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Problems of Selection of Lubricants for Ethylene High-Pressure Compressors. 4. Investigation of Antifriction Properties of Naphtene and Polyglycol Oils during High Loading of Solid Lubricant Pair

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The antifriction properties of naphtene and polyglycol oils during little loading with lubrication of pair bronze-tungsten-carbide-alloy WK-6 (WK-ll) and graphelon-20-WK-6 (WK-11) and high loading with lubrication of pair ball-bearing-high-chromium steel ШХ-15 - steel ШХ-15 are investigated. New correlations of viscous-and-thermal and antifriction properties of different polyglycol oils permit to creating effective composition on its base. The dependence of seizure loading during testing on FBFM on the molecular mass of different polyglycols, wear spot on the axial loading and boundary loading on concentration of additives in naphtene and mineral oils are found. The mean-square relative deviation of diameter of spot of wear from the spot by Hertz give generalization assessment of antiwear properties of lubrication oils.

Key words: lubricant, ethylene compressors, four-ball friction machine, properties, bronze, graphelon-20, mineral, naphtene, polyglycol and polybutene oils.

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Introduction

Analysis of literature [1-14, 20-30] shows that 3 types of lubricants: naphtene, polybutene and polyglycol oils are used for lubrication of ethylene compressors. Naphtene oil which ingresses into polyethylene do not lower quality indexes of polyethylene but have shortcomings:

- substantial solubility of ethylene in oil and as a result substantial lowering of viscosity and others hydrodynamic properties forces to feed for lubrication substantial quantity of oil;
- substantial solubility of oil in ethylene which leads to substantial oil ingress into ethylene and as a result increasing of extracting substances and «smoking» of mass during processing of polyethylene into products and to scale formation on piston's surfaces;
- low loading ability which forces to limit by ethylene plants of little and medium productivity.

For large technological lines was required equipment, which guarantee high coefficient of using working times. One of the essential factors directed to this was using synthetic lubricants with high antiwear and antiseizure properties.

Use of naphtene and polybutene oils for lubrication of friction pair of the ethylene high-pressure compressors substantially decreases using coefficient of compressors equipment, but use of polyglycol oils decreases properties of polyethylene – dielectrical and sanitarian-hygienical indexes and resistance to atmospheric and electromagnetic influences.

Alloying of compressors lubricants with viscous, antiseizure or others additives substantially decreases temperature of flashing and decreases dielectrical properties of polyethylene.

The ways of finding effective compressors oils are alloying of oils with high- temperature or viscous additives, which are similar to accordingly naphtene and polyglycol oils and also synthesis of new polyglycols.

I. Experimental

Practical significance of turned out results consists of exposed appropriateness, which let substantially choose oil for lubrication of ethylene high-pressure compressors and define ways for subsequent investigations. New criterions of assessment of viscous-and-thermal and

Table 1

Antifriction properties of naphtene and polyglycol oils during investigation of pair specimens (bronze, graphelon-20) – counterface (metalceramic material) during low loading

Lubricant	Specimen	Wear intensiveness of specimen J, (x 10^{-8}) $mm^3/(N \cdot m)$	
		Counterface	
		BK-11	BK-6
Risella-33	Bronze (firm «Kranz»)	1.48	1.17
Laprol 2502-2-70	Bronze (firm «Kranz»)	2.40	2.05
Laprol 2002	Bronze (firm «Kranz»)	2.02	1.30
Risella-33	Bronze Бр ОФ 10-1	0.33	0.53
Laprol 2502-2-70	Bronze Бр ОФ 10-1	0.83	0.76
Laprol 2002	Bronze Бр ОФ 10-1	0.76	0.70
Risella-33	Bronze Бр ОС 12-2	0.32	0.53
Laprol 2502-2-70	Bronze Бр ОС 12-2	0.47	0.68
Laprol 2002	Bronze Бр ОС 12-2	0.42	0.62
Risella-33	Bronze Бр ВНТ 2.5-1-68	0.21	0.32
Laprol 2502-2-70	Bronze Бр ВНТ 2.5-1-68	1.05	1.55
Laprol 2002	Bronze Бр ВНТ 2.5-1-68	1.23	1.26
Risella-33	Graphelon-20	1.50	1.56
Laprol 2502-2-70	Graphelon-20	1.24	1.17
Laprol 2002	Graphelon-20	0.95	0.77

antiwear properties which are brought in let use them for assessments of others lubrication materials.

Wearing of bronze (firm «Kranz»), Beryllium bronze (Бр ВНТ-2,5-1-68), Tina-Stannum bronze (Бр ОС 12-2), Tina-phosphorous bronze (Бр ОФ-10-1) and composition material on the base of aromatic polyamide phenilon C-2+20% of graphite fiber from hydrocellulose (viscose) graphelon-20 was investigated on three-pin-disk friction machine. Specimens (pins) were made in shape of three fingers with diameter 6 mm and height 15 mm (last sphere 6.35 mm). Counterfaces were made by method of pressing and annealing of metal-ceramic bronze (wolfram group BK-6 and BK-11) as inserts with d_c= 45.0 mm, d_i = 25.0 mm and thickness 15 mm (HB 8200-8400 MPa; Ra_o = 0.04-0.06 mkm). Normal loading on one specimen N_i = 67 N, velocity of sliding 1.3 m/s, time of investigation 4 hours (friction track 16.14 km), temperature 318 ± 2°C. Lubricant – polyglycols Laprol 2502-2-70, Laprol 2002 and naphtene oil Risella-33.

Intensiveness of wearing was calculated by diameter of wear spot (wear capacity):

$$J=\frac{V_i}{N_i S} \quad \left[\frac{mm^3}{N \cdot m}\right], \qquad (1)$$

where V_i – average volume of wear capacity on one sample [mm^3];

N_i – normal loading on one sample [N];

S – wear track [m].

Results of investigation are represented in Tabl. 1. The result of wear intensity $J = (0.21\text{-}2.4) \cdot 10^{-8}$ $mm^3/(H \cdot m)$ are calculated by diameter wear spots d_3 = 0.754-1.461 mm, according to which it is possible to estimate approximately the limits of lubricating film specific loads. As we can see from the Tabl. 1, during little loadings (N_i = 67N) and relatively high sliding velocity (ϑ = 1.3 m/s) for pair «bronze – BK-11» and «bronze – BK-6» preferences of polyglycol (statistic polymer of propylene and ethylene oxides Laprol-2502-2-70 and linear polypropyleneglycol Laprol 2002) oils to naphtene oil Risella-33 are not seen and on the contrary, for pair «graphelon-20-BK-11» and «graphelon-20-BK-6» polyglycols are more effective than naphtene oil.

Except specimens of bronze (firm «Kranz») and Бр ОФ 10-1, for which intensiveness of wearing in friction on BK-11 during lubrication with polyglycols 1.09-1.55 time larger than on BK-6, for the rest of specimens from bronze (Бр ОС 12-2 and Бр БНТ 2,5-1-68) wearing on BK-6 1.02-1.48 time bigger than on BK-11.

In general: wearing of specimens from bronze during lubrication with polyglycol oils 1.31-5.86 time in friction on BK-11 and 1.11-4.84 time in friction on BK-6 bigger than with naphtene oil.

It is necessary to give an estimation of the antiwearing and antiscratching properties on the results of tests on a four-ball friction machine. The specific loads of 1850-7500 MPa can be achieved in contact of working bodies of a four-ball friction machine.

1.1. Four-ball friction machine

Comparable characteristic of loading capacity and antiwear properties of lubricants on four-ball friction machine in high-load contact conditions lets choose the most effective one.

Tests were carried out on four-ball friction machine [15-18], Machine parameters and wear indexes were found:

1) relative sliding velocity

$$\nu = \frac{d_b\, \omega\, \sin\alpha}{2} = 0.576\pi d_b n, \qquad (2)$$

where d_b – ball's diameter (d_b = 12.7 mm);

ω – angular rotation velocity of upper ball;

α – angle in the base of pyramid from the balls (between tetrahedron height and edge -rib of tetrahedron), which (when diameter of balls d_b= 12.7 mm) equals 35°20';

Table 2

Statistic findings of wear tests on FBFM

Lubricant	Diameter of wear spot, mm (recurring tests)				
	1	2	3	4	5
First series (Ni=82 N; τ=4 hours; n=1140 rot. /min.)					
Risella-33	0.475	0.499	0.449	0.474	0.477
Risella-33	0.463	0.486	0.472	0.489	0.492
Orites-270 DS	0.624	0.700	0.640	0.648	0.690
Laprol-2002	0.439	0.453	0.477	0.458	0.454
Syntheso-D 201	0.540	0.534	0.571	0.616	0.568
Sum					
Second series (N_i=82 N; τ =4 hours; n=1140 rot. /min.)					
EBPE	0.544	0.515	0.551	-	-
Risella-33+5%					
of Orites- 270DS	0.486	0.499	0.426	-	-
Laprol-2502 +					
+20% of EBPE	0.480	0.440	0.460	-	-
Laprol-2502+					
+20% of EBF	0.418	0.377	0.421	-	-
Laprol-2002+					
+20% of EBF	0.495	0.576	0.480	-	-
Laprol-2002+					
+20% of EBPE	0.480	0.464	0.538	-	-
Sum					
Third series (Ni=82 N; τ=4 hours; n=1470 rot. /min.)					
Risella-17	0.992	0.784	1.010	0.930	0.926
Risella-33	0.652	0.780	0.788	0.750	0.754
NKM-40	0.710	0.580	0.683	0.656	0.662
NKM-70	0.445	0.457	0.477	0.428	0.488
5350	0.491	0.643	0.585	0.474	0.548
Vitorex-334	0.568	0.505	0.601	0.560	0.520
Esso-Christo Orites-270 DS	0.738	0.728	0.637	0.694	0.686
1 series	0.662	0.734	0.513	0.636	0.644
2 series	0.544	0.760	0.640	0.646	0.650
Sum					

n – rotation velocity of upper ball; n=1470 rot./min., (f=24.5 s^{-1}) during wear testing; n=1140 rot./min. (f=19 c^{-1}) during testing of loading capacity; linear velocity 0.09 i 0.07 m/c accordingly;

f – rotation frequency;

2) loading on one ball in theoretical point of contact:

$$N_i = \frac{N}{3\cos\alpha} = \frac{N}{3\cdot 0.8158} = 0.4086N \approx 0.41N, \qquad (3)$$

where N – axial loading on three balls;

3) friction coefficient:

$$f = \frac{F_{fr}}{N_i} = \frac{f_{fr}l}{3\alpha N_i} = \frac{f_{fr}l}{3\alpha\frac{N}{\cos\alpha}} =$$

$$= \frac{f_{fr}l}{\frac{d_b}{2}\frac{\sin\alpha}{\frac{\cos\alpha}{3}}N} = \frac{2lf_{fr}}{d_bN\,\mathrm{tg}\,\alpha'}, \qquad (4)$$

where F$_{fr}$ – friction force;

l – distance from the rotation axis to the contact point of lever with tensiometer (*l* = 83 mm);

f$_{fr}$ – force, that bends tensilebeam:

$$f = \frac{2\cdot 83\cdot f_{fr}}{12.7\cdot 0.7089N} = 18.4382\frac{f_{fr}}{N}, \qquad (5)$$

4) static initial specific loading P$_N$, which stands lubrication layer at the end of friction:

$$P_L = \frac{N_i}{\frac{\pi d_H^2}{4}} = \frac{4\cdot 0.41N}{\pi d_H^2} = \frac{0.5223N}{d_H^2}, \qquad (6)$$

where d$_H$ – diameter of elastic deformation area by Hertz, which is calculated by Hertz's formula:

$$\frac{d_H}{2} = 0.872\sqrt[3]{\frac{0.41Nd_b/2}{E}}; \qquad (7)$$

$$d_H = 1.744\sqrt[3]{\frac{0.205d_bN}{E}} = 1.744\sqrt[3]{\frac{0.205\cdot 12.7N}{210000}} =$$

$$= 0.040364\sqrt[3]{N}\ [mm], \qquad (8)$$

where E – modulus of ball's elasticity (for steel IIIX-15 E = 2.1·10^5 N/mm^2);

N – normal loading on 3 balls [N];

5) specific loading, which is at the end of friction:

$$P_E = \frac{N_i}{\frac{\pi d_W^2}{4}} = \frac{4\cdot 0.41N}{3.14d_W^2} = \frac{0.5223N}{d_W^2}, \qquad (9)$$

where d$_w$ – wear spot diameter;

6) overfall of specific loading, which stands lubrication layer at the beginning of sliding:

Continuation of tabl. 2

Lubricant	Average diameter of wear spot, mm	Dispersion, $(\cdot 10^{-4})$ mm^2	Mean-square deviation, $(\cdot 10^{-2})$ mm	Vary coefficient, %
First series (Ni=82 N; τ=4 hours; n=1140 rot. /min.)				
Risella-33	0.4748	3.142	1.773	3.73
Risella-33	0.4804	1.533	1.238	2.58
Orites-270 DS	0.6604	10.848	3.294	4.99
Laprol-2002	0.4562	1.867	1.366	3.00
Syntheso-D 201	0.5658	10.572	3.251	5.75
Sum		27.962		
Second series (N_i=82 N; τ =4 hours; n=1140 rot. /min.)				
EBPE	0.5367	3.645	1.909	3.56
Risella-33+5% of Orites- 270DS	0.4703	15.163	3.894	8.28
Laprol-2502 + +20% of EBPE	0.4600	4.000	2.000	4.35
Laprol-2502+ +20% of EBF	0.4053	6.044	2.458	6.07
Laprol-2002+ +20% of EBF	0.5170	26.67	5.164	9.99
Laprol-2002+ +20% of EBPE	0.4940	15.16	3.894	7.88
Sum		70.682		
Third series (Ni=82 N; τ =4 hours; n=1470 rot. /min.)				
Risella-17	0.9284	78.25	8.846	9.53
Risella-33	0.7448	29.57	5.440	7.30
NKM-40	0.6582	21.00	4.580	6.96
NKM-70	0.4590	5.80	2.410	5.24
5350	0.5482	46.00	6.780	12.37
Vitorex-334	0.5508	14.25	3.770	6.84
Esso-Christo Orites-270 DS	0.6966	15.50	3.940	5.65
1 series	0.6378	63.25	7.950	12.46
2 series	0.6480	58.45	7.650	11.79
Sum		332.07		

$$\Delta p = P_l - P_E = 0.5223N\left(\frac{1}{d_H^2} - \frac{1}{d_W^2}\right), \qquad (10)$$

7) load capacity coefficient of oil:

$$k_1 = \frac{P_H}{P_E} = \frac{d_3^2}{d_H^2}; \qquad (11)$$

$$k_2 = \sqrt{\left(\frac{d_W - d_H}{d_H}\right)^2}; \qquad (12)$$

8) hydrodynamic effects, which characterize conditions of boundary friction were calculated by formulas:

- at the beginning of testing

$$S_{hH} = S_{h(N)} = \frac{\eta v d_H^2}{N_i} = \frac{v \rho \upsilon d_N^3}{N_i}\ [m^2]; \qquad (13)$$

- at the end of testing

$$S_{hw} = S_{h(k)} = \frac{\eta v d_w^2}{N_i} = \frac{v \rho \upsilon d_W^3}{N_i}\ [m^2], \qquad (14)$$

where ρ – density of oil [kg/m^3];

η – dynamic viscosity of oil [N·s/m^2];
ν – kinematic viscosity of oil [m^2/s];
υ – sliding velocity [m/c];
d_H, d_w – diameter by Hertz and diameter of wear spot;
N_i – normal loading on one ball Ha [N];

9) generalized wear index (by testing results on seizure loading or long-duration wearing:

$$J_1 = \frac{\sum_{i=1}^{n} d_{wi}}{n}\ [mm] \qquad (15)$$

$$J_2 = \frac{\sum (d_{wi} - d_{Hi})}{n}\ [mm] \qquad (16)$$

$$J_3 = \sqrt{\frac{\sum_{i=1}^{n} (d_{wi} - d_{Hi})^2}{n}}\ [mm] \qquad (17)$$

$$J_4 = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{(d_{wi} - d_{Hi})^2}{d_{Hi}}\right)}\ [dimensionless] \qquad (18)$$

where d_{Wi}, d_{Hi} were chosen from N = 200 N to N ≈ N_{cr}. (seizure) by 100 N + d_w at N_{cr} (seizure).

Dimension generalized wear index is known as well [33]:

$$GWI = I_W = \frac{SS_1+SS_2}{n}[N], \qquad (19)$$

where $SS_1 = \sum_{j=1}^{n_1} N_j \; d_{Hj}/d_{3j}$(up to N<3100 N);

$SS_2 = \sum_{\nu=1}^{n_2} N_\nu \; d_{\Gamma\nu}/d_{3\nu}$ (N≥3100N); n – 20.

Artificial approach of this index structure is present.

10) during analysis of antiwear properties of oils conditional antiwear index was used [3]:

$$I_1 = \frac{N_{cr}}{d_w}\left[\frac{N}{mm}\right] \qquad (20)$$

Table 3

Antifriction and viscous-and-thermal properties of mineral oils

Oil	Temperature of flashing, °C		Loading capacity		Antiwear properties during tests τ=4 hours, N_i=82 N	
	closed crucible	opened crucible	ν, мм^2/s (90°C)	Ni, N	ν, мм^2/s (45°C)	S_{hH}, $(\cdot 10^{-16})m^2$ (45^{0}C)
Vitorex-334	206	-	11.3	238	49.7	6.04
Esso-Christo	212	-	10.6	213	53.8	6.74
5350	202	-	11.9	205	52.5	6.58
Risella-33	202	221	10.4	199	49.1	6.17
Risella-17	-	-	4.15	164	12.3	1.51
NKM-40	195	-	10.7	201	47.8	5.92
NKM-70	205	-	15.9	203	83.2	10.45
NKM-200	-	-	10.6	226	80.0	10.03
Compressorna 12(M)	-	-	11.5*	278	109.8	13.99
Industrial 20	-	-	9.2	242	32.6	-
Industrial 45	-	-	12.1	269	60.2	-
Aviacijna MC-20	-	-	28.2	281	198	25.00
MGD-14M on the base of diesel oil F-14	210	-	13.6*	349	-	-
N-50	-	-	-	213	-	-
ChR-200	-	-	-	205	45.1**	-
BMT-15	-	-	-	175	-	-
Vaseline medical	-	-	10.0	201	44.6	5.55

*100°C; **50°C

Continuation of table 3

Oil	Antiwear properties during tests τ=4 hours, N_i=82 N		Density, kg/m^3	
	d_3, mm	S_{hw}, $(\cdot 10^{-14})$ m^2 (45°C)	45°C	90°C
Vitorex-334	0.60	0.99	842	819
Esso-Christo	0.69	1.69	869	845
5350	0.55	0.83	869	845
Risella-33	0.85	2.88	871	848
Risella-17	0.93	0.93	852	826
NKM-40	0.66	1.30	859	833
NKM-70	0.46	0.77	871	848
NKm-200	0.82	4.21	869	835
Compressorna 12(M)	0.92	8.29	883	861
Industrial 20	1.07	-	-	-
Industrial 45	0.85	-	-	852
AviacijnaMC-20	0.57	3.52	875	-
MGD-14M on the base of diesel oil F-14	0.54	-	-	-
N-50	0.60	-	-	-
ChR-200	0.50	-	-	-
BMT-15	0.96	-	-	-
Vaseline medical	0,65	1,16	863	838

where N_{cr} – critical seizure loading [N];

d_w – average diameter of wear during long-duration testing; then we can calculate generalized index of antiwear properties of oils:

$$I_2 = \frac{N_{cr}}{d_w} \cdot K_w \left[\frac{N}{mm}\right] \qquad (21)$$

(higher value of I_2, higher assessment of antiwear properties of oils), where $K_w = \frac{N_{cr}}{N_w}$ (dimensionless) – index of wear loading; N_w – loading, in which testing of long-duration wearing was done.

Conditional character of this index is seen.

1.2. Statistic information of three series of wear testing for these lubricants was accumulated for the assessment of the experiment error: naphtene oils Risella-33 (3 series), Risella-17, NKM-40, NKM-70, 5350, Vitorex-334, Esso-Christo; polyglycol oils Orites-370 DS (3 series), Laprol-2002, Syntheso- D 201 and compositions of oils Risella + 5 % of Orites-270 DS, EBPE, Laprol-2502-2-70 + 20 % of EBPE, Laprol 2502-2-70 +20% of EBF, Laprol 2002 + 20 % of EBF, Laprol -2002+20% of EBPE (Tabl. 2). In first and third series number of recurring tests was 5, and in second series-3. 20 lubricants were tested (individual and compositions).

For each series average diameter of wear spot, dispersions, mean-square deviations, coefficients of variation and Cochran's criterion were calculated. For three series coefficient of variation varied from 2.58 to 12.46. Table values of Cohran's and Student's criterions were taken by [23].

For the first series of tests calculated Cochran's criterion was Gc=0,3880, which is less than from the table $G_T\{N = 5; n = 5; \alpha = 0.01\} = 0.5875$ and $G_T\{N = 5; n = 5; \alpha = 0.05\} = 0.5065$ for significance level α = 0.01 and α = 0.05 accordingly. This confirms the zero hypothesis about row homogeneity (5) of dispersions. Error of experiment for the first series:

$$S_{er} = \sqrt{\frac{\sum_{i=1}^{N=5} s_i^2}{N}} = \sqrt{\frac{0.0027962}{5}} = 0.02365 \text{ mm}, \qquad (22)$$

Proxy interval for average value:

$$\Delta d = \pm \frac{t_T\{\alpha = 0.05; f = (N \cdot n) - 1\} \cdot S_{er.}}{\sqrt{N \cdot n}} =$$

$$= \pm \frac{2.06 \cdot 0.02365}{\sqrt{25}} = \pm 0.0097 \text{ mm}. \qquad (23)$$

For the second series:

G_{calc}= 0.3773, which is less than from the table $G_T\{N = 6; n = 3; \alpha = 0.01\} = 0.6321$ and $G_T\{N = 6; n = 3; \alpha = 0.05\} = 0.5391$. This confirms homogeneity of dispersions row (6). Error of experiment for the second series:

$$S_{er} = \sqrt{\frac{\sum_{i=1}^{N=6} s_i^2}{N}} = \sqrt{\frac{0.00706815}{6}} = 0.03432 \text{ mm}. \qquad (24)$$

Proxy interval for average value:

$$\Delta d =$$

$$= \pm \frac{t_T\{\alpha = 0.05; f = (Nn) - 1 = 14\} \cdot S_{er.}}{\sqrt{N \cdot n}} =$$

$$= \pm \frac{2.11 \cdot 0.03432}{\sqrt{18}} = \pm 0.0171 \text{ mm}. \qquad (25)$$

For the third series:

G_{calc} = 0.2356, which is less than from the table $G_T\{N = 9; n = 5; \alpha = 0.01\} = 0.3934$ and $G_T\{N = 9; n = 5; \alpha = 0.05\} = 0.3344$. This confirms homogeneity of dispersions row (9). Error of experiment for the third series:

$$S_{er} = \sqrt{\frac{\sum_{i=1}^{N=10} s_i^2}{N}} = \sqrt{\frac{0.033207}{9}} = 0.0608 \text{ mm}, \qquad (26)$$

Proxy interval for average value:

$$\Delta d = \pm \frac{t_T\{\alpha = 0.05; f = (Nn) - 1 = 44\} \cdot S_{er.}}{\sqrt{N \cdot n}} =$$

$$= \pm \frac{2.01 \cdot 0.0608}{\sqrt{44}} = \pm 0.0182 \text{ mm}. \qquad (27)$$

Joining up of first and third series of tests has lead to such statistic assessments:

G_{calc}= 0.2173, which is less than from the table $G_T\{N = 14; n = 5; \alpha = 0.01\} = 0.29624$ and $G_T\{N = 14; n = 5; \alpha = 0.05\} = 0.25114$. This confirms homogeneity of dispersions row (14). Error of experiment:

$$S_{er} = \sqrt{\frac{\sum_{i=1}^{N=15} s_i^2}{N}} = \sqrt{\frac{0.0360032}{14}} = 0.0507 \text{ mm} \qquad (28)$$

Proxy interval for average value:

$$\Delta d = \pm \frac{t_T\{\alpha=0.05; f=(Nn)-1=69\}\cdot S_{er.}}{\sqrt{N\cdot n}} = \pm \frac{2\cdot 0.0507}{\sqrt{70}} = \pm 0.0121 \text{ mm} \qquad (29)$$

Results of recurring tests of oils: a) Risella-33[(1)], Risella-33[(2)], Orites-270 DS, Laprol-2002, Syntheso-D 201 (1 ser.) б) Risella-17, Risella-33, NKM-40, NKM-70, 5350, Vitorex-334, Esso-Christo, Orites-270 DS (3 ser.) (n=5); в) oils EBPE, Risella-33+5% of Orites-270 DS, Laprol-2502 +20% of EBPE, Laprol-2502 +20% of EBF, Laprol-2002+20% of EBF, Laprol-2002 +20% of EBPE (2 ser.) are represented in tabl. 2.

Results of calculation show that dispersion of this

Table 4

Antifriction and viscous-and-thermal properties of naphtene and polybutene and others oils and compositions on their base

Oil	Temperature of flashing, °C		Loading capacity		Antiwear properties during tests τ=4 hours., N_i=82 N	
	closed crucible	opened crucible	ν, mm²/s at 45°C .	N_i, N	ν, mm²/s at 45°C .	S_{hH}, $(\cdot 10^{-16})$ m² at 45°C
Risella-33+50% of PVBE	85	166	68.7	217	304	-
Risella-33+of peroxide FGK	-	-	-	262	-	-
KPL-201	220	-	15.4	185	89.0	-
Witco CL-1000	230	≥240	23.0	190	143	-
Witco CL-1200	250	≥250	26.0	195	184	-
Witco CL-15 00	250	≥250	29.5	220	215	-
Polybutene-200	-	-	-	267	-	-
Polybutene for succynimide additives	-	-	374	320	5839	735.41
Polybutene Tredkat-99	-	-	146	201	1074	131.24
Lowmolecular polyethylene	-	-	172.3	320	13842	1837.2
PVBE	-	170	720.6	385	3850	516.56
Glycerin	-	-	15.6	275	129	-
Poly-α-olefin	306	-	35.8**	287	234.5***	28.45***
Poly-α-olefin + 4% of polymer SKEP	240	-	39.1**	277	257.5***	31.39***
KPL (additive)	-		-	220	-	-
SKTN-A (additive)	180	-	-	267	-	-
Peroxide ФЖК	-	-	-	287	-	-

* 293 K; ** 373 K; ***323 K

Continuation of table 4

il	Antiwear properties during tests τ=4 hours, N_i=82 N		Density, kg/m³	
	d_3, mm	S_{hw}, $(\cdot 10^{-14})$ m² at 45°C	45°C	90°C
Risella- 33+50% of PVBE	0.63	-	-	-
Risella-33+of peroxide FGK	0.93	-	-	-
KPL-201	0.87	-	-	-
Witco CL-1000	0.45	-	-	-
Witco CL-1200	0.46	-	-	-
Witco CL-1500	0.46		-	-
Polybutene-200	0.70	-	-	-
Polybutene for succynimide additives	0.45	50.98	873	850
Polybutene Tredkat-99	0.45	9.10	847	821
Lowmolecular polyethylene	0.47	145.11	920	-
PVBE	0.56	69.01	930	-
Glycerin	0.64	-	-	-
Poly-α-olefin	0.61	4.91***	869.6*	-
Poly-α-olefin + 4% of polymer SKEP	0.61	5.42***	871.8*	-
KPL (additive)	0.71	-	-	-
SKTN-A (additive)	0.88	-	-	-
Peroxide ФЖК	1.04	-	-	-

* 293 K; ***323 K

row is homogeneous (α=0.05). Proxy intervals for average value: ±0.0097; ±0.0177; ±0.0164; ±0.0113. Results of calculation are recalled. Error of experiment does not have big value.

1.3. Antifriction properties

Loading capacity and antiwear properties were tested on four-ball friction machine (FBFM) [15; 16; 17; 18; 19]: balls from the steel IIIX-15(HRC 52-54) with diameter 12.7 mm, loading time 1 min., rotation number of upper ball 1140 rot./min. (during testings of polyethyleneglycols rotation number of upper ball 1470 per minute) and 4 hours and rotation number 1470 per minute during tests on loading capacity and antiwear properties accordingly (in last test axial loading N=200 N; N_i=82 N).

Results of tests on FBFM on loading capacity (seizure loading on one ball N_i) and antiwear properties (average diameter of wear spot d_i) are adduced in Tabl. 3-5 and shown in Fig. 1.

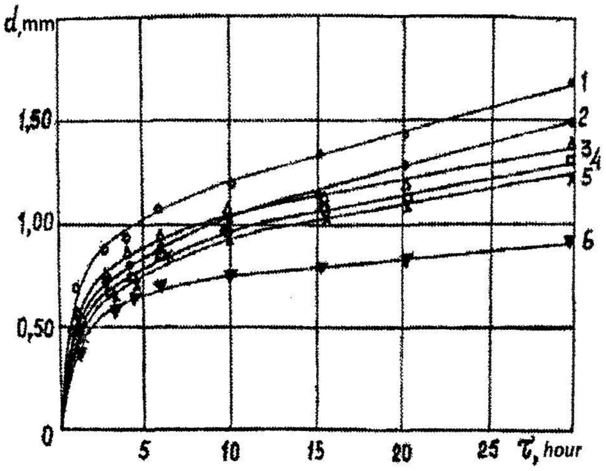

Fig. 1. Dependence of mean diameter of wear spot for steel balls (steel ШХ-15) on the time of testing on FBFM in oils : 1 – kompressorna 12(M); 2 – vaseline oil; 3 – naphtene Risella-33; 4 – mixture of Risella-33+PVBE (30:70); 5 – the same (50:50); 6 – PVBE. Testing conditions: n=1470 rot. /min.; N=200 N; N_i=82 N; f=24.5 s^{-1}; d_c=12.7 mm

As we can see from the Tabl. 3-5, by loading capacity oils are placed in a row (by seizure loading on one ball):

polyglycols (N_i =333 N) > mineral oil (N_i =245.9 N) > polybutene (N_i =225.4 N) > naphtene (N_i =206.1 N), and by antiwear properties by diameter of wear spot during long- duration tests:

polybutene (d_i=0.549 mm) > polyglycols(0.651 mm) > naphtene oils (d_i=0.695 mm) > mineral oils (d_i=0.740 mm).

This row is similar to the rows of hydrodynamic effects at the beginning (S_{hH}) and at the end (S_{hw}) of tests:

by S_{hH}: polybutene ≥ polyglycol ≥ mineral oils ≥ naphtene oils;

by S_{hw}: polybutene ≥ polyglycol ≥ mineral oils ≥ naphtene oils.

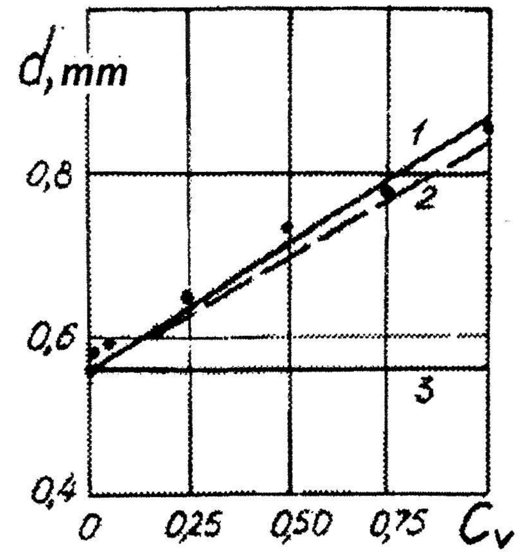

Fig.2. Dependence of mean diameter of wear spot of steel balls (steel ШХ-15) during tests on FBFM on concentration (c_v) of mineral oil in PVBE: 1 – Risella-33; 2 – industrial 45 oils; 3 – vaseline medical. Testing conditions: n=1470 rot./min., N=200 N (N_i=82 N), f=24.5 s^{-1}, τ=4hours., d_c=12,7 mm

That is, more «soft» conditions of boundary friction leas to smaller values of wear, when loading conditions of tests are relatively small. That is why index d_w, when N_i→min in 4 hours is not enough informative relatively with assessment of antiwear properties of oils.

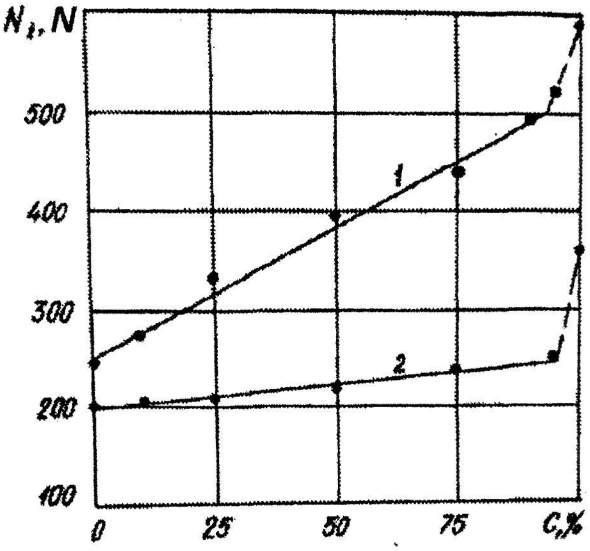

Fig. 3. Dependence of boundary loading on one ball from steel ШХ-15 during tests on FBFM on concentration of PVBE in naphtene oil Risella-33 (number of upper ball rotations: 1-835; 2-1470). Testing conditions: τ=1 min., d_c=12.7 mm

More information give results, when Ni→min in 30 hours of tests (Fig. 1), or realization of long-duration tests (4 hours) in boundary of loadings from N_i=80 N to N_i=362 N (Tabl. 6).

In this case we have a row by antiwear properties: polyglycols > polybutene compositions > naphtene.

Table 5

Antifriction and viscous-and-thermal properties of polyglycol oils

Oil	Temperature of flashing, °C		Loading capacity		Antiwear properties during tests τ=4 hours, Ni-82 N			
	closed crucible	opened crucible	ν, mm^2/s (90°C)	N_i, N	ν, mm^2/s (45°C)	S_{hH}, $(\cdot 10^{-16})$ m^2 (45°C)	d_w, mm	S_{hw}, $(\cdot 10^{-14})$, m^2 (45 °C)
PEG-200	-	-	-	246	-	-	1.0	-
PEG-400	-	-	-	328	-	-	0.81	-
Laprol 202	-	-	4.3	238	20.0	2.88	0.62	0.52
Laprol 602	-	-	8.4	242	34.5	4.98	0.53	0.56
Laprol 1002	-	-	15.3	246	61.0	8.81	0.51	0.89
Laprol 2002	234	-	40.5	262	157.0	22.67	0.47	1.79
Laprol 1502- 2-70	-	-	31.0	361	105.0	9.93	0.76	3.32
Laprol 2502- 2-70	216	250	60.0	402	230	33.19	0.66	7.26
KSM	218	250	61.0	398	232	-	0.77	-
Orites – 125 DS	-	-	-	395	-	-	0.72	-
Orites-270DS	220	250	59.0	447	237	34.2	0.64	6.82
Breox CL 660	-	-	-	287	-	-	0.80	-
Breox CL 1300	214	285	63.2	328	205.4	31.44	0.63	5.98
Breox CL 1400	247	290	58.2	369	221.7	34.06	0.66	7.45
Laprol 503	-	-	12.3	226	75.0	10.83	0.58	1.61
Laprol 3003	-	-	45.8	308	195	28.15	0.52	3.01
Polyol LG-56	-	-	41.8	320	168	24.24	0.41	1.27
Laprol 3503- 2-Б6	-	-	58.9	254	190	27.42	0.44	1.78
Laprol 5003- 2-Б10	-	-	101.2	373	325	46.90	0.49	4.20
Proxanol CL-3	-	-	-	340	-	-	0.83	-
Laprol 3503- 2-70	-	-	76.7	287 :	275	39.70	0.71	10.81
Laprol 10003- 2-70	-	-	82.0	418	~800**	123.78**	0.74	38.16**
Shyntheso D 201	242	≥250	62.0	287	245	35.38	0.57	5.30
Shyntheso D 201N	106	120	95.5	369	334.7	45.70	0.56	6.45
Shyntheso D 202	238	270	57.9	451	264.7	48.30	0.67	9.32
Hydropol-200	-	-	-	440	-	-	0.78	-
Laprol 2503-2-70*	-	-	-	369	-	-	0.67	-

* star structure;
** at 40°C.

Table 6

Influence of axial loading (N) on wear during long-duration tests (n=1140 rot./min., τ=4 hours, f=19 s^{-1})

Oil	Diameter of wear spot, mm							
	198 N	294 N	392N	491N	589 H	687 N	785 N	883 N
Orites-210 DS	0.64	0.76	0.72	0.67	0.71	0.72	1.55	2.80
Laprol-2502-2-70	0.68	0.76	0.76	0.67	0.78	1.26	1.37	1.60
NKM-70	0.52	0.57	0.61	2.80	-	-	-	-
NKM-40	0.65	0.61	1.28	1.36	-	-	-	-
Risella-33	0.63	0.50	0.53; 0.53*	0.65	0.90**	-	-	-
Risella-33+polybutene for succynimide additives:								
5%	0.45	0.52	0.56; 0.61*	0.91	1.70**	-	-	-
15%	0.51	0.53	1.60; 0.83*	-	-	-	-	-
30%	0.61	0.60	0.60;0.57*	0.94	-	-	-	-
Risella-33+50% of polybutene	0.49	0.65	0.82	0.88	0.83; 2.10**	-	-	-

* 436 N (N_i=180 N);
** 540 N (N_i=220 N).

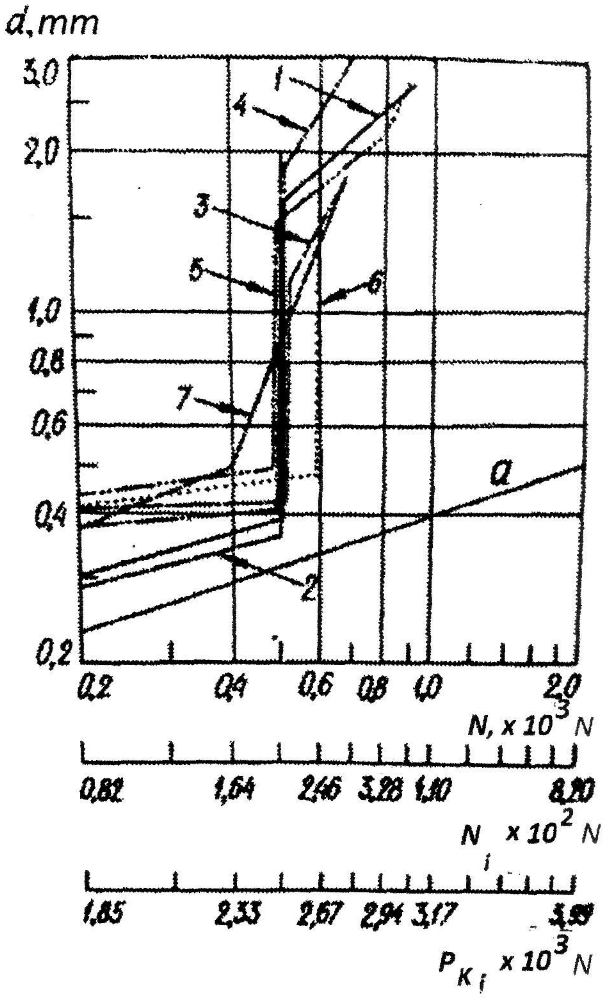

Fig. 4. Relations of wear spot (d) with the axial loading (N), loading on one ball in the theoretical point of contact (N_i) and average initial pressure in the contact point (P_c) for fluids: 1 – NKM-40; 2 – 5350; 3 – Esso-Christo; 4 – NKM-70; 5 – Risella-33; 6 – Vitorex-334; 7 – Risella-17.

It is known, that increasing of moisture in polyglycol oils decreases antiwear properties of oils and quality indexes of polyethylene.

Addition to naphtene (compare Risella-33 and Risella-33+50% of PVBE), poly-α-olefin (compare this oil and it with addition of 4% of SKEP) and polyglycol (compare Syntheso D-201 and Syntheso D-201 N) oils antiseizure, antiwear and viscous additives leads to substantial decreasing of flashing temperature.

Information of testing of relations of wear spot (d) with the axial loading (N), loading on ane ball in the teoretical point of contact (N_i) and average initial preassure in the contact point (P_c) for fluids is demonstrated on fig. 4-11.

Testing of mixtures of polyglycol oil and glycerin shows, that antiwear properties of such mixtures substantially become worse when content of glycerin is more than 3% in polyglycol oil (tabl. 7). Input of viscous polybutene additives to naphtene oils up to 5% decreases wear of steel, and input of more than 5% – not substantially influences on wear.

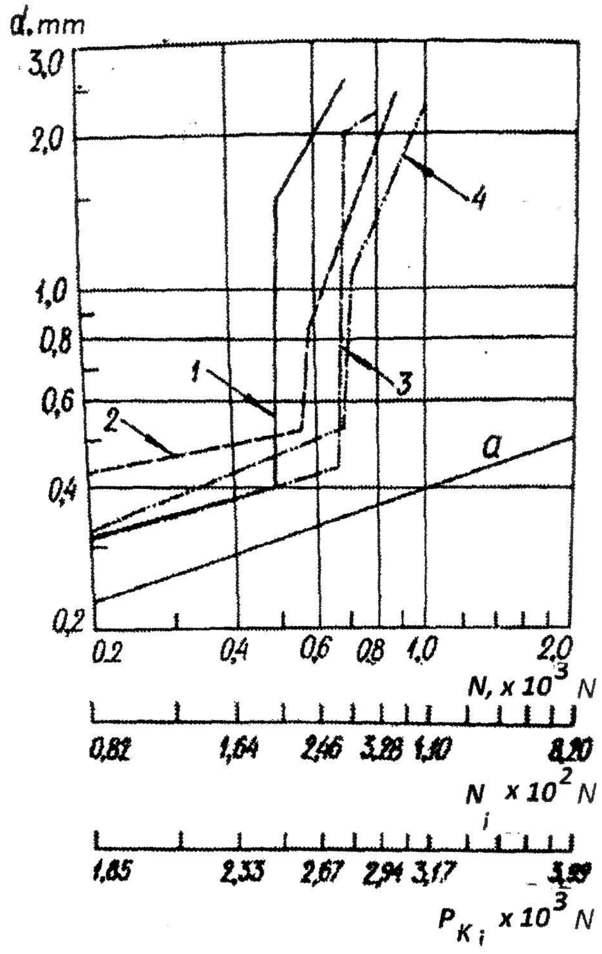

Fig. 5. Relation of wear spot (d) with the axial loading (N), loading on one ball in the theoretical point of contact (N_i) and average initial pressure in the contact point (P_c) for fluids: 1 – vaseline oil (medical); 2 – industrial oil-20; 3 – compressor house oil – 12 M; 4 –aviation oil MC-20.

Testing of wear from loading during long-duration tests (Tabl. 6), which determine temporary resistance of lubricant to thermomechanical influences shows the advantages of Risella-33 over naphtene oil NKM-40 and advantages of polyglycol oil Laprol over Orites. Input of viscous additives into naphtene oil also decreases wear during long-duration testing, but critical loadings do not change much (Tabl.6 i 7).

From, the synthetic oils Orites 210 DS has the highest antiwear properties (Fig. 6).

As it seen from the fig. 9, ramified polypropyleneglycols on the base of glycerin give substantial increasing of loading capacity, when molecular mass of oligomer increases.

In Fig. 12 dependence of seizure loading on one ball on molecular mass of polyglycols is represented:

- linear polypropyleneglycols (1);
- ramified polypropyleneglycols on the base of glycerin (2);
- statistics copolymers of propylene and ethylene oxides (70%) Laprol (3);

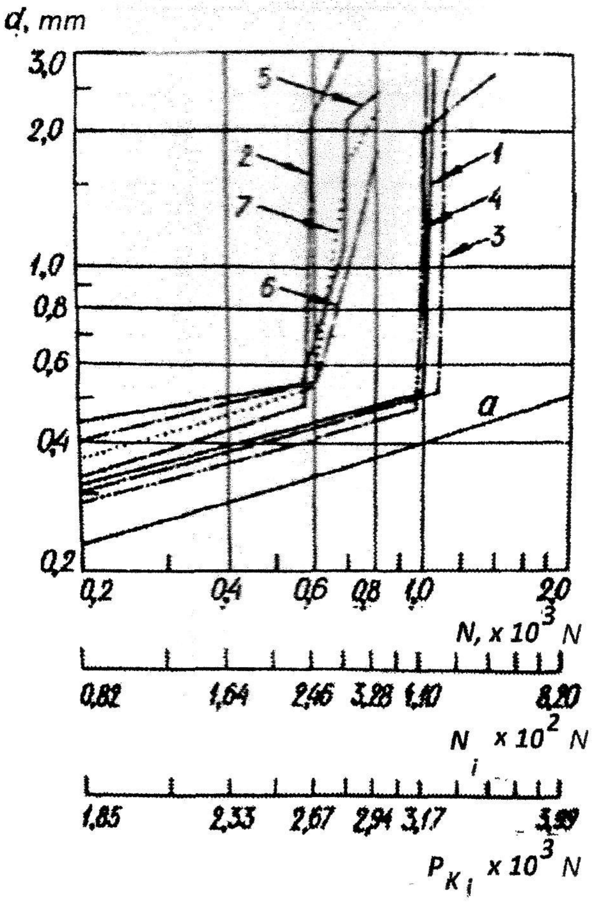

Fig. 6. Relation of wear spot (d) with the axial loading (N), loading on one ball in the theoretical point of contact (N_i) and average initial pressure in the contact point (P_c) for fluids: 1 – Laprol-2502-2-70; 2 – Anderol-500; 3 – Orites 210 DS; 4 – KSM; 5 – dibutylphtalat; 6 – monoglycidyl ether of benzylphenils; 7 – monoglycidyl ether of xilylphenils.

- statistics copolymers of propylene and ethylene oxides (%) Orites (4);
- blockcopolymers of ethylene oxide (6-18%) and propylene oxide on the base of glycerin (5);
- statistics copolymers of propylene oxides and ethylene oxides (70%) on the base of glycerin (6);
- polyethyleneglycol PEG-400 (7);
- copolymer of propylene oxides (30%), ethylene oxides (67%) and glycerin residua (3%) (molecule with star jointing of bonds; number of opened oxygen groups is minimum (8);
- Syntheso D202 (9);
- Syntheso D201 N (10);
- Hydropol-200 (11);
- Proxanol CL-3 (12).

As we can see from the Fig.12, when molecular mass increases loading capacity of polyglycols increases linearly, more over for each class of polyglycols there is different inclination of straight line to the abscissa axis.

By increasing of the inclination angle there is a row of polyglycols:

$$(1) < (6) < (2) < (3,4) < (5). \quad (30)$$

By the prognosis of N_i when M=10000 there is a row of polyglycols:

$$(1) < (6) < (2) < (5) < (3); \quad (31)$$

$$N_i, N: 345 < 418 < 542 < 675 < 695. \quad (32)$$

With information of testing (fig.1-11) on seizure loading (τ=60 s) by relations $d_H=f(N)$ and $d_w=\psi(N)$ we can estimate antiwear properties with formulas (12), (13), (14), (15). Calculations are represented in Tabl. 8.

As we can see from the tabl. 8, values of criterions of antiwear properties of oils (τ=60 s; step-by-step loading) are different from the ones when τ=4 hours and N=const=200 N, that is why J_1-J_4 can be reliable assessments of antiwear properties.

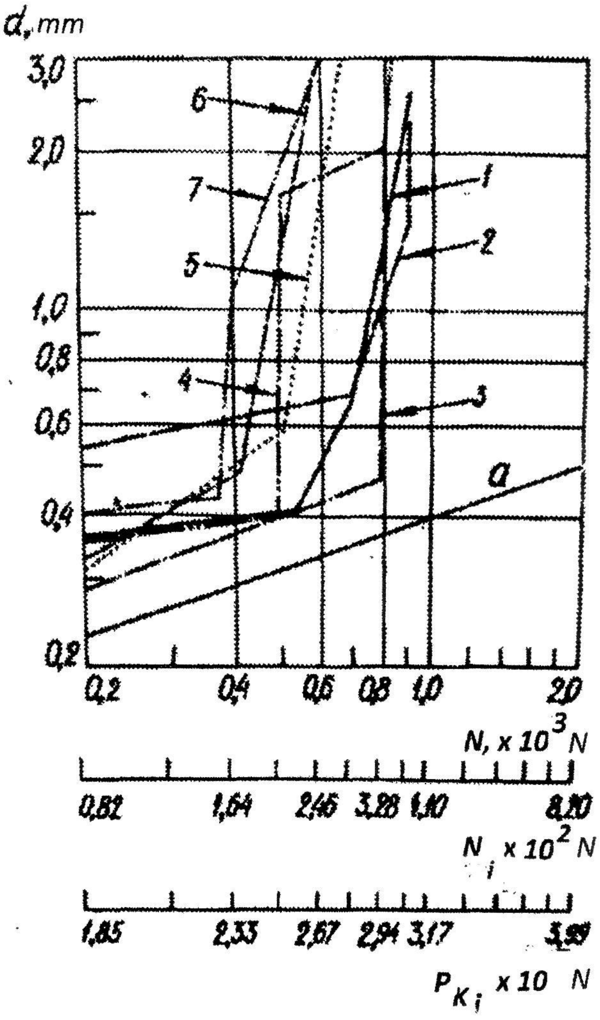

Fig. 7. Relation of wear spot (d) with the axial loading (N), loading on one ball in the theoretical point of contact (N_i) and average initial pressure in the contact point (P_c) for fluids: 1 – lowmolecular polyethylene (fluid); 2 – polyphenilether Ф4E; 3 – polybutene for succynimide additives; 4 – polybutene "Tredcat-99"; 5 – Risella-33+50% of polybutene; 6 – Risella-33+30% of lowmolecular polyethylene; 7 – Risella-33+30% of polybutene for succyimide additives.

This is confirmed by correlations of criterions of such pairs of oils: Risella-33/5350, Syntheso D201 N / Syntheso D 201, Laprol 2502/ Laprol 1502, Risella-33+50% PVBE / Risella-33 (100%), Risella-33+50% PVBE / PVBE (100%) (tabl.9), that is why new criterions show another side of antiwear properties of oils in comparing to known ones, which are obtained at low loadings and long-duration tests.

Table 7

Antiwear properties of mixtures (f=19 s^{-1}, τ=4 hours, N=200 N, n=1470 rot./min.)

Basic oil	Additive		Diameter of wear spot, mm
	name	%	
		0	0.85
	Polybutene for	5	0.48
Risella-33	succynimide additives	15	0.48
		30	0.48
		100	0.45
		5	0.46
Risella-33	Lowmolecular	15	0.48
	polyethylene	30	0.46
		100	0.47
	Polybutene for		
Risella-33	succynimide additives+	5	0.49
	lowmolecular polyethylene		
Risella-33	Polybutene	50	0.59
		0	0.46
NKM-70	Polybutene for	5	0.50
	succynimide additives	15	0.50
		30	0.47
		0	0.64
		1	0.60
Orites-210 DS	Glycerin	5	0.74
		10	0.79
		100	0.64

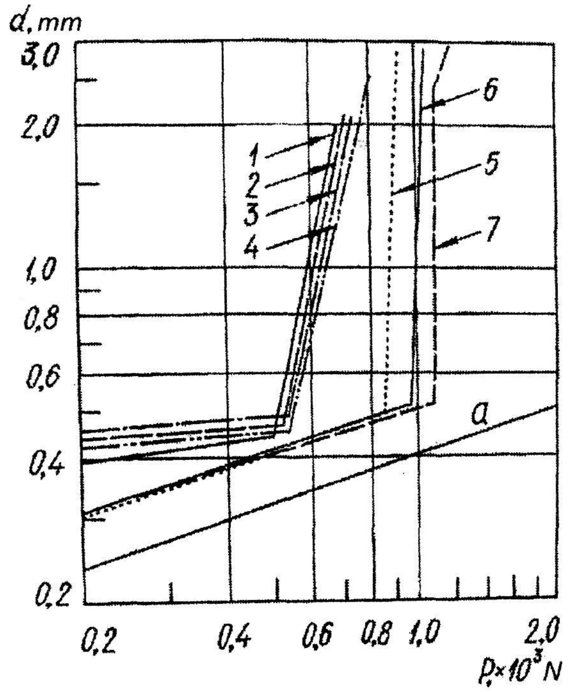

Fig. 8. Relation of wear spot (d) with the axial loading (N) for linear polypropyleneglycols and statistic copolymers of ethylene and propylene oxides:
1 – Laprol 202; 2 – Laprol 602; 3 – Laprol 1002; 4 – Laprol 2002; 5 – Laprol 1502-2-70; 6 – Laprol 2502-2-70; 7 – Orites 210 DS.

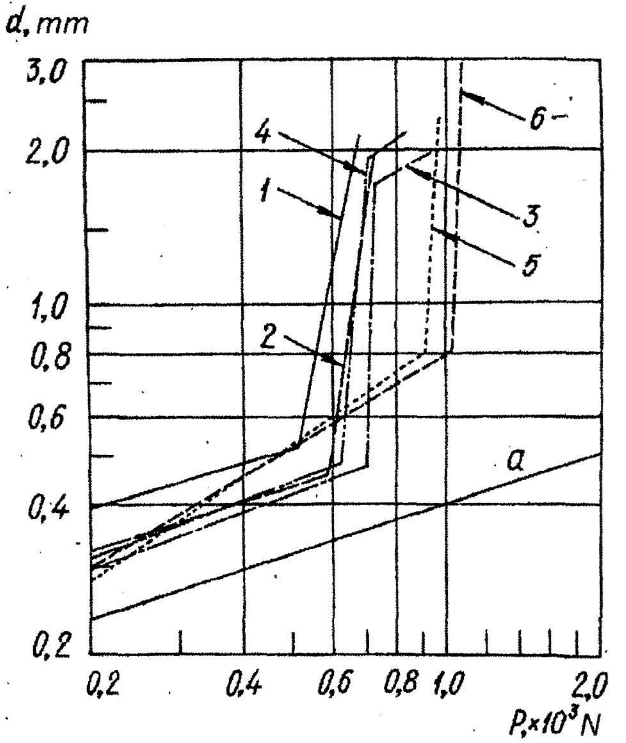

Fig. 9. Relation of wear spot (d) with the axial loading (N) for ramified polypropylene on the base of glycerin:
1 – Laprol 503; 2 – Laprol 3003; 3 – Laprol 3503-2-70; 4 – Laprol 3503-2-65; 5 – Laprol 5003; 6 – Laprol 10003-2-70.

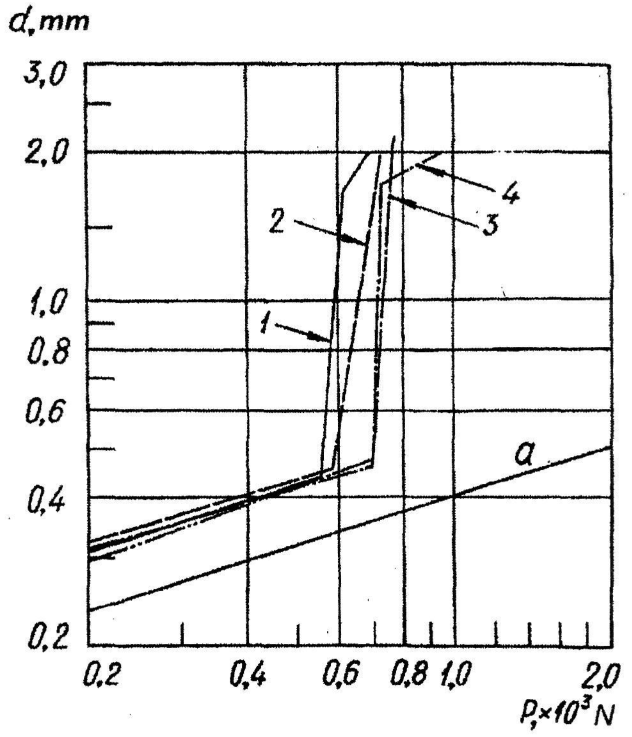

Fig. 10. Relation of wear spot (d) with the axial loading (N) for ramified polypropyleneglycols:
1 – Polyol LG-56; 2 – Laprol 3003;
3 – Syntheso D 201 N; 4 – Laprol 3503-2-70.

Table 8

Criterions of assessment of oils antiwear properties

Oil	τ=60s; step-by-step loading				τ=4 hours; N=200 N=const	
	J_1, mm	J_2, mm	J_3, mm	J_4	d_3, mm	J_4^*
Laprol 2002	0.4425	0.1407	0.1429	0.5122	0.47	0.9915
Laprol 1500	0.4076	0.0848	0.0853	0.2646	0.76	2.2203
Laprol 2500	0.4306	0.0987	0.0997	0.2981	0.66	1.7966
Orites 270 DS	0.4302	0.0897	0.0901	0.2675	0.64	0.7119
Syntheso D 201	0.3870	0.0835	00840	0.2768	0.61	0.5847
Syntheso D 201 N	0.4281	0.1049	0.1053	0.3284	0.56	0.3729
Hydropol-200	0.6990	0.3587	0.3629	1.0492	0.78	2.3051
Proxanol CL-3	0.3769	0.0550	0.0563	0.1943	0.83	2.5169
Risella-33	0.4680	0.1820	0.1882	0.6907	0.85	2.6017
5350	0.3278	00470	0.0471	0.1730	0.55	1.3305
PVBE (100%)	0.4816	0.1503	0.1728	0.4674	0.56	1.3730
Risella-33+ 50% of PVBE	0.4910	0.2010	0.2230	0.7147	0.63	1.6690

Table 9

Comparable characteristic of antiwear properties of oils based on the criterions d_w, J_1-J_4

Oil	τ=60s; step-by-step loading				τ=4 hours; N=200 N=const	
	J_1/J_1'	J_2/J_2'	J_3/J_3'	J_4/J_4'	d_3/d_3'	$J_4^*/J_4^{*\prime}$
Risella-33/5350	1.428	3.872	3.996	3.992	1.545	1.955
Syntheso D201 N/ Syntheso D 201	1.106	1.256	1.254	1.1867	0.918	0.866
Laprol 2502 / Laprol 1502	1.056	1.164	1.169	1.127	0.868	0.809
Risella-33+50% PVBE / Risella-33 (100%)	1.049	1.104	1.185	1.035	0.741	0.642
Risella-33+50% PVBE /PVBE(100%)	1.020	1.337	1.291	1.529	1.125	1.216

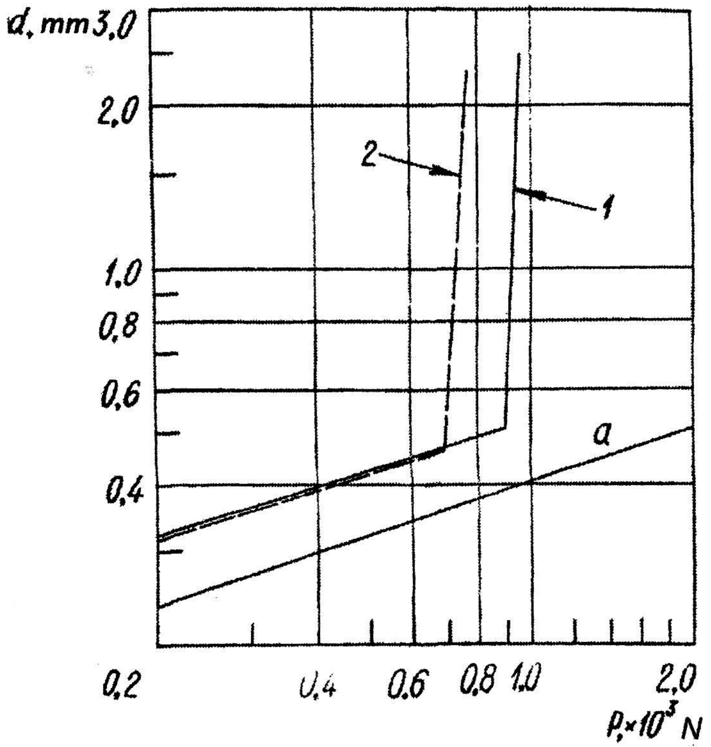

Fig. 11. Relations of wear spot (d) with loading (N) on one ball in theoretical point of contact of polyglycol oils: 1 – Syntheso D-201 N; 2 – Syntheso D 201.

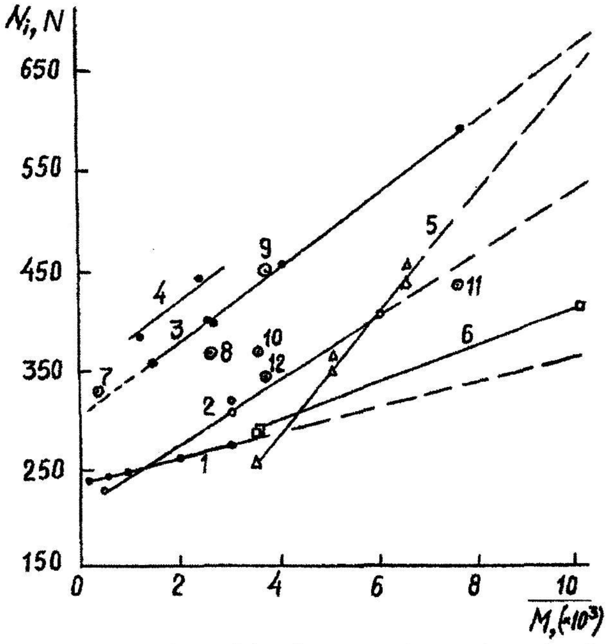

Fig. 12. Relation of loading capacity with molecular mass of polyglycols during testing on four-ball friction machine: 1 – linear polypropylene; 2 – ramified polypropyleneglycols on the base of glycerin ; 3- statistic copolymer of propylene oxide and ethylene oxide (70%) Laprol; 4 – statistic copolymer of propylene oxide and ethylene oxide (%) Orites; 5 – blockcopolymer of propylene oxide and ethylene oxide (6-8%) on the base of glycerin; 6 – statistic copolymer of propylene oxide and ethylene oxide (70%) on the base of glycerin; 7 – polyethyleneglycol PEG-400; 8 – copolymer of propylene oxide (30%), ethylene oxide (67%) and glycerin residua with the star structure of molecule; 9 – Syntheso-202; Syntheso-201 N; 11 – Hydropol- 200; 12 – Proxanol CL-3.

Conclusions

1. Analysis of literature shows that solubility of oils in ethylene and of ethylene in oils at high pressure decreases when molecular mass and viscosity increase, when physic-chemical properties of hydrocarbon oils are not similar with ethylene, more over hydrocarbon oils with normal structure are less soluble in the ethylene than ramified.

2. Wearing of specimens from bronze during lubrication with polyglycol oils 1,31-5,86 time in friction on BK-11 and 1,11-4,84 time in friction on BK-6 is bigger than with naphtene oil.

3. Results of recurring tests on four-ball friction machine of oils: a) Risella-33[(1)], Risella-33[(2)], Orites-270 DS, Laprol-2002, Syntheso-D 201 (1 ser.) б) Risella-17, Risella-33, NKM-40, NKM-70, 5350, Vitorex-334, Esso-Christo, Orites-270 DS (3 ser.) (n=5); в) oils EBPE, Risella-33+5% of Orites-270 DS, Laprol-2502 +20% of EBPE, Laprol-2502 +20% of EBF, Laprol-2002+20% of EBF, Laprol-2002 +20% of EBPE (2 ser.) are showed homogeneous (α=0.05) dispersion of this row and data proxy intervals for average value are ±0.0097; ±0.0177; ±0.0164; ±0.0113.

4. The increasing of moisture in polyglycol oils decreases antiwear properties of oils and quality indexes of polyethylene.

5. Testing of mixtures of polyglycol oil and glycerin shows, that antiwear properties of such mixtures substantially become worse when content of glycerin is more than 3% in polyglycol oil. Input of viscous polybutene additives to naphtene oils up to 5% decreases wear of steel, and input of more than 5% – not substantially influences on wear.

6. Testing of wear from loading during long-duration tests, which determine temporary resistance of lubricant to thermomechanical influences shows the advantages of Risella-33 over naphtene oil NKM-40 and advantages of polyglycol oil Laprol over Orites. Input of viscous additives into naphtene oil also decreases wear during long-duration testing, but critical loadings do not change much.

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Проблеми вибору мастил для етиленових компресорів високого тиску. 4. Дослідження антифрикційних властивостей нафтенових і полігліколевих мастил під час високих навантажень твердих пар тертя

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Досліджено антифрикційні властивості нафтових та полігліколевих олив при невеликих навантаженнях на пари бронзи: вольфрам-карбідного сплаву ВК-6 (ВК-11) – графелон-20-ВК-6 (ВК-11) і великих навантаженнях на пари вальникових висохромованих сталей ШХ-15 – ШХ-15. Нові кореляції в'язкотермічних та антифрикційних властивостей різних полігліколевих олив дозволяють створити ефективні композиції на їх основі. Виявлено залежність величини навантаження від молекулярної маси різних поліглеколів, плями зносу від осьового навантаження та граничного навантаження від концентрації добавок в нафтенових та мінеральних оливах. Середньоквадратичне відносне відхилення діаметра плями зносу від діаметра за Герцом дає узагальнюючу оцінку протизносних властивостей мастильних масел.

Ключові слова: мастильні матеріали, етиленові компресори, чотирикульова машина тертя, властивості, бронза, графелон-20, мінеральні, нафтенові, полігліколеві та полібутенові оливи.