LUBRICITY OF THERMO-OXIDIZED ENGINE OILS

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Severe temperature load of engine oils effects their relatively rapid thermo-oxidation. Some types of combustion engines cause, a particularly high permanent temperature load of engine oil. Gas combustion engines of cogeneration units of biogas plants are also operated in a similar way. These combustion engines operate for long periods at full load and constant speed. Biogas produced by fermentation of waste organic materials is used as a fuel. Intensity of degradation of engine oil is caused most often by high and long-term temperature load, total number of wear particles and contamination of combustion products. Content of combustion products depend on the individual content of crude biogas.

The aim of the paper is to examine partial effect of long-term temperature load and thermo-oxidative stability of selected types of engine oils for gas engines used in cogeneration units. Mineral oil, hydrocracked oil and full synthetic oil was tested. All of selected oils are recommended for use in gas engines. Oil lubricity was tested on Reichert tester device during standard conditions. As results show, for some types of engine oil a long-term temperature load had positive effect and for some types of engine oil a long-term temperature load had adverse effect on lubricity.

KEYWORDS

engine oil, thermo-oxidation, lubricity, Reichert test, oil degradation

1 INTRODUCTION

Gas combustion engines of cogeneration are operated at constant speed but under variable load. This load depends mostly on requirements of electricity distribution network and also on actual composition of used biogas. Due to forced shutdowns and conditions mentioned before, the thermal load of engine and oil varies. This operational mode has extremely high requirements on engine oils, especially on their thermo-oxidative stability. For that reason, the engine oils of cogeneration units used in biogas plants belongs to most challenging products of its kind. Viscosity, performance parameters and service interval of engine oils are prescribed by manufacturers. The operators perform the oil change, filter cleaning and replacing after reaching relevant service interval. Usually as part of these operations the oil samples are taken and subjected to tribological analysis. Based on analysis result, the next service interval is appropriately modified. This method of control of engine oil change is not optimal, because, as mentioned above, the particular composition of used biogas varies depending on the condition of its production. Actual biogas composition affect also oxidation, sulfatation and nitration rate. The crucial factor for decision about oil change can be limitexceeding of any of these parameters.

Engine oils used in gas combustion engines are operated under severe operating conditions. This is given by many factors such as long-term thermal stress, variable composition combustion products affecting oil chemistry and friction contact surfaces circumstances. In general point of view there can be agreed, that this factors are very important and able to significantly influence engines operation.

As example, [Haycock 2004] states that crankshaft is very important part of combustion engine and its failure is always considered as base failure. The most common reason of loss of operability is abrasive wear of main bearings and rod bearings. The crankshafts journals wear out circumferentially, however, this wear appears significantly on thrust surfaces. This is manifested by oval shape of journals. Inadequate oil filtration leads to higher wear of journals at place of oil feed drilling, caused by higher influence of abrasive particles. Similarly, as in case of journals, the bearing inserts shows even greater wear. The main structural parameters describing technical condition of piston group are axial clearance of piston rings, radial clearance of piston pin and wear of cylinder skirt. Wear of cylinder bore is directly tied to wear of cylinder skirt. In this case, the structural parameter is ovality. Furthermore, there appears conicity, caused by higher wear at highest point of travel of pistons where piston rings change their movement direction. Tightness of combustion chamber is affected by ring gap of compression rings.

As stated in [Dmitrij, Dogopolov 2013], it was found that, when the friction temperature is high enough, the oxidation of iron surfaces always happened. While the oxidation films are not generated or they are broken, the heavy wear dominate.

[Stachowiak, Batchelor 2001] states even more wear mechanism, so called "melting wear". This occurs when contact force and speed are high enough to melt of surface layers.

[Tanaka 2014] states that oil consumption of engine is strongly dependent on oil contact angle on the piston ring surface. Contact angle of oil is related to oil viscosity and piston ring surface texture. Both of these factors can influence engine oil consumption up to 3.8 times.

According to [Committee 1992] there occur two of base geometry of lubricated surfaces called conformal and non-conformal. Conformal surfaces are usually separated by oil or gas film, which is caused by the motion of contacting surfaces in case of hydrodynamic lubrication or by externally applied oil pressure in case of hydrostatic lubrication. Non-conformal lubrication occurs in extremely small region known as Hertzian contact. In case of non-conformal contact, the oil film thickness is very low (in order of roughness) and lubrication pressure is very high. Lubrication of two surfaces may vary between one of four modes depending on operation conditions. This is fluid film lubrication, elastohydrodynamic lubrication, mixed-lubrication and boundary lubrication.

[Bhushan 2001] states that, oil films separating two surfaces are often very thin and can be hardly observed. In general oil film thickness is in range of 1 – 100 µm, individual oil film thickness maybe even thicker of course.

Scientific opinions on sulfatation, oxidation and nitration effect are inconsistent and varies in time. As an example [Cerny 2005] states that exploited oil keeps lubricating and load-carrying capacity can be even higher as effect of polar oxidation products formed while machine operation. Waste oil has to be changed in another reasons than lubricity loss. Waste oils contain, in most cases, mechanical wear particles and lot of soot particles in case of diesel engines. Petrol engines oils can be excessively oxidative deteriorated and they may effect significantly corrosion, etc. [Svoboda 2015] states that lubrication of oil is crucial in term of boundary friction. But [Cerny 2015] also states that while oil oxidation there are created numerous oxidation products, i.e. while nitrification organic nitrates are formed. These substances have polar character and affect positively on carrying-load capacity of lubricating film and lubricity of oil in general. On the other side during operation there is loss of synthetic anti-wear and friction modifiers additives which act also as antioxidants. The final effect is that intensity of oil lubricity degradation after decrease of additives concentration is faster.

[Novacek 2013] states that transition of actual oils from Group I to Group II and III was accompanied with general changes in oil composition. New generation of oils mentioned above deteriorate another way as traditional oils. Nonlinear degradation of most of modern lubricants is determined by antioxidants additive selection and oxidation stability of base oils belonging to Group II and III. This base oils show lower oxidation stability than Group II and III. When this kinds of oils lose antioxidant additives, they deteriorate rapidly. As consequence, most of standard oil analyses gives none of alert when the oil begins degraded or exhibit oil deposits.

[Sejkorova 2013] states that oil lubricity commonly rises by higher viscosity and density, but not in all cases. Mainly, lubricity of oil depends on oil composition. Nowadays, there are many of usable testing methods, which are able to simulate real operation conditions as close as possible. For evaluation of lubricity, procedures described in IP 240, 326, ASTM D 2782, D 2509 and DIN 51434 standards are used.

For a more accurate understanding of various effects experiment was performed which aimed to determine how thermal load affect overall oil degradation. As samples, three recommended kinds of engine oils were used for lubricating of gas engine.

2 MATERIALS AND METHODS

Engine oils used in test:

1. mineral oil with low content of sulphated ash intended for use in stationary gas engines;
2. hydrocracked oil with mid-range content of sulphated ash, without content of Zn, intended for use in stationary gas engines;
3. synthetic oil, without content of Zn, intended for use in diesel engine equipped with a turbocharger.

Detailed description is show in Tab. 1.

Engine oils under test were exposed for t = 312 hours to high temperature in open to the air conditions. Oils samples of equal volume was placed in oil bath so that both bath level and samples level were in the same level. Oil bath was heated by immersion heather controlled by thermostat permanently in the range of 143 ±5°C.

At the beginning and end of each test, the test of lubricity and load-carrying capacity according to Reichert was performed. Test conditions are shown in Table 2.

Lubricity of oil was evaluated by measuring of wear area according to Formula 1. Load-carrying capacity was evaluated using Formula 2. Schematic for surface measurement and view of cylinder roll is shown in Fig. 1.

Furthermore, viscosity of oil at 40°C and 100°C was measured at each beginning and end of appropriate test.

Table 1. Base technical parameters of tested engine oils

Properties	Units	Mineral oil	Hydrocracked oil	Synthetic oil	Standard
SAE classification	-	40	---	5W-30	SAE J300
Density at 15 °C	$kg.m^{-3}$	893	866	861	DIN 51 757
Flash point	°C	240	260	238	DIN ISO 2592
Pour point	°C	-15	- 35	- 45	DIN ISO 3016
TBN	$mgKOH.g^{-1}$	5.5	8.9	---	DIN ISO 3771
Sulphate ash	% hm.	0.45	0.7	0.99	DIN 51 575
Kinematic viscosity at 40°C	$mm^2.s^{-1}$	149	105,00	71.8	DIN 51 562-1
Kinematic viscosity at 100°C	$mm^2.s^{-1}$	14.5	13.40	12.16	DIN 51 562-1

Figure 1. Reichert test – schematic for wear area calculation and view of cylinder rolls exposed to test

$$S = 0{,}785 \cdot h \cdot b \qquad (1)$$

$$U = \frac{2000 \cdot G \cdot 9{,}81}{S} \qquad (2)$$

Where *S* is wear area mm^2; *h, b*is areadimensions of wear area mm; *U* is load-carrying capacity $N.cm^{-2}$; *G* is weight of load kg.

Table 2. Conditions of Reichert test

Load	1.5 kg
Test duration	100 m
Sliding speed	1.7 m/s
Sample volume	25 ml
Temperature	22°C
Roll material	steel, Petrotest 150021
Ring material	steel, Petrotest 150023

Table 3. Conditions of viscosity test - Stabinger viscometer SVM 3000

Dynamic viscosity	0.2 to 20 000 mPa.s*
Kinematic viscosity	0.2 to 20 000 mm2/s*
Density	0.65 to 3 g/cm3*
Repeatability	typical 0.10% / 0.0002 g/cm3 / 0.005 °C
Reproducibility	typical 0.35% / 0.0005 g/cm3 / 0.02 °C
Temperature range	15 to 105 °C (lower temperatures on request)
*) depending on sample type and temperature	

3 RESULTS AND DISCUSSION

Results of lubricity and load-carrying capacity tests are shown in Tab. 4 and illustrated in Fig. 2. The values represent arithmetic mean calculated for each 4 measurements. Fig. 2 also shows error bars calculated by implicit factions in Microsoft Excel.

Results of measurement of dynamic viscosity η, kinematic viscosity ν, density ρ are shown in Tab. 5. Fig. 3 shows changes of kinematic viscosity measured at 40°C and 100°C during the time of 312 h under temperature stress at approximately 143°C. The values represent arithmetic mean calculated for each 4 measurements. Fig. 3 also shows error bars calculated by implicit factions in Microsoft Excel.

Table 4. Results of Reichert test of lubricity and load-carrying capacity of oil film

	Mineral oil	Hydrocracked oil	Synthetic oil	Mineral oil	Hydrocracked oil	Synthetic oil
t/T h/°C	0	0	0	312/143	312/143	312/143
S mm^2	16.120	5.715	11.324	11.801	14.240	14.837
U $N.cm^{-2}$	1841.384	5242.78	2612.700	2496.04	2070.15	2011.141

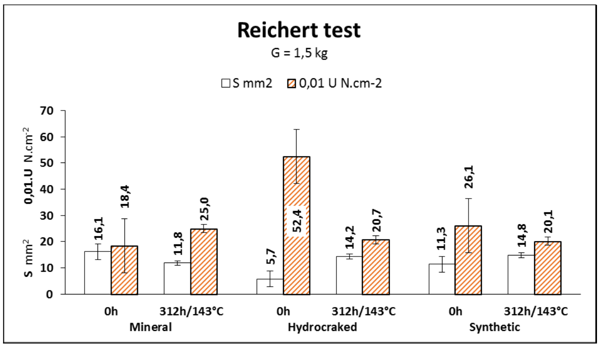

Figure 2. Influence of temperature stress on lubricity and load-carrying capacity of engine oil film

Experimental results proved that long term thermal stress is apparently influencing characteristic of engine oil, because is affecting oil oxidation processes by various degree and speed. Oxidation products are polymerising and presence of polymers alter lubricity, load-carrying capacity and viscosity of oil.

Table 5. Results of viscosity measurement

	Mineral oil	Hydrocracked oil	Synthetic oil	Mineral oil	Hydrocracked oil	Synthetic oil
t/T h/°C	0	0	0	312/143	312/143	312/143
40°C						
η Pa.s	133.29	84.91	57.13	144.65	92.18	55.82
ν $mm^2.s^{-1}$	151.75	99.93	68,21	166,00	109.23	66.53
ρ $kg.m^{-3}$	879	850	837	882	846	835
100°C						
η Pa.s	12.83	11.30	9.57	13.38	11.57	9.28
ν $mm^2.s^{-1}$	15.17	13.92	11.96	15.85	14.22	11.58
ρ $kg.m^{-3}$	843	812	800	846	814	801

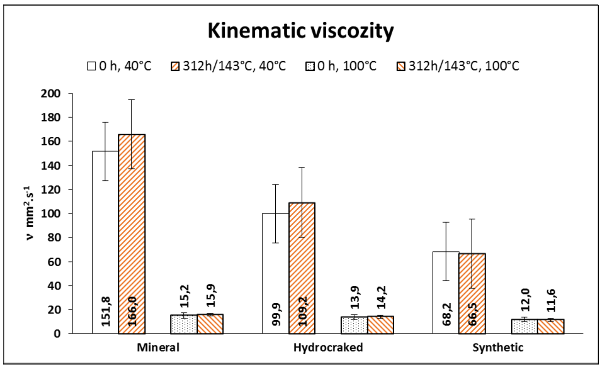

Figure 3. Influence of temperature stress on lubricity and load-carrying capacity of engine oil film

In case of mineral engine oil based on base oils refined by common methods, the lubricity, load-carrying capacity and viscosity are increasing during long term thermal stress. In terms of experimental results, wear area has changed from 16.120 mm^2 to 11.801 mm^2, it means that the lubricity of mineral oil increased by 29.8%, the load-carrying capacity increased from 1841.384 $N.cm^{-1}$ to 2496.048 $N.cm^{-1}$, i.e.by 41.9%, viscosity at 40°C increased from 151.75 $mm^2.s^{-1}$ to 166.00 $mm^2.s^{-1}$, i.e.by 9.3% and viscosity at 100°C increased from 15.17 $mm^2.s^{-1}$ to 15.85 $mm^2.s^{-1}$, i.e.by 4,5% versus baseline values. This kind of oil is therefore not limited in operation by lubricity itself. This corresponds with published conclusions [Cerny 2005], [Novacek 2015].

In case of engine oil hydrocracked oil based on hydrocracked oils, the lubricity and load-carrying capacity are decreasing while viscosity increases during long term thermal stress. In terms of experimental results, wear area has changed from 5.715 mm^2 to 14.240 mm^2, it means that the lubricity of hydrocracked oil decreased by 149%, the load-carrying capacity decreased from 5242.784 $N.cm^{-1}$ to 2070.146 $N.cm^{-1}$, i.e.by 60.5%, viscosity at 40°C increased from 99.93 $mm^2.s^{-1}$ to 109.23 $mm^2.s^{-1}$, i.e.by 9.3% and viscosity at 100°C increased from 13.92 $mm^2.s^{-1}$ to 14.22 $mm^2.s^{-1}$, i.e. by 2.1% versus baseline values. This also corresponds with published conclusions [Cerny 2015].

In case of synthetic engine oil, the lubricity and load-carrying capacity and viscosity are decreasing during long term thermal stress. In terms of experimental results, wear area has changed from 11.324 mm^2 to 14.837 mm^2, it means the lubricity of synthetic oil decreased by 31%, the load-carrying capacity decreased from 2612.700 N.cm^{-1} to 2011.141 N.cm^{-1},i.e.by 23%, viscosity at 40°C increased from 68.21 mm^{2}.s^{-1} to 66.53 mm^{2}.s^{-1}, i.e.by 2.5% and viscosity at 100°C increased 11.96 mm^{2}.s^{-1} to 11.58 mm^{2}.s^{-1}, i.e.by 3.2% versus baseline values. This behaviour corresponds with published conclusions [Novacek 2013]. It is possible also accept his conclusion that most of standard oil analyses give none of alert when the oil begins degraded or exhibit oil deposits.

4 CONCLUSIONS

Experiment proved that:

1. In case of mineral engine oil, the thermo-oxidation process runs gradually from the beginning of operation. Thermo-oxidation products increases adhesion of oil and therefore this is reflected in increase of lubricity, load-carrying capacity even viscosity. The lubricity and load-carrying capacity increased by 30% and viscosity at 100°C increased by 4.5% in this case. Accordingly, thermo-oxidation process of mineral oil can be easily monitored using tribological analyses.
2. In case of hydrocracked engine oil, the increase of adhesion was not observed, lubricity and load-carrying capacity decreased by 150% and viscosity at 100°C increased by 2.5% times. Accordingly, thermo-oxidation process of hydrocracked oil cannot be easily monitored using tribological analyses.
3. In case of synthetic engine oil, the increase of adhesion was not observed, lubricity decreased by 31%, load-carrying capacity decreased by 23% and viscosity at 100°C increased by 3.2%. Accordingly, thermo-oxidation process of synthetic oil cannot be easily monitored using tribological analyses.

Currently used tribotechnical analyses does not provide definite diagnosis in case of observing the thermo-oxidative degradation of highly doped hydrocracked and synthetic oils. It is necessary to look for another suitable indicator, which must include other operating factors, which have been eliminated in this experiment.

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