POLISH MARITIME RESEARCH 1(77) 2013 Vol 20; pp. 39-47
10.2478/pomr-2013-0005

Multi-stage magnetic-fluid seals for operating in water – life test procedure, test stand and research results

Part II

Results of life tests of multi-stage magnetic - fluid seal operating in water

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ABSTRACT

The edge criteria for magnetic-fluid seals durability research were described in previous article [24] and now the tests results are presented. The tests were made with three magnetic fluids using various magnets quantity in magnetic assemblies. If values obtained in the repeated test deviated by more than 10 % from results of the first test an additional control test was made for final characteristics. The characteristics are: critical pressure, critical motion velocity and working life of the seal. The test stands were prepared for particular seals dimensions and results of tests are presented in the form of tables, cross section draws and diagrams. In conclusion one can see that multi-stage magnetic-fluid seals could be efficiently used in water for rotating shaft seals in a limited range of motion velocity and cycles quantity. Nevertheless a particular applications can be provided by magnetic-fluid seals only.

Keywords: shaft sealing; magnetic fluid; utility water; seal durability; critical pressure; critical motion velocity

INTRODUCTION

This paper presents the most significant results of the research projects performed in the years 2009÷2012. All the projects were carried out on the test stands located at the Faculty of Mechanical Engineering and Robotics, Mining and Metallurgy Academy (AGH), Cracow, Poland.

As described in the first part of the paper [24] the research methodology of the performed projects ensured determination of static penetration pressure and limiting working speed of the seal for each of its tested versions. Each of the tests introduced important information which made it possible to draw seal life curve and determine the largest motion speed at which failure-free operation (lack of leakage) is possible up to the basic number of cycles (equal to 1 million rotations), assumed for the seal.

This author conducted the research projects on the application of magnetic fluid (MF) seals operating in utility water in collaboration with the Laboratory of Seals and Application of Magnetic Fluids, AGH, [12, 13, 14]. The tests performed on the research stand adjusted to operation of seal in liquids [15] showed that application of some commercial magnetic fluids to MF seals being in direct contact with water in operational conditions typical for ocean engineering, mainly to driving systems, is possible. In the tests which had an utilitarian character, multi-stage MF seals representing models of real MF seals were used and their operational conditions were limited to the selected technical task. In this paper, due to a limitation of its volume, only some example diagrams are presented.

1. RUN OF THE TESTS

In the tests in question the MASTL1 – V2 test stand was used. The stand contains a special test head intended for realizing the assumed research aims, driving system composed of an electric motor and its controller, as well as a measurement system composed of gauges and transducers for measuring pressure, motor's torque and operational temperature. The stand is fitted with multi-channel measuring instruments for measurement data acquisition, processing and recording. Their detailed description was given in the first part of the paper [24].

1.1. Tests of seal critical pressure

The tests of seal static critical pressure were performed in compliance with the procedure described in the paper titled "Multi-stage magnetic-fluid seals for operating in water – life test procedure, test stand and research results, Part 1." [24]. The pressure in the test chamber was gradually increasing up to occurrence of penetration of MF seal. The sealed medium was pure utility water. Value of seal static critical pressure is the basis for determining pressure values to be set to obtain the appropriate values of the relative pressure $\mathbf{p_r/p_{krI}}$ = 0.8, 1.6, 2.4, complying with the test programme. The tests were conducted for three magnetic fluids: FLS 040.040, FLA 002.25, FLA 003.45, with using 14 magnets in the magnetic system, and additionally with 10 and 18 magnets for the fluid FLA003.45. In all the tests the nominal gap height for magnetic fluid was equal to 0,1 mm at 100µl magnetic fluid dosage applied to each of the sealing stages. Each test was repeated. If values obtained in the repeated test deviated by more than 10 % from results of the first test an additional control test was made.

In Fig. 1.1 the example diagram of pressure run during determination of statical critical pressure is presented.

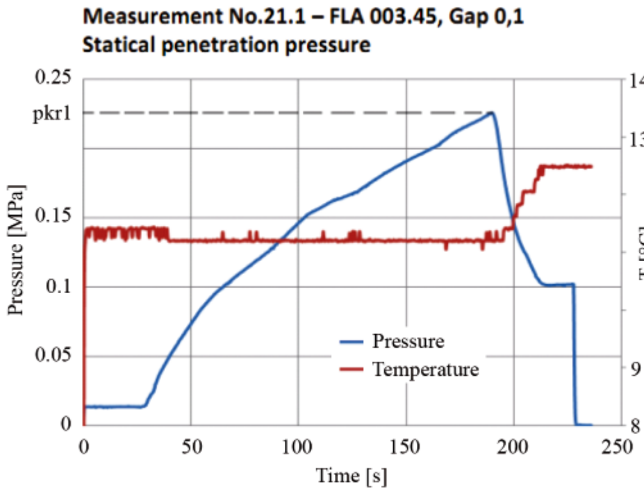

Fig. 1.1. The example diagram of determination of statical penetration pressure for the fluid FLA 003.45 at 0.1 mm gap height and three-stage sleeve: the pressure curve peak value represents the value of the statical penetration pressure (for the whole three-stage seal)

1.2. Tests of critical motion speed of MF seal

The tests of MF seal critical motion speed were performed to determine the lowest value of motion speed at which loss of sealing capability of a seal occurs "immediately". Information on critical motion speed value makes performing seal life test easier. The tests were conducted with gradually increasing speed in compliance with the procedure described in the first part of the paper, for the magnetic fluids: FLS 040.040, FLA 002.25, FLA 003.45, and with the use of the seals of 0.1 mm nominal gap height and 100 µl dosage of magnetic fluid applied to each sealing stage. According to the test programme relative pressure values were used. Each measurement was repeated to eliminate random results.

For FLA003.45 fluid additional measurements were made at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, 2.4 and 10 and 18 permanent magnets used in the magnetic system.

In Fig. 1.2 is presented the example diagram of run of determination of limiting penetration speed recorded during the tests.

1.3. Life tests of MF seal

The MF seal life tests were carried out to determine the seal motion speed at which MF seal life for the assumed seal operating conditions and gap geometry would be equal to 1mln cycles (number of rotations). To determine one-million-cycle life it was necessary to perform series of measurements at constant, but lower and lower for each successive measurement, seal motion speed. The series of measurements were started from a motion speed equal or close to a seal critical motion speed specific to a seal under the test. The tests were conducted

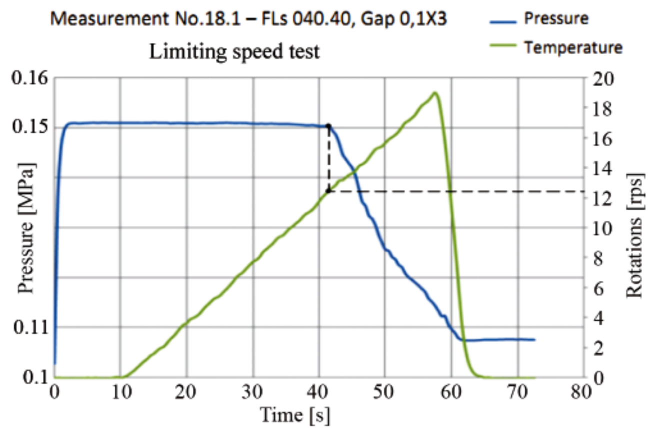

Fig. 1.2. The example diagram of determination of the seal critical speed for the fluid FLS 040.40 at 0.1 mm gap height and three-stage sleeve. The instance of exceeding the critical speed is signalled by sudden drop of pressure

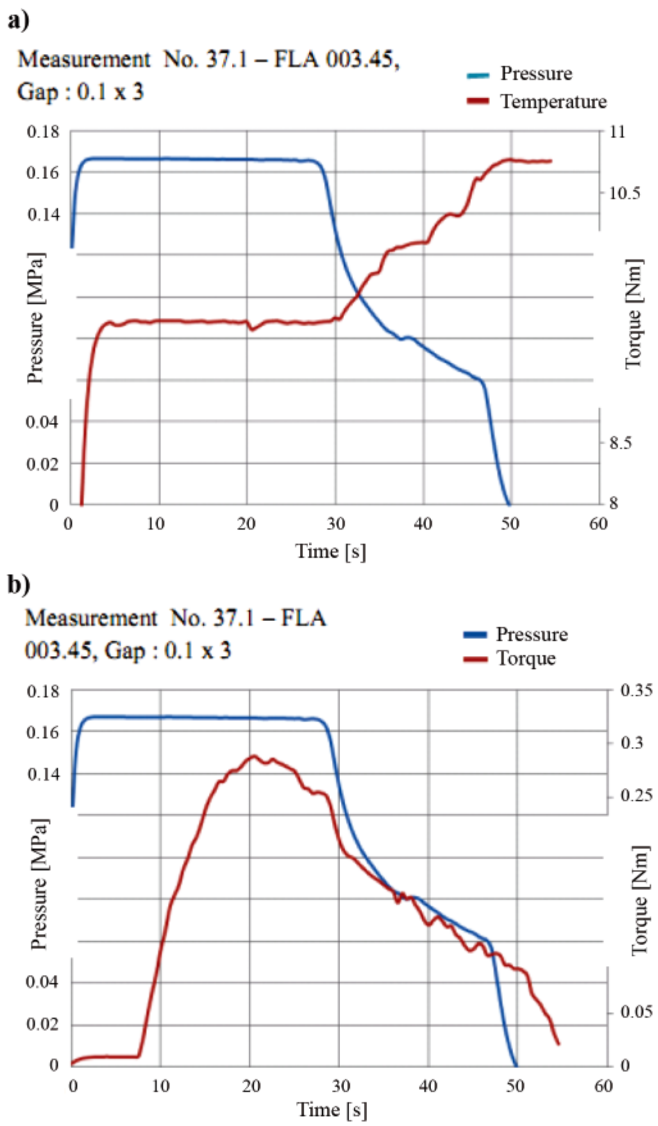

*Fig. 1.3. The example diagram of pressure and temperature runs in function of duration time counted from the instant of disclosure of a leakage. The MF seal with FLA 003.45 magnetic fluid at 10 rps; the relative pressure of 2.4, the gap height of 0.1 mm with 3 edges; **a)** temperature change of the seal during its leakage, **b)** change of drag- to-motion moment of the seal during its leakage.*

for three magnetic fluids: FLA 002.25, FLS 040.040, FLA 003.45, and with the use of the seals of 0.1 mm nominal gap height and 100 µl dosage of magnetic fluid applied to each sealing stage. The relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = = 0.8, 1.6, 2.4 were used. For FLA003.45 fluid additional measurements were performed with 10 and 18 permanent magnets used in the magnetic system in accordance with a respective programme.

The life criterion will be satisfied if during the test at an assumed shaft rotational speed no leakage is observed after one million of cycles, then the test is stopped and the speed is considered to be corresponding to one-million-cycle life. In Fig. 1.3 the example diagrams of run of MF seal life test, is presented. In Fig. 1.3a is shown an increase of temperature at the instant of leakage, caused probably by penetration of water of a higher temperature into cooled zone of the seal. In Fig. 1.3b is shown a drop of moment of drag to motion of the seal at the instant of leakage, caused by loss of the magnetic fluid from the seal. During this test the leakage was very intensive.

2. RESULTS OF THE TESTS

The test results are collected in the form of tables, curves and diagrams. In the tables are given values of test parameters and measurement results obtained during the tests, and on the curves and diagrams are shown values of the achieved results in function of the parameters of the tested seals or of test running time.

The test results for three kinds of the tested magnetic fluids are elaborated seperately for each of the standard research tests:

- total statical critical pressure of a seal,
- critical motion speed of a seal,
- long-term operation speed of a seal.

On the curves and diagrams are presented the obtained values in function of particular testing factors, as well as in the form of comparisons of various parameters of the tests.

All the tests were conducted with the use of the same sleeve with three sealing stages, at 0.1 mm gap and 100 µl dosage of magnetic fluid applied to each of the gap. A variable design parameter was number of permanent magnets in the magnetic system: 14 magnets were used for three kinds of the tested magnetic fluids, and additionally 10 and 18 magnets in the tests with FLA 003.45 magnetic fluid.

2.1. Test results of total statical critical pressure of the seal

In Fig. 2.1 are shown the penetration pressure values for the seal with three sealing stages, obtained from the tests with three tested magnetic fluids. The penetration pressure measurements were made after one hour of fluid stabilization in the seal.

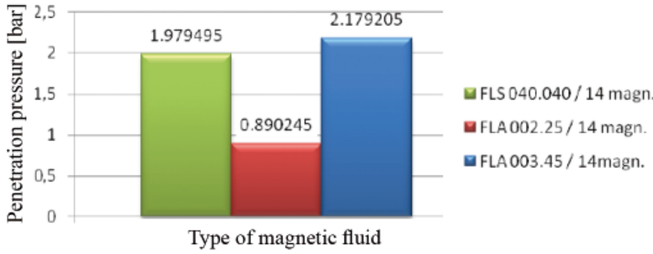

Fig. 2.1. *Comparison of values of the total statical critical pressure for three tested magnetic fluids*

In the successive series of the tests were determined penetration pressure values for the seal of three sealing stages, obtained for FLA 003.45 magnetic fluid from the testing with the use of different number of permanent magnets in the sealing system. In all the tests 100 µl dosage of magnetic fluid was applied to each sealing stage.

2.2. Test results of critical speed of the seal

In Tab. 1 are collected the critical speed test results at different values of relative pressure for three magnetic fluids and 14 magnets used in the magnetic system of the seal.

Tab. 1. *Test results of critical speed for MF seal. Number of permanent magnets in the magnetic system: 14*

Relative pressure $\mathbf{p_r/p_{krI}}$	FLA 00.2.25	FLA 003.45	FLS 040.040
	Critical speed [rps]		
0.8	> 100	> 100	90
1.6	80	83	47
2.4	76	10	12

In Fig. 2.2 are shown the results of limiting speed tests for three magnetic fluids at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, with 14 permanent magnets.

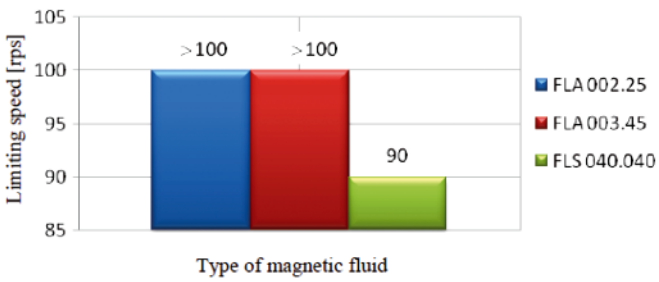

Fig. 2.2. *Comparison of limiting speed values for the tested magnetic fluids at the relative pressure* $\mathbf{p_w = p_r/p_{krI}}$ *= 0.8, and with 14 permanent magnets used in the sealing system*

In the case of two magnetic fluids the critical speed exceeded the value of 100 rps at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = = 0.8. Because of mechanical limitations in operation of the test stand it was not possible to increase the rotational speed of the seal in question. In the successive test series were obtained measurement results of critical speed for three magnetic fluids at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 and 14 magnets used in the sealing system, and the critical speed values of the tested fluids were compared to each other at the relative pressure $\mathbf{p_w}$ = = $\mathbf{p_r/p_{krI}}$ = 2.4 and 14 magnets.

When comparing the critical speeed values obtained for the magnetic fluids at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 2.4 attention should be paid to significant differences between real pressure values set in the test chamber. During the tests with FLA 003.45 and FLS 040.040 fluids the pressure in the test chamber was over twice higher than that assumed in the tests with FLA 002.25 fluid. It indicates significant influence of absolute pressure value on operational efficiency of MF seals working in water. Influence of magnetic field on limiting speed for FLA 03.45 fluid was tested additionally at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 and different number of magnets in the magnetic system of the seal. It was demonstrated that along with increasing number of magnets installed in the test head (i.e. increasing magnetic flield intensity) critical speed value for FLA 003.45 fluid also increases.

Tab. 2. Results of seal life tests in function of seal motion speed for FLA 002.25 magnetic fluid

Stabilization time: 1h	**Kind of magnetic fluid**	**Statical critical pressure of the seal: total value /value per one stage. p_{krIII}/p_{krI} [MPa]**	**Number of magnets in the sealing system**
Nominal gap height: 0.1 mm	FLA 002.25	0.0890245/0.0296748	14
Relative pressure (set pressure) $p_w = p_r/p_{krI}$ (p_r) [MPa]	**Critical speed [rps]**	**Rotational speed [rps]**	**Number of rotations to leakage (time of operation [h])**
0.8 (0.023)	over 100	100	1700 (0.00472)
		80	1840 (0.00639)
		60	99936 (0.4627)
		45	2251800 (13.9) No leakage. exceeded 1mln rotations
1.6 (0.047)	80	80	80 (0.05383)
		70	2450 (0.00972)
		50	171780 (0.2071139)
		30	257040 (2.38)
		20	388800 (5.4)
		10	648000 (18)
		5	100000 (55.6) No leakage. exceeded 1mln rotations
2.4 (0.071)	76	76	356 (0.02583)
		70	3000 (0.01389)
		30	5400 (0.05)
		5	34200 (1.9)

Notations which appear on the below presented drawings, are explained on the example of Fig. 2.3:

FLA 002.25 - symbol of the tested magnetic fluid

$z = 3$ - number of stages of the test sleeve

$\delta = 0,1$ - height of the test gap, [mm]

$P_r = 0.023$ - value of the set operational pressure, [Mpa]

$p_r/p_{krI} = 0.8$ - the relative pressure equal to 0.8, the ratio of the set operational pressure p_r and the statical critical pressure per one stage, p_{krI}, (in the case of three-stage sleeve: 1/3 of the total penetration pressure)

353532.6 - full distance passed by the seal up to leakage occurrence, [m].

2.3. Life test results of the seal with the basic number of permanent magnets in the magnetic system (equal to 14 pieces)

In Tab. 2 are collected the life test results of the seal with FLA 002.25 magnetic fluid and 14 magnets installed in the head. Number of rotations to leakage constitutes a seal life measure.

In Fig. 2.3 is presented the diagram of number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 0.8. On the diagram is shown the trend line in the form of the function:

$$y = -6.47\ln(x) + 137.7$$

In Fig. 2.4 is presented the diagram of number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 1.6. On the diagram is shown the trend line in the form of the function:

$$y = -7.88\ln(x) + 123.7$$

In Fig. 2.5 is shown the diagram of number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 2.4. On the diagram the trend line is given in the form of the function:

$$y = -22.94\ln(x) + 241.39$$

The successive series of tests were conducted for different kinds of magnetic fluids, i.e. the FLA 003.45 and FLS 040.040, as well as with different numbers of magnets located circumferentially: 10, 14 and 18. Relevant tables and diagrams are not included in the paper due to limitation of its volume.

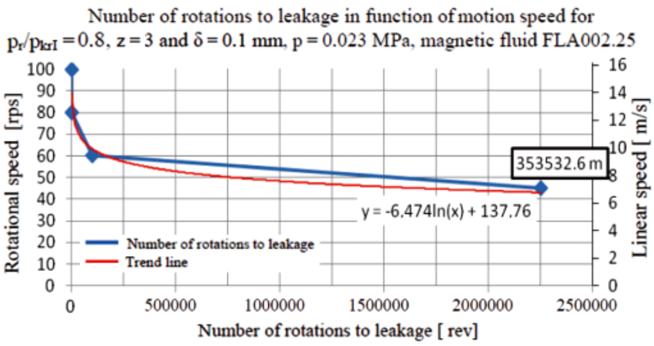

Fig.2.3. Number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the set operational parameters

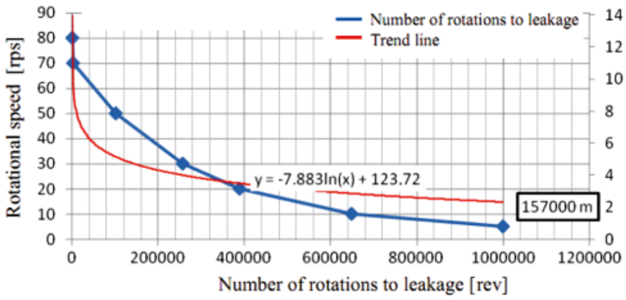

Fig. 2.4. Number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the set operational parameters

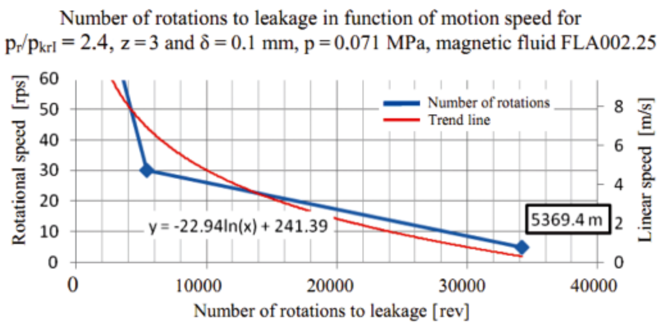

Fig. 2.5. Number of rotations to leakage in function of motion speed of the seal with FLA 002.25 magnetic fluid at the set operational parameters

3. COMPARISON OF TEST RESULTS

Series of the tests aimed at determination of MF seal life in function of magnetic field intensity, external pressure and kind of magnetic fluid, were performed.

3.1. Seal life in function of magnetic field intensity in the system

In Fig. 3.1 are presented the diagrams of number of rotations to leakage in function of rotational speed of the seal for different values of magnetic field intensity in the gap filled with magnetic fluid, dependent on number of magnets applied in the magnetic system of the seal. Results of the tests for FLA 003.45 magnetic fluid at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 and with 10, 14 and 18 permanent magnets used in the sealing system, were compared to each other.

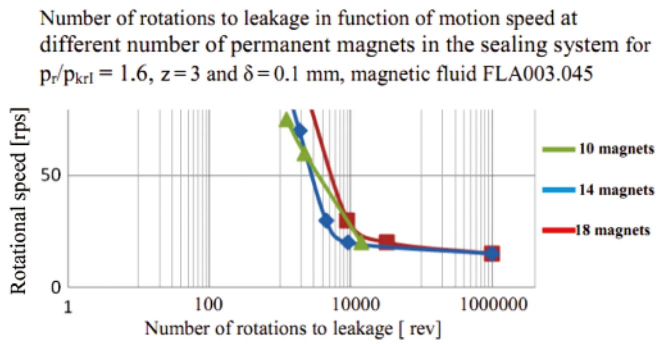

Fig. 3.1. Influence of change in magnetic field intensity on number of rotations to leakage in the seal

3.2. Seal life in function of set value of relative pressure

In Fig. 3.2 are presented the diagrams of number of rotations to leakage in function of rotational speed for different values of relative pressure set in the tests with FLA 002.25 magnetic fluid. The tests were carried out at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, 2.4 and the same number of magnets equal to 14.

In Fig. 3.3 are presented the diagrams of number of rotations to leakage in function of rotational speed for different values of relative pressure set in the tests with FLA 003.45 magnetic fluid. The tests were carried out at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, 2.4 and the same number of magnets equal to 14.

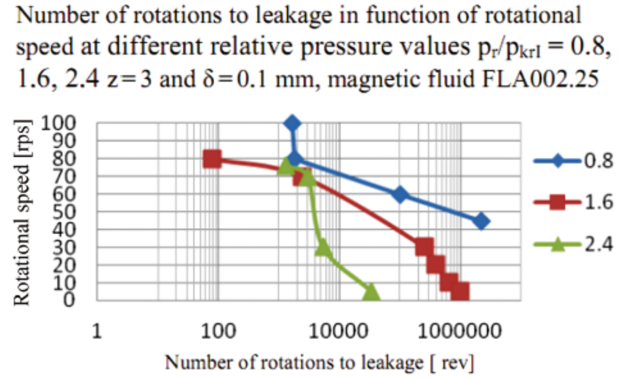

Fig. 3.2. Number of rotations to leakage in function of rotational speed at different relative pressure values for FLA 002.25 magnetic fluid

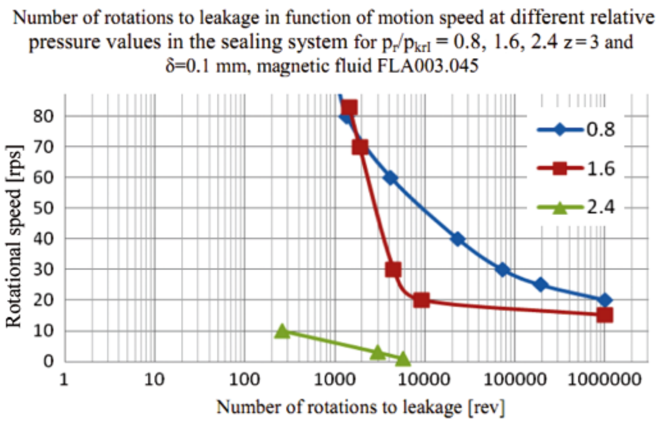

Fig. 3.3. Number of rotations to leakage in function of rotational speed at different relative pressure values for FLA 003.45magnetic fluid

In addition, were investigated and determined numbers of rotations to leakage in the seal in function of rotational speed for different values of relative pressure set in the tests with FLA 040.040 magnetic fluid, i.e. at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, 2.4, and the same number of magnets equal to 14. The tests were repeated for different values of relative pressure set in the tests with another magnetic fluid, i.e. FLA 003.45, and 10 magnets applied in the magnetic system. The tests were carried out at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, 2.4.

3.3. Seal life in function of kind of magnetic fluid

In Fig. 3.4 are presented the diagrams of number of rotations to leakage in function of rotational speed for three magnetic fluids: FLA 002.25, FLA 003.45 i FLS 040.040, at the set relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 0.8. The tests were carried out in the magnetic system with 14 magnets.

Moreover, were investigated and determined numbers of rotations to leakage in the seal in function of rotational speed for three magnetic fluids: FLA 002.25, FLA 003.45 i FLS at the relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 and with 14 magnets used in the magnetic system.

The tests were repeated and numbers of rotations to leakage in function of rotational speed were determined also for three magnetic fluids: FLA 002.25, FLA 003.45 i FLS 040.040 but at the set relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 2.4. The tests were carried out in the magnetic system of 14 magnets.

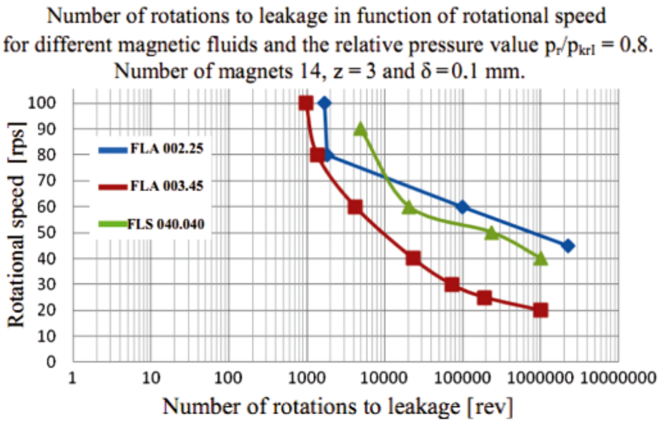

Fig. 3.4. Number of rotations to leakage in function of rotational speed for different magnetic fluids and relative pressure value equal to 0.8

3.4. Rotational speed for seal life of one million number of rotations

In Tab. 3 are presented the rotational speed values at which, during testing the seals, one million number of rotations was exceeded. The table contains results obtained for three magnetic fluids at different numbers of magnets, i.e. 10, 14, 18, in the magnetic system and different relative pressure values $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 0.8, 1.6, 2.4.

Tab. 3. The rotational speed values at which one million number of rotations was exceeded, in function of number of magnets in the magnetic system, for three magnetic fluids and different relative pressure values $p_w = p_r/p_{krI}$ = 0.8, 1.6, 2.4

Number of magnets	Kind of magnetic fluid	Rotational speed values [rps]		
		Relative pressure $p_w = p_r/p_{krI}$		
		0.8	1.6	2.4
14	FLA 002.25	45	5	below 5
14	FLA 003.45	20	15	below 1
14	FLS 040.040	40	10	2
10	FLA 003.45	20	below 20	10
18	FLA 003.45	not tested	not tested	not tested

In Fig. 3.5 is presented a comparison of rotational speed values for three tested fluids, at which one million number of rotations was reached at the relative pressure $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = = 0.8.

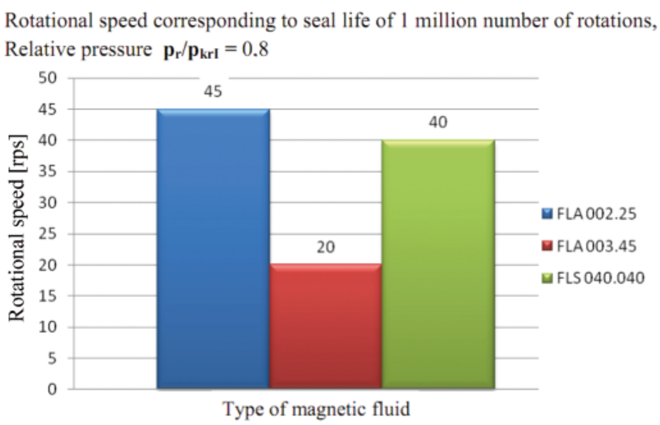

Fig. 3.5. Comparison of rotational speed values at which one million number of rotations was reached for three tested fluids at the relative pressure $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 0.8

The tests were repeated for the tested fluids at the relative pressure values $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 1.6 and 2.4, respectively.

Fig. 3.6 is shown a comparison of rotational speed values at which the condition of reaching 1 mln number of rotations was fulfilled for particular fluid FLA002.25 at three relative pressure values $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 0.8, 1.6, 2.4.

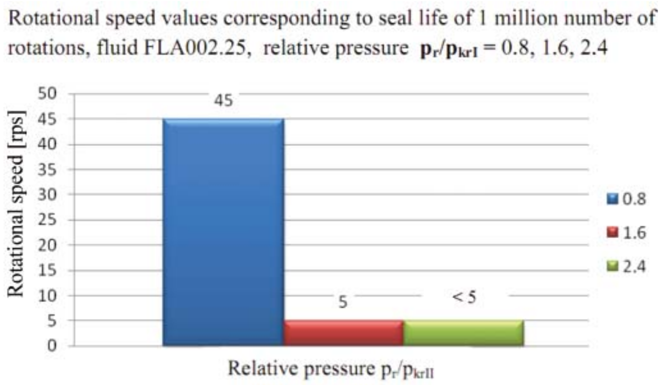

Fig. 3.6. Comparison of rotational speed values at which one million number of rotations was reached for FLA 002.25 fluid at the relative pressure values $p_w = p_r/p_{krI}$ = 0.8, 1.6, 2.4

The tests were repeated for the magnetic fluids: FLA 003.45 and FLS 040.040, at the relative pressure values $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 0.8, 1.6, 2.4 and in configurations with 10, 14 and 18 magnets.

In Fig. 3.7 is presented an example comparison of rotational speed values at which the condition of reaching 1 mln number of rotations was fulfilled for FLA 002.25 magnetic fluid at three relative pressure values $\mathbf{p_w} = \mathbf{p_r/p_{krI}}$ = 0.8, 1.6, 2.4 and with decreased number of magnets in the sealing system, i.e. 10 pieces.

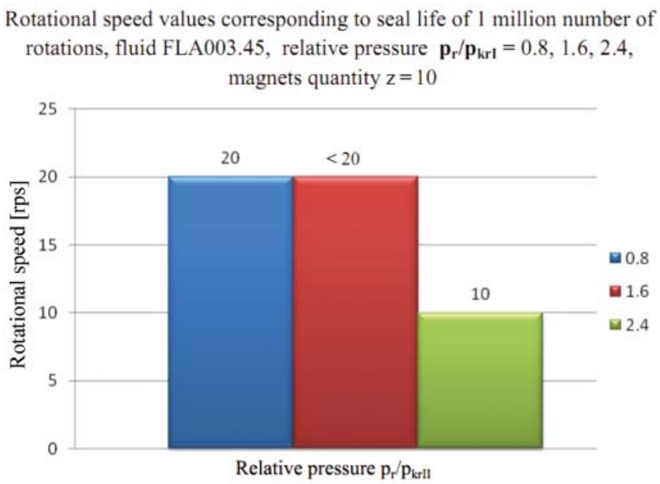

Fig. 3.7. Comparison of rotational speed values at which one million number of rotations was reached for FLA 002.25 fluid at the relative pressure values $p_w = p_r/p_{krI}$ = 0.8, 1.6, 2.4 and with decreased number of magnets in the sealing system, i.e. 10 pieces

4. DISCUSSION OF TEST RESULTS

In the frame of the conducted experimental projects on the MF seal with three sealing stages operating in water, three kinds of magnetic fluid were tested in conditions of different values of factors which influence operational effectiveness of the seal. The three effectiveness measures were applied:

- critical pressure of the seal (penetration pressure),
- critical motion speed („immediate" penetration motion speed),
- motion speed for a limited seal life (motion speed for one-million-cycles life).

The two external factors and one design factor affecting seal operation were taken into account:

- external factors:
  - water pressure in the test chamber,
  - seal motion speed,
- design factor:
  - number of magnets in magnetic system of the seal.

To estimate influence of the factors on the seal, 120 test runs lasting from about 1 hour up to over 30 hours, were performed.

The test results were elaborated separately for each kind of the performed tests (critical pressure, critical speed, long-term operation speed), and then they were compared mutually to make it possible to assess operational features of the seals working with different magnetic fluids and in different external conditions.

4.1. Critical pressure tests of the seal

Results of the tests are presented in Fig. 2.1 and 2.2. In each case the total critical pressure $\mathbf{p_{krI}}$ of the seal with three sealing stages was tested by using 100μl magnetic fluid dosage per one stage.

In the tests of the seals with 14 magnets the highest critical pressure value equal to 0.217 MPa was achieved for FLA 003.45 magnetic fluid of the saturation magnetization M_s = 45 kA/m [17]. A little lower value equal to 0,198 MPa was obtained for FLS 040.040 magnetic fluid for which the value of M_s = (40 ÷ 50) kA/m was specified by its producer [17]. It seems that for the tested fluid the value of $M_s \approx 40$ kA/m is more realistic. For FLA 002.25 magnetic fluid of the saturation magnetization M_s = 25 kA/m the critical pressure value equal to 0,089 MPa was obtained.

The tests on FLA 003.45 magnetic fluid with the use of 10 and 18 permanent magnets show that either at this smaller or greater number of magnets used in the magnetic system the critical pressure value was lower than that obtained for 14 magnets.

4.2. Critical speed tests of the seal

The critical pressure is defined as the smallest value of rotational speed at which – at given constant values of parameters – a leakage occurs during continuous increasing the rotational speed from 0 to its maximum value of 100 rps. As the maximum value of rotational speed was limited by torque meter characteristics in some cases it was not possible to determine this value because it exceeded the 100 rps - limit. The critical speed was tested at each of three relative pressure values, for each of the magnetic fluids. For FLA 003.45 magnetic fluid the tests were also performed with the use of different number of permanent magnets (in configurations of 10, 14, and 18 magnets).

The test results are collected in Tab. 1 and presented in Fig. 2.3 through 2.6. In the tests, at the relative pressure values $\mathbf{p_w = p_r/\ p_{krI}}$ = 0,8 and $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 the greatest limiting speed values were observed for FLA 002.25 and FLA 003.45 magnetic fluids. In the tests at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = = 0.8 the 100 rps speed value was exceeded for both the fluids, whereas at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 the speed values amounted to 80 and 83 rps, respectively. However the magnetic fluids in question produced on the basis of the same primary liquid - SILOXAN, greatly differ to each other in saturation magnetization value: M_s = 25 kA/m and M_s = 45 kA/m, respectively. And, smaller limiting speed values were obtained in the tests with the use of FLS 040.040 magnetic fluid produced on the basis of silicon liquids.

In the tests at the relative pressure $\mathbf{p_w = p_r/p_{krI}}$ = 2.4 the greatest limiting speed value equal to 76 rps was achieved in the tests with the use of FLA 002.25 fluid of the smallest saturation magnetization value. The limiting speed values for the remaining fluids are about six times smaller despite their almost twice greater saturation magnetization. It should be taken into consideration that absolute pressure values set in the tests with FLS 040.040 and FLA 003.45 fluids were significantly greater than that used in the tests with FLA 002.25 fluid. The value resulted from the assumed test concept according to which absolute pressure values are derived from relative pressure values: $\mathbf{p_w = p_r/p_{krI}}$. Since great differences appeared between statical penetration values for the magnetic fluids in question, pressure values set in the tests with FLA 002.25 magnetic fluid were consequently much lower than those set in the tests with the remaining fluids.

In the limiting speed tests at the number of magnets: 10, 14, 18, performed with the use of FLA 003.45 magnetic fluid at the relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 1.6 (Fig.2.6) the greatest limiting speed value of 91 rps was obtained for 18 magnets, and the smallest value of 75 rps for 10 magnets in number.

4.3. Life tests of the seal

Life of MF seals was the most thoroughly investigated issue in this research project. In most of the tests the number of cycles (number of rotations) performed by a seal up to leakage was taken as its life criterion. Full sets of the tests with 14 permanent magnets in the magnetic system and at the relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, and 2.4 were performed for three kinds of magnetic fluids described in article [24]. The tests were aimed at checking relation between number of performed cycles and rotational speed set in test.

For FLA 003.45 magnetic fluid were additionally performed tests with 10 and 18 magnets installed in the test head. One million rotations of the seal were assumed to be the basic number of cycles. For so defined basic number of cycles was determined the largest motion speed at which no leakage was observed in the tested seal. The quantity was called one-million-cycle life. It should be stressed that in some tests for the above mention speed a greater number of cycles without leakage was achieved, whereas in other tests it was decided not to continue running up to the basic number of 1 mln cycles as it would require to do long-lasting tests not planned in the project in question.

The results of the seal life tests are collected in Tab. 2 through 6 and shown on the diagrams in Fig. 2.7 through 3.6

The seal life diagrams for three kinds of magnetic fluids tested at three relative pressure values $\mathbf{p_w = p_r/p_{krI}}$ = 0.8, 1.6, and 2.4 indicate large differences in values of the speed for which number of cycles to leakage, corresponding to them, was obtained. The differences appear both if to compare the tests for particular fluids at different relative pressure values and if they concern comparison of the results obtained from the tests of different kinds of fluids.

The largest speed for long-term operation was reached in the test with FLA 002.25 fluid at the relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 0.8. It was equal to 45 rps, and in the test the basic number of 1 mln cycles was exceeded. The smallest speed for long-term operation was reached in the test with FLA 003.45 fluid at the relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 2.4.

It was equal to 1 rps, and in the test the basic number of cycles was not reached. However it should be stressed that in the test with FLA 002.25 fluid in which the largest long-term operation speed was obtained the pressure set in the test was equal to 0.0232 MPa, whereas in the test with FLA 003.45 fluid, in which the smallest motion speed was obtained, the set pressure was equal to 0.1824 MPa. The experimental data obtained from all the tests were approximated by logarithmic trend lines of different coefficients depending on a given test.

The seal tests under different magnetic field intensity (different numbers of permanent magnets in the magnetic system of the seal) were performed for FLA 003.45 magnetic fluid at the relative pressure value $\mathbf{p_w = p_r/p_{krI}}$ = 1.6. Comparison of results of the tests indicates that the largest limiting speed of 91 rps was obtained in the test with the use of the magnetic system of the highest magnetic field intensity (18 permanent magnets). And, the values of operational speed for the basic number of 1 mln cycles without leakage were close to each other. From the comparison of the results the value of about 15 rps was achieved.

5. RECAPITULATION AND CONCLUSIONS

According to the applied testing methodology it was decided, for each tested version of the seal, to determine the following:

- statical penetration pressure of the seal,
- limiting operational speed of the seal.

Each of the measurements introduced important information which made it possible to reach the research aim as follows:

- to determine seal life curve and the highest motion speed for which it is possible to achieve, without leakage, the basic number of cycles (rotations) equal to 1 mln as assumed for the tests in question.

In the tests water pressure value set in the measurement chamber was a crucial factor. The factor was accounted for in the form of the relative pressure defined as the ratio of the set pressure and the critical pressure i.e. the seal penetration pressure per one sealing stage, determined in the statical test, ($\mathbf{p_w = p_r/p_{krI}}$).

The using such concept of setting the testing pressure of water made it possible to simply account for influence of the factor on seal life for particular magnetic fluids, but in the same time it made comparing life values of different fluids more difficult because of large differences in set testing pressures resulting from highly different values of the statical penetration pressure of the tested magnetic fluids. For instance the highest long-term operational speed equal to 45 rps was reached in the tests with FLA 002.25 magnetic fluid at the set pressure value of 0,0237 MPa ($\mathbf{p_w = p_r/p_{krI}}$ = 0.8) resulting from its low penetration pressure value equal to 0,0297 MPa per one sealing stage. As in the analogous test at the value $\mathbf{p_w = p_r/p_{krI}}$ = = 0.8 for FLA 003.045 fluid (of the penetration pressure per one sealing stage equal to 0.072 MPa) it was required to set the water pressure of 0.058 MPa, the long-term operation speed of the seal with the fluid in question amounted to 20 rps only. The results show that the pressure greatly influences life of MF seal operating in water.

The limiting operational speed of seal constitutes an important testing information as it makes it possible to estimate speed value from which determining seal life curve should be started - and consequently – determining the seal life for the basic number of cycles equal to 1 mln. However this parameter is not very important from practical point of view.

The tests with various numbers of magnets in the sealing system revealed influence of magnetic field intensity on limiting speed of magnetic fluids, but they did not confirm a significant influence of the factor on life of MF seals operating in water.

Results of the life tests for majority of the tested magnetic fluids and seals show similar picture on the diagrams. At higher rotational speed values a short period of operation to leakage (small number of cycles) is observed. At lower motion speed values failure-free operation period is much longer and distinctly tends to the speed value which could be taken as that for long-term operation. Such character of seal life curve could be best described by a logarithmic trend line.

The performed tests make it possible to offer the following conclusions:

1. The tests confirmed correctness of the assumed testing methods.
2. The test stand design is appropriate and allows to carry out the tests correctly.
3. The tested magnetic fluids produced on the basis of liquids with strong hydrophobic properties (silicon liquid, siloxan) may be applied to rotational seals operating in water, however only in a limited range of motion speed.
4. The tests confirmed that the assumed research hypotheses were right:
   - Motion speed influences life of MF seal operating in water: at lower speed values a significant increase of seal life is observed.
   - Water pressure influences MF seal life: at higher pressure values set in the tests a significant decrease of MF seal life is observed.
5. For each of the tested fluids it was possible to determine a motion speed value at which the assumed life of 1 mln cycles (number of rotations) was reached without any leakage from the seal.
6. The seal life diagrams for different motion speed values indicate that for each of the fluids can be observed a range of speed values below which a significant extension of failure – free operation period of the seal occurs. The process is probably associated with Kelvin – Helmholtz phenomenon of instability [2, 3, 11].
7. Value of statical penetration pressure depends on the saturation magnetization intensity of magnetic fluid, M_s.
8. Magnetic field intensity in the seal system only slightly influences the increasing of statical penetration pressure values of the seal. In the tests with the use of 18 permanent magnets, only a small decrease of the penetration pressure was observed in comparison with that obtained in the tests with 14 permanent magnets.
9. Magnetic field intensity has a low influence on a rotational speed value at which the basic value of seal life equal to 1 mln rotations is obtained.

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