150	120	150
Thermal expansion	5×10^{-6}/°C	4.6×10^{-6}/°C	4×10^{-6}/°C

Note: Carbon A is the same material which is used in the performance test

is because the carbon wear was occurred during the performance test. The carbon A, which is the same material conducted to the performance test, has the average wear rate of 0.242 μm/sec. Compared to the average wear rate of 0.151 μm/sec in Fig. 6, it is increased about 60%. Reminding that the rotational speed and the pressure difference correspond to those of performance test, it is believed that the increase of wear rate is mainly caused by high temperature in turbine side. The carbon B and C show the average wear rate of 0.197 μm/sec and 0.464 μm/sec, respectively.

Throughout the whole life time of mechanical face seal, the carbon thickness should not be less than 50% of the initial thickness. Thus from the standpoint of carbon thickness, the criteria is 50%. Considering the life time requirement of 1200 seconds and the average wear rate, the final thickness of carbon A is expected to be 70% of initial thickness. Also those of carbon B and C are expected to be 76% and 44%, respectively. Thus the carbon B has the finest wear resistance, while the carbon A also has the acceptable wear resistance. The mechanical face seals with the carbon A and the carbon B operated without any failure during the whole endurance test. Thus those mechanical face seals are possible to use for the turbopump. However the carbon C does not meet the criteria and it is not suitable.

5. Conclusion

The mechanical face seal is tested for turbopump applications. Under the practical operating conditions, the acceptance test including the performance test and the endurance test is carried out to guarantee the reliability of mechanical face seal. The performance test is conducted by simulating the nominal rotational speed and the pressure difference. Through the performance test it is found that the tendency of carbon wear depends on the rotational speed. Additionally it is also showed that the leakage flow is ignorable compared to the flow rate of fuel pump. The endurance test with three different carbon materials is also conducted and all operating conditions are simulated in accordance with the practical ones. Among the tested carbon materials, the acceptable candidates for the mechanical face seal of turbopump are found. Moreover the mechanical face seal successfully has operated without any failure during the whole endurance test. Consequently the reliability of mechanical face seal for turbopump is proved.

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