INVESTIGATION OF THE HYDRODYNAMIC PRESSURE IN THE CLEARANCE BETWEEN FRICTION ELEMENTS OF END-FACE SEALS

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G. I. Shkurupii, L. I. Mamon, and M. A. Lokshin

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The hydrodynamic pressure of the working medium formed in the clearance h between the friction elements of an end-face seal (Fig. 1) tends to disengage the friction surfaces, thus causing the failure of the seal. The magnitude and the nature of the distribution of this pressure over the width of the contact surface 1 depends on the pressure p_n of the working liquid, the mean specific pressure p_s, the mean sliding velocity v_{av}, the viscosity of the working liquid, the roughness of the surfaces involved, and on other factors.

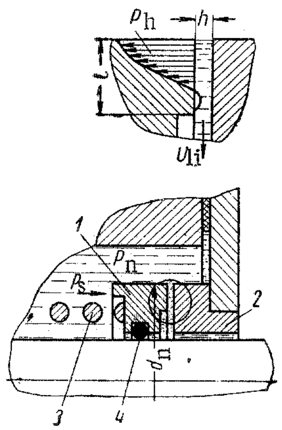


Fig. 1. Schematic diagram showing the internal end-face seal: 1) rotating sleeve; 2) stationary sleeve; 3) spring; 4) sealing element.

Some authors [1-3] neglect the effect of the specific pressure and believe that the distribution of the hydrodynamic pressure over the width of the contact surface shows only a small deviation from the linear law. For determining the type of distribution of the hydrodynamic pressure Mayer and Denny [4, 5] carried out tests in which the hydrodynamic pressure was measured by pressure gauges connected to capillary holes drilled in the contact surface of the stationary sleeve.

In the paper referred to, Denny did not arrange the data systematically and did not determine the dependence of the pressure distribution on the working conditions of the seal. Mayer showed that the hydrodynamic pressure exceeds the pressure of the liquid being sealed in the case of friction surfaces the roughness of which is more than 3 μ and that the pressure is absent in the case of friction surfaces with irregularities of less than 3 μ.

In order to clarify the causes of the formation and the character of distribution of the hydrodynamic pressure the authors carried out tests at various pressures of the sealed liquid (p_n = 1-12 kg/cm^2), specific pressures (p_s = 1-10 kg/cm^2), and average sliding velocities (v_{av} = 0.5-18 m/sec). The tests were carried out with kerosene, AK-10 oil, and P-28 oil at body temperature not exceeding 27°C. The width of the contact surface was 4.5, 8.5, and 14 mm for a constant external diameter d_n = 80 mm. The finish of the contact surfaces was of the 9-10th class. The rotating contact sleeve was made of "45" steel (hardened to HRC 54) while the stationary sleeve was made of Br. OF 4-0.25 bronze.

The work was carried out systematically on a special machine, the main subassembly of which is shown in Fig. 2 [6].

The results obtained in measuring the hydrodynamic pressure of different media are given in Figs. 3-6 and in the table.

Figure 3 shows the distribution of the hydrodynamic pressure as a function of the pressure of the liquid being sealed and the specific pressure. At pressures of the sealed liquid below the specific pressure (see curve for p_n = 1 kg per cm^2), the hydrodynamic pressure in the clearance is absent or insignificant. In this case the liquid film does not separate the friction surfaces completely. The thickness of the liquid film has a value close to zero while leakage of the liquid is absent (see table).

When the pressure of the liquid was increased to 3 kg/cm^2, the thickness of the liquid film increases, causing an insignificant leakage while a hydrodynamic pressure is produced in the clearance. The curve representing the pressure

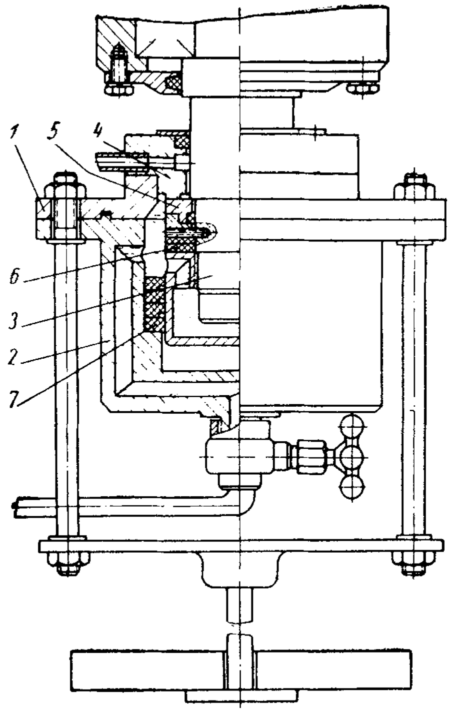


Fig. 2. Part of experimental apparatus: 1) cover; 2) body; 3) shaft; 4) stationary sleeve; 5) rotating sleeve; 6) elastic element; 7) additional seal; 8) weight.

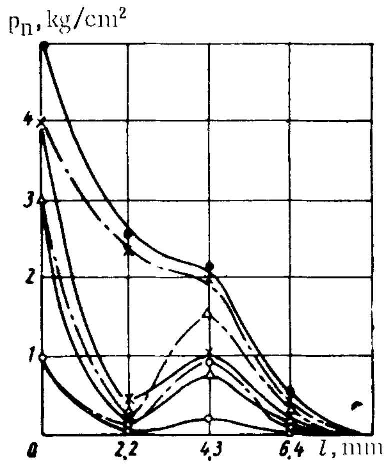


Fig. 3. Dependence of the distribution of the hydrodynamic pressure of AK-10 oil in the clearance between friction elements on the pressure of the liquid being sealed and on the specific pressure at v_{av} = 3 m/sec, l = 8.5 mm: —·—·—·) p_s = 5 kg/cm²; ——) p_s = 2 kg/cm²; O) p_n = 1 kg/cm²; Δ) p_n = 3 kg/cm²; x) p_n = 4 kg/cm²; ●) p_n = 5 kg/cm².

Testing of End-Face Seal in AK-10 Oil with l = 8.5 mm

Mean sliding speed v_{av}, m/sec	Mean spec.pressure p_s, kg/cm²	Total load on seal, kg	Pressure in working medium p_n, kg/cm²	Hydrodynamic pressure p_h, kg/cm²	Hydrodynamic force P_f, kg	Clearance height h, μ	Leakage U_{li}, cm³/h	$\frac{p_h}{p_n}$
3,0	2,0	38,0	1,0	0,21	4,3	0,7	—	0,21
			2,0	0,55	8,1	1,4	2,0	0,27
			3,0	0,74	14,2	2,2	14,2	0,25
			4,0	1,8	31,2	3,0	45,0	0,33
			5,0	2,1	38,5	6,8	150,0	0,42
10,0	2,0	38,0	1,0	0,33	8,6	1,8	1,5	0,33
			2,0	0,64	13,4	2,5	7,0	0,32
			3,0	1,1	18,7	3,8	20,0	0,36
			4,0	1,65	33,3	6,0	85,0	0,41
			4,5	2,12	38,5	10,0	190,0	0,48
10,0	5,0	95,0	3,0	1,25	26,3	2,3	2,5	0,41
			5,0	2,0	38,2	3,4	19,5	0,40
			7,0	3,1	57,4	5,2	50,0	0,44
			8,0	4,0	81,0	8,0	320,0	0,50
			9,0	4,45	94,5	10,5	500,0	0,50

distribution has a wavy shape and becomes reduced as the contact area increases. At p_n = 3 kg/cm², the friction is, apparently, semiliquid. This distribution of pressure can be explained as follows. During the semiliquid friction the interaction of the surfaces of solids becomes combined with the viscous resistance of the liquid and its hydrodynamic action [7]. The contact between the surfaces is formed by microirregularities which produce microcavities while, on a larger scale, the contact between the surfaces which are not perfectly level forms macrocavities. These micro- and macrocavities are sometimes narrow and sometimes wide. During relative sliding, the liquid is carried away by the friction surfaces forming a hydrodynamic pressure in the narrow gaps which can be smaller than, equal to, or larger than the pressure of the liquid being compressed. Sharp fluctuations of pressure on the curves suggest the presence of a hydrodynamic pressure in the micro- and macrocavities.

During a further increase of pressure of the sealed liquid to 5 kg/cm², the pressure in the microwedges increases and lifts one of the surfaces above the other, during which process the pressures gradually become equalized and the curve of the distribution of the hydrodynamic pressure smooths, approaching a linear form. The thickness of the liquid film sharply increases, reaching a critical value at which the seal loses its tightness completely, i.e., the surfaces in contact begin to work in the condition of liquid friction. The average value of the hydrodynamic pressure becomes about 0.5 p_n and the hydrodynamic force P_f is approximately equal to the total load on the sliding metal surfaces.

As the specific pressure increases, other conditions remaining constant, the hydrodynamic pressure of AK-10 oil also increases. For example, if for p_n = 3 kg/cm² at p_s = 2 kg/cm² the hydrodynamic pressure is 1.1 kg/cm² and

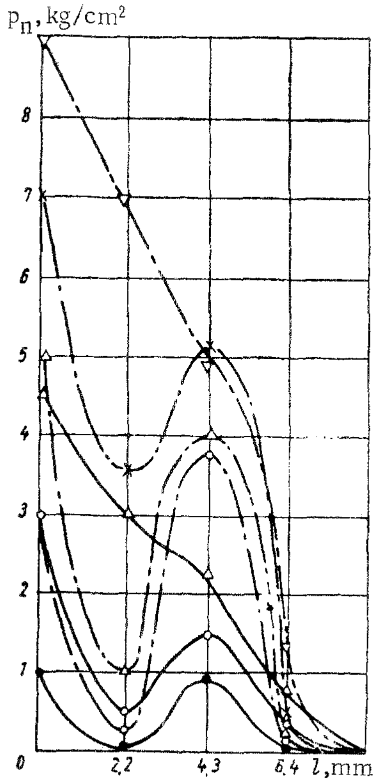
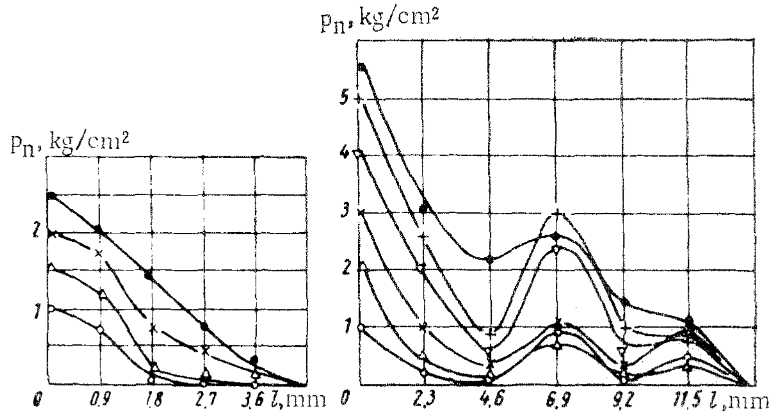


Fig. 4. Dependence of the distribution of the hydrodynamic pressure in AK-10 oil in the clearance between the sliding elements on the average sliding velocity of the seal sleeves at p_s = 2 kg/cm^2 and l = 8.5 mm: —) v_{av} = 3 m/sec; —·—·) v_{av} = 10 m/sec; ⊙) p_n = 1 kg/cm^2; O) p_n = 3 kg/cm^2; △) p_n = 5 kg/cm^2; ×) p_n = 7 kg/cm^2; ▽) p_n = 9 kg/cm^2.



a) b)

Fig. 5. Dependence of the distribution of the hydrodynamic pressure in AK-10 oil in the clearance on the width of the contact surface at v_{av} = 10 m/sec, p_f = 2 kg/cm^2: a) for l = 4.5 mm: O] p_n = 1 kg/cm^2; △] p_n = 1.5 kg/cm^2; ×] p_n = 2.0 kg/cm^2; ●] p_n = 2.5 kg/cm^2; b) for l = 14 mm: O] p_n = 1 kg/cm^2; △] p_n = 2 kg/cm^2; ×] p_n = 3 kg/cm^2; ▽] p_n = 4 kg/cm^2; +] p_n = 5 kg/cm^2; ⊙] p_n = 5.5 kg/cm^2.

the hydrodynamic force P_f = 18.7 kg, then for p_s = 5 kg/cm^2 at the same pressure of the medium p_h and P_f are respectively 1.25 kg/cm^2 and 2.63 kg (see table).

The magnitude and the nature of the distribution of the hydrodynamic pressure are markedly affected by the mean sliding velocity. The experimental results (Fig. 4) show that an increase of the sliding velocity from 3 to 10 m/sec increases the hydrodynamic pressure in the clearance. In addition, the distribution of pressure between the sliding surfaces is affected by the width of the contact surface and by the viscosity of the liquid. Figure 5, a and b, shows the distribution of the hydrodynamic pressure for sleeves with l = 4.5 and 14 mm. It may be seen that at a small width of the contact surface and $p_n < p_s$ the hydrodynamic pressure in the clearance is absent or insignificant. As the pressure of the liquid being sealed increases to $p_n \geq p_s$, the pressure distribution curve approaches a straight line. The curve of hydrodynamic pressure is close to a triangle. The friction between the parts becomes liquid and the seal fails (Fig. 5a).

Figure 5b shows the distribution of hydrodynamic pressure for sleeves with l = 14 mm. At liquid pressures of $p_n \leq p$ the hydrodynamic pressure in the clearance is insignificant and the curve of its distribution is, in contrast to the previous case, wavy. This can be attributed to the fact that an increase of l increases the deviation of the contact surfaces from the perfect form, which adds to the probability of the formation of micro- and macrocavities in the clearance.

If the pressure of the liquid being sealed $p_n > p$ the tightness decreases more rapidly in seals with a small width of the contact surface. This is observed at p_s = 0.3-0.5 p_n according to the specific pressure, the average sliding speed, and other factors.

Figure 6 shows the effect of the viscosity of the liquid being sealed on the pressure distribution. The experiments with kerosene and P-28 oil showed that these media have different hydrodynamic pressure distributions.

For kerosene at $p_n \leq p_s$, the hydrodynamic pressure is practically absent, and at $p_n > p_s$, the distribution curve of the hydrodynamic pressure is concave and approaches a straight line as the pressure of the liquid being sealed is further increased.

For $p_n \leq p_s$, as well as for $p_n > p_s$, the curve showing the distribution of the hydrodynamic pressure in kerosene has no fluctuations. The viscosity of P-28 oil is much higher (for kerosene at 50°C, $\nu = 0.012 \cdot 10^{-4}$ m^2/sec, and for P-28 at 50°C, $\nu = 3.4 \cdot 10^{-4}$ m^2/sec).

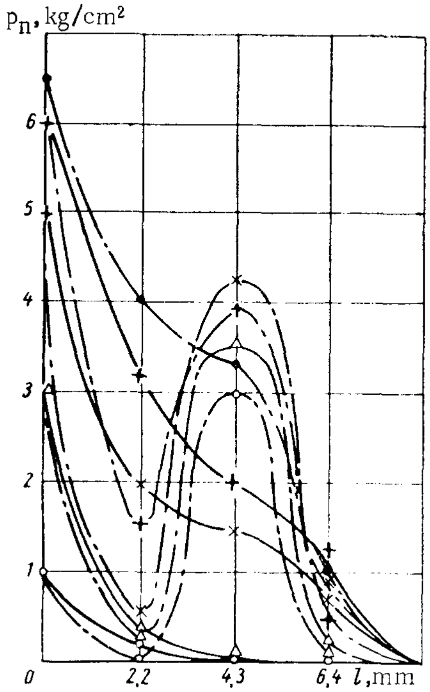


Fig. 6. Dependence of the distribution of the hydrodynamic pressure in the clearance between the materials in contact on the viscosity of the liquid at v_{av} = 10 m/sec, p_s = 3 kg/cm², and l = 8.5 mm: ——) kerosene; —·—·—) P-28 oil; O) p_n = 1 kg/cm²; Δ) p_n = 3 kg/cm²; ×) p_n = 5 kg/cm²; +) p_n = 6 kg/cm²; ●) p_n = 6.5 kg/cm².

The curve showing the distribution of the hydrodynamic pressure for P-28 oil has a clearly wavy nature with considerable variations for $p_n \leq p_s$ as well as for $p_n > p_s$ up to the value $p_s \leq 0.5\ p_n$, i.e., until the critical value of the hydrodynamic force is reached at which the tightness of the seal is disturbed. After this the curve of hydrodynamic pressure approaches a triangular form. The analysis of the curves of Fig. 6 shows that liquids with a higher viscosity show a greater tendency to the formation of a thin liquid film between plane parallel surfaces with a finish of the 9-10th class.

An examination of the pressure distribution curves for the clearance between two friction elements shows that in certain service conditions the liquid film is retained and prevents the escape of the working liquid; the thickness of this film depends on p_n, p_s, v_{av}, l, and the viscosity of the liquid. With a liquid film between the surfaces in contact and with the leakage eliminated or minimized, semiliquid friction conditions become established between the friction elements; the curve representing the distribution of the hydrodynamic pressure becomes wavy with the waves being damped as the width of the contact surface decreases. The hydrodynamic pressure is much lower than 0.5 p_n. With the decreasing width of the contact surface, their improving finish and the p_s and p_{av} values remaining constant, the distribution curves of the hydrodynamic pressure are smoothly concave. The assumptions of the authors [4, 8, 9] that the hydrodynamic pressure in the clearance is approximately 0.5 p_n applies only to the case of pure liquid friction. The liquid friction case is not characteristic for real service conditions of end-face seals since under these conditions the surfaces in contact are completely separated by the layer of liquid, a condition which causes excessive leakage.

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