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ANALYSIS OF THE MODERN OIL VISCOSITY CHANGES DURING THEIR OPERATION IN COMBUSTION ENGINES

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Abstract

During normal operation, oxidation products gradually foul lubricating oil and external contaminants like fuel, water, sulphur compounds and friction nodes wearing products. As a result, lubricating oil changes its properties, among other things viscosity.

In normal service conditions of marine diesel engines lubricating oil viscosity increases due to vaporizing of lube oil light ends during operation in high-temperature areas and oxidation process. Quantity of organic particulates accumulated in lubricating oil increases as a result of oxidation process. Oxidation products have bigger than lubricating oil molecular weight. So as to prevent oxidation process-lubricating oils are provided with antioxidant additives. On the other hand mechanical breakdown of high molecular substances in diesel engine bearings and gas oil leakages cause lubricating oil viscosity drop.

The test results presented in the paper show that the lubricating oil viscosity during its operation in the internal combustion engines decreases. The value of viscosity decrease depends mainly on the motor's technical condition, the amount of oil in lube oil system, mode of ignition and its operation. Viscosity tests were performed for the lubricating systems of different engines on a Haake III Mars rheometer at 90 °C for variable shear rates. Additionally, in order to determine engine condition, the detail analysis of the tested oil chemical content has been made oil using Spectrol Q100 spectrometer. In the most cases, the research results indicate lubricating oils viscosity decrease and it is possible to determine the relationship between the dynamic viscosity changes and shear rates for the particular engines.

In authors opinion the viscosity drop of the tested modern lubricating oils may be caused by better antioxidant additives, which effectively moderate or even prevent the oxidation process. Lubricating oils viscosity drop is dangerous phenomena due to the lowering of the bearings capacity force and possibility of boundary friction.

Keywords: *lubricating oil deterioration, viscosity, operating time, combustion engine*

1. Introduction

During normal operation, lubricating oil is gradually fouled by oxidation products and external contaminants like fuel, water, sulphur compounds and friction nodes wearing products. As a result, lubricating oil changes its properties, among other things viscosity.

In normal service conditions of marine diesel engines lubricating oil viscosity increases due to vaporizing of lube oil light ends during operation in high-temperature areas and oxidation process. Quantity of organic particulates accumulated in lubricating oil increases as a result of oxidation process. Oxidation products have bigger than lubricating oil molecular weight. Lubricating oil molecular weight is 300, resins molecular weight is about 600 and asphaltenes molecular weight is higher than 1000 [8]. Lubricating oil is the dispersion mixture which viscosity in specified temperature depends on the ratio of disperse phase to total mixture volume. Increase of dispersion phase volume (in case of lubricating oil it means increase of particulates quantity and size) causes lubricating oil viscosity growth.

Lubricating oil fouling by water (cooling system failure, condensation of water from air caused by idle run or partly loaded diesel engine) and fuel (fuel system failure) is also possible in marine diesel engines working conditions [1, 2]. If water gets into lubricating oil than dispersants remaining in it (which act equally well on solid and liquid insoluble matters) act on water and finally make water-oil emulsion. These emulsions are characterized by reduced viscosity.

If fuel gets into crankcase and contaminates lubricating oil (as a result of fuel valves failure), it causes lube oil viscosity drop in case of gas oils or viscosity growth in case of heavy fuels.
Research results of lubricating oils deterioration in trunk piston diesel engines show that if oil is not contaminated by water or light fuel than its viscosity slightly rises during operation. Both in standard and extended operations periods (until 17 000 h) this growth was a few percentages and none case of exceeding the upper lube oil viscosity limit was observed. Bigger lubricating oils viscosity changes were observed in engines lube oil systems with simultaneous increase of solid impurities. If solid impurities mass fraction is stable, the lubricating oils viscosity changes do not exceed 5% [3, 4, 6, 7, 12, 13].

So as to lower lube oils freezing temperatures and improve its viscosity indexes specified high-molecular substances are added to base oils. The drawback of these substances is that they are sensitive to mechanical shearing loads. Shearing values in diesel engines bearings can be about 10^6 s^{-1}. Mechanical breakdown of high-molecular substances takes place in these conditions and consequently non-reversible lubricating oils viscosity drop. The phenomenon partly compensates lubricating oils viscosity growths caused by raise of solid impurities content [11].

2. Research methodology

Lubricating oil samples were taken from combustion engines operated in various conditions (marine engines and motorcar engines). Tested oils and engines with their operation periods are summarized in Tab. 1.

Tab. 1. Tested oils and engines

Engine manufacturer	Oil manufacturer	Viscosity Class SAE	Oil type	Engine Type	Operation period
Toyota	Castrol Professional A3	10W40	semi synthetic	petrol	13 400 km
Volkswagen	Shell Helix AVL	5W30	synthetic	diesel	21 000 km
Caterpillar	Fuchs Titan Truck Plus	15W40	semi synthetic	diesel	1 000 h
Caterpillar	Fuchs Titan Truck Plus	15W40	semi synthetic	diesel	1 300 h

The studies included two samples: fresh oil sample and used oil sample taken from engine lubricating oil system just before planned oil exchange. Dynamic viscosity studies were performed by means of Haake Mars III rheometr. The device enables tests for temperatures range from -10ºC to 95ºC and for shear rates range from 10 to 200 000 s^{-1}. The studies were conducted under conditions at most close to real operating conditions in engines from which the samples were taken. Testing temperature was 90ºC whereas shear rates were changed from 100 s^{-1} to 73 000 s^{-1}, which is the maximum shear rate possible to obtain on Haake Mars III rheometr. Real shear rates in the combustion engines friction nodes differ greatly. They mainly depend on oil clearance and mating elements relative velocity.

So as to determine possible causes of the tested lubricating oils viscosity change the detail analysis of the chemical content has been made. Spectrol Q100 spectrometer, which can specify content of 24 chemical elements in the examined oils, was used for this purpose.

On this basis the concentration drop of the elements came from lube oil additives and concentration growth of the elements originate from engine wear was determined.

3. Research results

Research results for each individual engine are presented below.

3.1. Toyota Yaris 1.0 L, petrol engine, used oil sample after 13393 km.

That car was used in combined mode with maximum rotational speed about 3500-4000 rpm. Lubricating oil Castrol Magnatec Professional A3 changes (from the beginning of the engine operation) were performed before the manufacturer ordered mileages, which was estimated at 15000 km. The studies reflect the mileage from 73507 to 86900 km. Lubricating oil system capacity was 3.5 l.

Dynamic viscosity changes for new and used Castrol Magnatec Professional A3 oil versus shear rate was presented in Fig. 1.

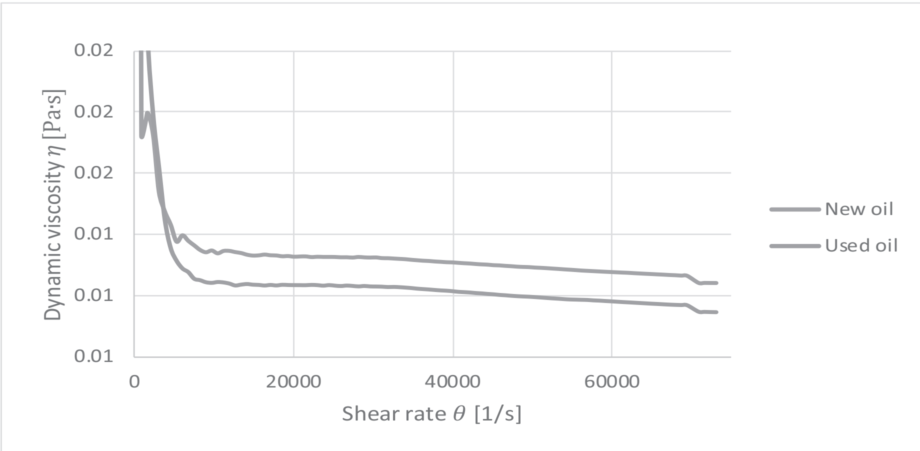

Fig. 1. Dynamic viscosity changes for new and used Castrol Magnatec Professional A3 motor oil

As it's shown in the Fig. 1, dynamic viscosity of used oil is lower than dynamic viscosity of the new oil, practically in the whole range of the shear rates. Moreover, the viscosity decrease by the shear rates over 10.000 s-1 has a cogenial value. For the gained results, comparisment in the tabelar form has been performed and showed in the Tab. 2.

Tab. 2. Castrol Magnatec Professional A3 lubricating oil dynamic viscosity changes

		Average viscosity for several shear rates							Average value
Shear rate	[1/s]	9752	20047	30340	39900	50196	59757	72951	40420
New oil viscosity	[mPas]	0.013	0.013	0.013	0.013	0.012	0.012	0.012	0.013
Used oil viscosity	[mPas]	0.012	0.012	0.012	0.012	0.011	0.011	0.011	0.012
Viscosity change	[mPas]	0.078	0.069	0.071	0.071	0.074	0.074	0.076	0.073
Viscosity change	[%]	7.8%	7.0%	7.1%	7.2%	7.4%	7.5%	7.7%	7.38%

The analysis, showed in the Tab. 2, has shown that average decrease of used oil viscosity in comparison to the new oil, has reached 7.38 %. This value can be accepted as a normal and allowed decrease [11]. In order to check the motor condition, the spectral analysis has been performed. Results of the analysis are shown in the Tab. 3.

Tab. 3. Chemical elements content in Castrol Magnatec Professional A3 engine oil

		Ag	Al	B	Ba	Ca	Cd	Cr	Cu
New oil	[ppm]	0.613	2.196	178.44	0.223	2140.3	0.733	0	0.259
Used oil	[ppm]	0.479	12.271	62.975	1.105	3096	1.004	2.581	7.341
		Fe	K	Mg	Mn	Mo	Na	Ni	P
New oil	[ppm]	0.415	0.633	20.262	10.333	63.726	0.154	3.424	129.5
Used oil	[ppm]	36.493	194.82	32.513	9.424	71.839	4.884	3.271	986.3
		Pb	Si	Sn	Ti	V	Zn	H	C
New oil	[ppm]	0.746	3.771	0	2.024	0.519	867.7	126000	185000
Used oil	[ppm]	1.499	25.221	0	1.909	1.645	1027	136000	219000

Taking into account the small volume of the oil in the engine, considerable increase of the cooper and iron concentration in the operation time can be observed. This concentration increase clearly proves wearing of the friction elements in the engine.

3.2. Volkswagen Touran 2.0 Tdi, diesel engine, used oil sample after 21.000 km

This vehicle was equipped with diesel particulate filter and was mainly used in the city mode. Oil samples of Shell Helix AVL have been taken in the mileage range of 87.803-108.640 km. Recommended maintenance time for this car is 30, 000 km and the nominal volume of the oil in the engine is estimated on 4.68l.

Oil viscosity dependence on the shear rate is shown in Fig. 2.

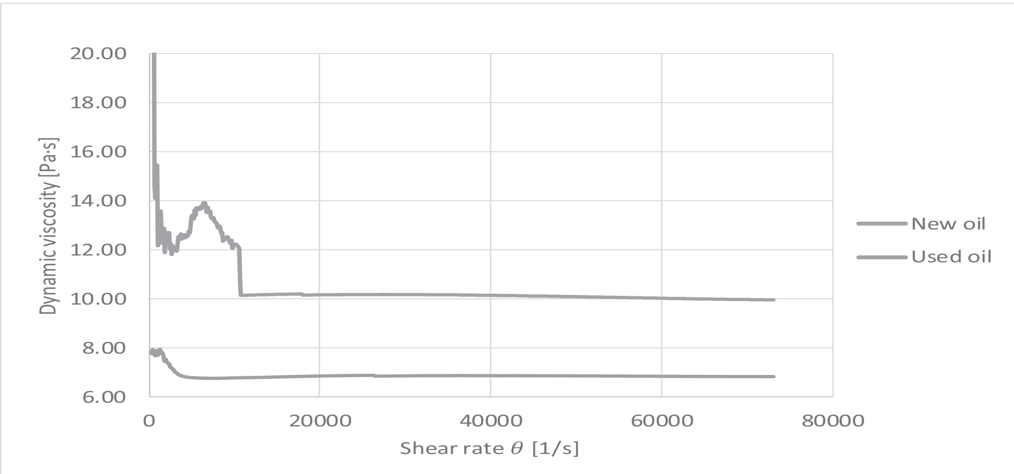

Fig. 2. Dynamic viscosity changes for new and used Shell Helix AVL motor oil

Dynamic viscosity of the used oil is lower than viscosity of the fresh oil in the full scope of the shear rates. Moreover, the shear rate has no influence on the dynamic viscosity, what suggest, that Shell Helix AVL has a Newtonian fluid properties and it does not change with the operation time. By the Castrol Magnatec Professional A3 oil sample, dynamic viscosity was decreasing by shear rate increase. Possible cause of this difference is fact, that Castrol Magnatec Professional A3 is a semi-synthetic oil; on the other hand, Shell Helix AVL is a full synthetic motor oil. It should be checked and proved by the other research.

In order to estimate viscosity's decrease in oil operation time, adequate calculations have been performed and results are shown in Tab. 4.

Tab. 4. Shell Helix AVL lubricating oil dynamic viscosity changes

		Average viscosity for several shear rates							Average value
Shear rate	[1/s]	10010	20030	30040	29990	49970	59980	73000	39003
New oil viscosity	[Pas]	12.26	10.20	10.21	10.18	10.13	10.06	9.99	10.43
Used oil viscosity	[Pas]	6.80	6.88	6.88	6.89	6.88	6.87	6.85	6.86
Viscosity change	[Pas]	0.44	0.32	0.32	0.32	0.32	0.31	0.31	0.33
Viscosity change	[%]	44.5%	32.5%	32.5%	32.3%	32.0%	31.7%	31.4%	33.85%

Viscosity decrease of the Shell Helix AVL oil, which is bigger than 30%, is unacceptable. It should be noticed, that in this case recommended operation time between oil changes is estimated on 30 000 km. Other research [9] shows that already after 14 000 km, this oil viscosity has dropped down in 25.5%, what was a limit value and after this time, the oil should be changed. Such a big viscosity decrease could be caused by the engine condition or manner of use. In order to estimate the engine condition, the spectra analysis has been performed and the results are shown in Tab. 5.

Tab. 5. Chemical elements content in Shell Helix AVL engine oil

		Ag	Al	B	Ba	Ca	Cd	Cr	Cu
New oil	[ppm]	0	8.669	0.378	0.372	1627.5	0.0067	0.001	0.094
Used oil	[ppm]	0.196	60	2.213	0.623	1372	0.283	18.263	36.783
		Fe	K	Mg	Mn	Mo	Na	Ni	P
New oil	[ppm]	1.14	7.437	6.813	1.277	2.944	4.817	0.336	698.42
Used oil	[ppm]	572.156	11.96	10.423	13.286	5.016	8.653	10.36	452.3
		Pb	Si	Sn	Ti	V	Zn	H	C
New oil	[ppm]	1.638	15.526	0	0.414	0.132	828.02	136000	252000
Used oil	[ppm]	10.686	186.41	0	1.163	0.873	533.16	168000	254000

Significant increase of iron and cooper indicates on the intensive wear of the friction nodes in the engine, what might be caused by incorrect exploitation and lower oil viscosity. Lower viscosity, in turn, might be caused by the leaks of unburned gas oil.

3.3. Caterpillar 3512B, V12, 4-stroke-cycle diesel engine, used oil sample after 1000 h

The Caterpillar 3512B engine provides the main drive of the harbour tug. Nominal rotational speed of the engine is 1 600 rpm and volume of the oil system – 625 l. Recommended by the producer operation time between oil changes is 1.000 hours. Oil dynamic viscosity dependence on the shear rate for the fresh and used Titan Truck Plus 15W40 oil, used in this engine, is shown on Fig 3. As its shown on the Fig. 3, viscosity of the used oil is lower than viscosity of the fresh oil in the full range fo the shear rates. For the shear rates higher than 10.000 s^{-1}, the characteristics are almost the same, with the constant difference – value of the viscosity decrease.

In order to estimate viscosity decrease, the relevant calculations have been performed and the results are shown in Tab. 6.

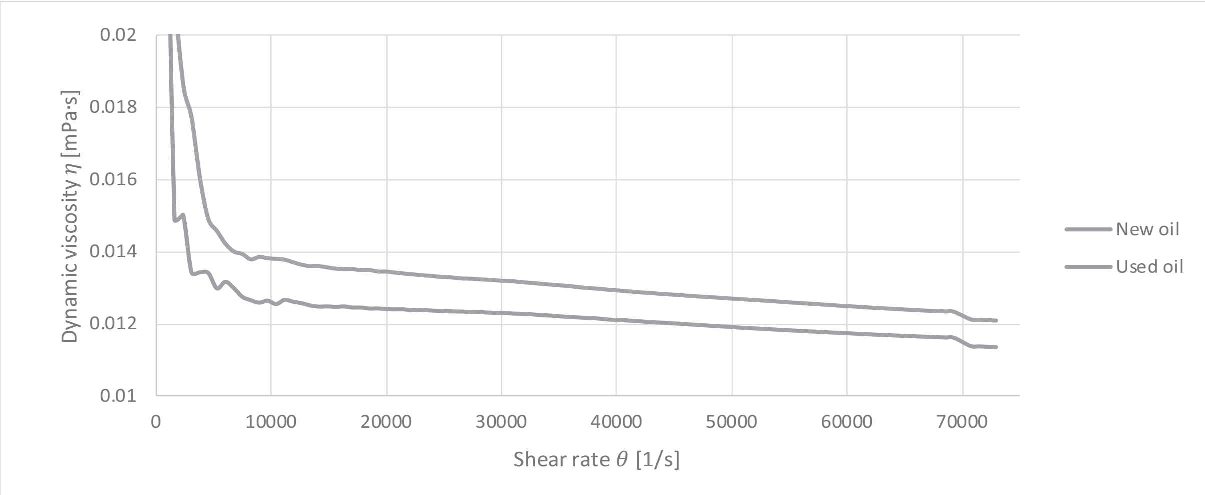

Fig. 3. Dynamic viscosity changes for new and used Titan Truck Plus engine oil

Tab. 6. Titan Truck Plus lubricating oil dynamic viscosity changes

		Average viscosity for several shear rates							Average value
Shear rate	[1/s]	9750	20046	30340	39900	50195	59757	72952	40420
New oil viscosity	[Pas]	0.0138	0.0135	0.0132	0.0129	0.0127	0.0125	0.0121	0.0130
Used oil viscosity	[Pas]	0.0126	0.0124	0.0123	0.0121	0.0119	0.0118	0.0114	0.0121
Viscosity change	[Pas]	0.0857	0.0778	0.0681	0.0643	0.0628	0.0608	0.0614	0.0687
Viscosity change	[%]	8.57%	7.78%	6.81%	6.43%	6.28%	6.08%	6.14%	6.87%

As shown in Tab. 6, the average oil viscosity decrease for the Caterpillar 3512B engine has reached 6.87% in the whole operation time, what is an acceptable value, because limit value for this engine is 20% [5]. Results of the spectral analysis of the chemical elements contamination in the Titan Truck Plus oil, after 1.000 h operation time, are shown in in Tab. 7.

Tab. 7. Chemical elements content in Titan Truck Plus engine oil

		Ag	Al	B	Ba	Ca	Cd	Cr	Cu
New oil	[ppm]	0.264	4.225	0	0.457	2704.4	1.136	0.284	0
Used oil	[ppm]	0.262	5.031	4.307	0.246	3488.3	1.134	0.376	3.816
		Fe	K	Mg	Mn	Mo	Na	Ni	P
New oil	[ppm]	0	2.472	9.425	2	9.281	48.766	1.362	1261.1
Used oil	[ppm]	1.271	1.717	12.037	1.596	9.625	25.44	1.229	1233.5
		Pb	Si	Sn	Ti	V	Zn	H	C
New oil	[ppm]	1.785	3.553	0	0.612	2.698	1375.7	141000	232000
Used oil	[ppm]	2.172	2.785	0	0.71	2.512	1361.4	138000	238000

Iron and cooper contamination are on the very low level in the used oil, what denotes minor wear of the engine components and effective filtration. Influence on that has also high volume of the oil in the engine system.

Both, viscosity decrease on the low level and contamination of iron and cooper at low level, allow to state, that engine is in a good condition and the oil is well selected for this type of engine.

3.4. Caterpillar 3516 DITA, 4-stroke-cycle diesel engine, used oil sample after 1319 h

Detailed results of the examination of Titan Truck Plus oil, used in Caterpillar 3516 main drive of the harbour tug are shown in the earlier author's paper [9]. This engine was characterised by the quite strong wear, and the oil samples were taken about 1.500 hours before class maintenance. Dynamic viscosity dependence of the fresh and used Titan Truck Plus 15W40 oil, used in Caterpillar 3516 is shown on Fig. 4.

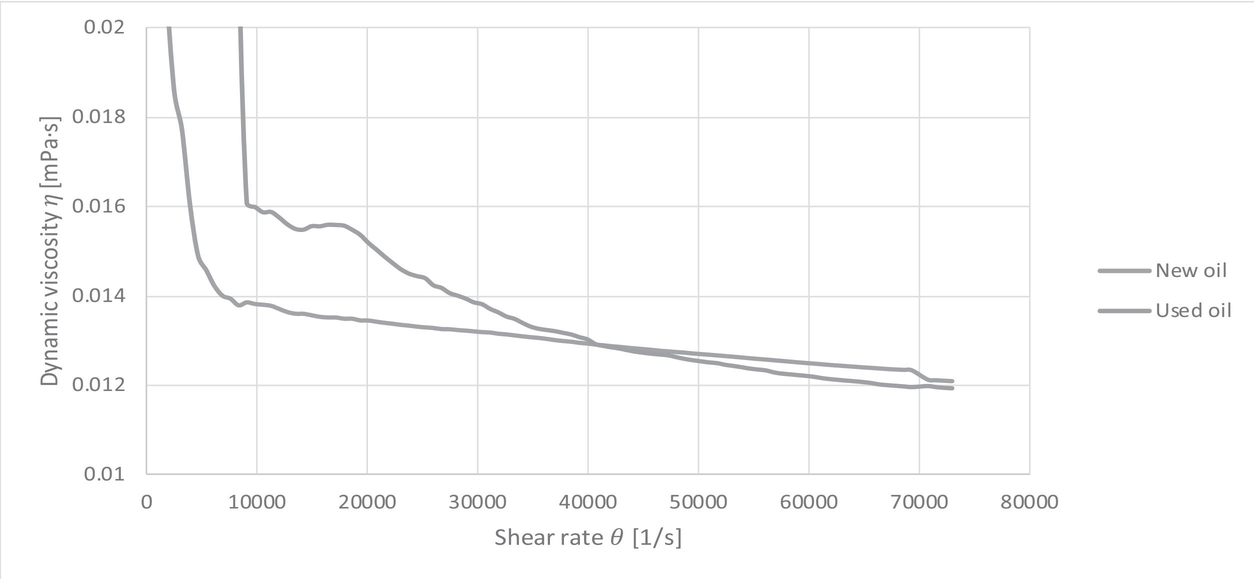

Fig. 4. Dynamic viscosity changes for new and used Titan Truck Plus engine oil

As it is shown on Fig. 4, oil viscosity can increase in the operation time and the oil can change its properties (viscosity) in dependence on operating conditions (shear rate). Difference of the fresh and used oil's dynamic viscosity fits to the range from – 2.5% to +15.5%. However, as it is proved in the paper [10] oil viscosity in the operation time varied in the higher range. Reason of that was abnormal work of the fuel injector, what caused leaks of the gas oil to the oil. Contamination of the chemical elements in oil is shown in Tab. 8.

Tab. 8. Chemical elements content in Titan Truck Plus engine oil

		Ag	Al	B	Ba	Ca	Cd	Cr	Cu
New oil	[ppm]	0.009	1.507	0.0018	0.496	2536.1	0.182	0.112	0
Used oil	[ppm]	0.457	3.081	0.15	0.599	2886.2	0.751	0	4.471
		Fe	K	Mg	Mn	Mo	Na	Ni	P
New oil	[ppm]	1.618	1.496	10.426	0.859	3.64	2.314	0.17	1327.2
Used oil	[ppm]	6.871	1.654	4.888	9.091	5.812	49.331	2.598	1644
		Pb	Si	Sn	Ti	V	Zn	H	C
New oil	[ppm]	0.594	5.779	0	0.216	0.227	1379.2	158000	266000
Used oil	[ppm]	1.844	2.75	0	1.893	1.255	1324.8	140000	205000

Iron and cooper contamination in used oil is on the relatively low level, but in comparison with the other values (Tab. 7), it can be stated, that they are higher. For the relatively low level of iron and cooper in oil, has its influence big volume of oil in the engine system and effective filtration.

4. Conclusions

Presented results show that viscosity of modern lubricating oils used in combustion engines decrease during operations. In authors opinion it probably results, among other things, from application better anti-oxidant additives. Therefore when designing of the friction nodes or lubricating oils selecting that fact should be taken into consideration. Lubricating oil viscosity drop causes bearing hydrodynamic lift decrease and possibility of the boundary friction occurring. Content of iron and copper in used oils samples suggests the boundary friction in tested engines sliding bearings, what has been shown.

Thanks to this work, the correlation between influences of different shear rates on the value of dynamic viscosity was noticed. For the synthetic oil, the viscosity was almost independent on the shear rate, what should be checked and proved by the next researches. In the further researches, the boundary conditions for Newtonian properties of the oil can be estimated. Performance of such a research will allow implementing a proper constitutive model for the further modelling of flow and exploitation parameters of the slider bearings.

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