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LUBRICATING OILS FOR AUTOMOTIVE NATURAL GAS ENGINES

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Abstract: Because of their advantages, natural gas engines are very popular choice today, especially for use in commercial and public vehicles (commercial vehicles, trucks, buses, trains). Lubricant is an important element of the gas engine, as well as of any other type of internal combustion engine. The lubricant has multifunctional role. From reducing friction between surfaces, through transferring heat, neutralizing acids, removing hard carbon deposits and maintaining desired viscosity. In order to fulfill effective, long run and economical functioning of the engine, appropriate lubricant must be selected and used. Also, it has to be compliant with the fuel gas quality, exploitation conditions, environmental requirements et cetera. The purpose of this paper is to present the important properties of lubricating oils for automotive internal combustion engines powered by natural gas.
Keywords: Automotive engine oil, lubrication, lubricant, maintenance

1. INTRODUCTION

Concerns regarding increasing greenhouse gases (GHG) emissions, their negative impact on human health and the environment, and the availability of energy sources, especially alternative fuels for internal combustion (IC) engines, are always actual topics in automotive industry. During the following period, it is expected that the permissible emission limits will still be reduced (by new EURO norms). Therefore, use of automotive IC engines that run on alternative fuels such as natural gas (NG) will be intensified.

For example, in 2011, it was noted that there were about 15 million natural gas vehicles (NGV) in the world [1], and in 2015, their number had increased to 22.3 millions [2]. Leading countries by the number of NGVs in use are Iran, China, Pakistan and Argentina [3], while Serbia in 2014, had 878 registered NGVs and 10 natural gas pump stations [4].

Beside the natural gas fuel, much impact on fuel economy, engine efficiency, and especially GHG emissions is credited to the engine oil itself. Oil quality is determined by many parameters, but the most important are those related to engine design and exploitation conditions. Since the lubricating oils consist of a base oil and additive package, their mix ratio is optimized in order to satisfy all engine requirements during exploitation.

2. INTERNAL COMBUSTION ENGINES

Combustion engines are a well-known technology used in automobiles, trucks, construction equipment, marine propulsion, and backup power applications. Reciprocating internal combustion engines are characterized by the type of combustion: spark-ignited (SI) - gasoline or natural gas engine, and compression-ignited (CI), also known as diesel engine.

The SI engine is based on the Otto cycle, and uses a spark plug to ignite an air-fuel mixture at the top of a cylinder. On the other hand, in diesel engines, air is compressed until the temperature rises above the fuel self ignition temperature. As the fuel is injected into the hot compressed air inside the cylinder, it immediately ignites due to hot compressed air. The combustion gases expand and push the piston toward the bottom dead centre (BDC).

Diesel engines are generally heavier, noisier, more powerful and more fuel efficient than SI engines, and are predominantly used in heavy road vehicles, ships, railway locomotives, and light aircrafts. Gasoline engines are used in most other road vehicles including cars, motorcycles, and mopeds.

Modern engine designs have been developed to take advantage of the diesel process while maintaining the benefits of lean burning. Combustion engines can burn a variety of fuels, including natural gas, light fuel oil, heavy fuel oil, biodiesel, biofuels, and crude oil. In relation to how many fuels engine can run, there are three types of engines today:

- dedicated - these engines are designed to run only on one fuel,
- bi-fuel - these engines have two separate fueling systems that enable them to run on either gas or gasoline, and
- dual-fuel - these engines are traditionally limited to heavy-duty applications, have fuel systems that run on gas, and use diesel fuel for ignition assistance.

Light-duty vehicles are typically equipped with dedicated or bi-fuel systems, while heavy-duty vehicles use dedicated or dual-fuel systems [5].

Natural gas is a fossil fuel that has been recognized as more environmentally friendly than other fossil fuels. Compared with conventional gasoline engines, SI engines using natural gas can run at higher compression ratios, thus producing higher thermal efficiencies but also increased NOx emissions, while producing lower emissions of CO_2, unburned HC and CO. These engines also produce relatively less power than gasoline fueled engines. Natural gas is also used to power CI engines via dual-fuel mode. Thermal efficiency levels compared with normal diesel-fueled CI engine operation are generally maintained with dual-fuel operation, and smoke levels are reduced significantly. Power output is lower at certain conditions than diesel-fueled engines [6, 7]. In both cases the power output can be maintained with direct injection.

3. ENGINE OILS

Irrespective of the structure, purpose and operating conditions of IC engines, engine oil performs the functions such as lubrication, cooling, washing, acid neutralizing, sealing and corrosion protection. For the purpose of lubrication and proper functioning, the same oil lubricates components that have different requirements (piston rings, cylinder liners, crankshaft bearings, camshaft, piston pins, rocker arms, valves). In addition, those tribological pairs are made of different materials and are under different thermal loads during the engine exploitation, which implies that role of engine oil is very complex and important.

ENGINE OILS CLASSIFICATION

In terms of whether it is used for engines with two- or four-stroke duty cycle, oils are divided into the oils for two-stroke and four-stroke engine. The American Petroleum Institute (API) has categorized base oils into five categories. This classification is based on the refining method and the base oil's properties in terms of, among other things, viscosity and the proportion of saturates and sulfur content (see Table 1).

Table 1. Categorization of base oils [8]

Group	Type	Saturates (%)	Sulfur (%)	VI	Manufacturing method
I	Mineral based	< 90%	> 0.03%	80-120	Solvent refining
II	Mineral based	≥ 90%	≤ 0.03%	80-120	Hydro-processing
III	Mineral based	≥ 90%	≤ 0.03%	>120	All hydro-processing
IV	PAO	No	No	170-300	Chemical reactions
V	Synthetics	No	No	-	As indicated

With the change from lowest to highest group, the quality of base oil improves, and therefore the quality of the final product. Quality of base oil have an impact on properties such as viscosity stability, oxidation and thermal stability, volatility, solubility of additives, and foaming.

To determine the quality of engine oil there are used API, ILSAC and ACEA specifications. API specifications classify the engine oils as diesel engine oils (with the first letter "C") and gasoline engine oils (with the first letter "S"). American-Japanese specifications ILSAC - *International Lubricants Standardization and Approval Committee*, classify engine oils into six groups from GF1 to GF6, and European ACEA (*Association des Constructeurs Européens d'Automobiles*), classifies engine oils into three categories:

- ACEA A/B category - gasoline and diesel engine oils for passenger and light comercial vehicles,
- ACEA C category - catalyst compatibility oils for passenger and light comercial vehicles,
- ACEA E category - heavy duty diesel engine oils for heavy commercial vehicles.

Each higher category within these classifications, represents the engine oil: with higher or lower HTHS viscosity (High Temperature / High Share), with specific content of SAPS (Sulfated Ash, Phosphorus, Sulfur), with improved detergent and dispersant properties of oil, with extended replacement interval et cetera.

HTHS viscosity of engine oils is a critical property that relates to the fuel economy and durability of a running engine. Lower HTHS viscosity tends to improve fuel economy and reduce GHG emission, while higher HTHS viscosity provides better wear protection. SAPS content originates mainly from additives, where sulfated ash represents a portion of the lubricant left behind as a deposit after the oil complete burnout. Additives, which contribute to the creation of sulfated ash, are antioxidants, antiwear additives, detergents and additives for basicity improvement. Phosphorus is additive which improves oxidation stability and antiwear properties, while sulfur, beside oxidation stability and antiwear properties, helps in improvement of oil cleaning properties as a part of detergent additives.

As it can be seen from previously given review and insight into the professional literature, standards for natural gas engine oils (NGEO) do not exist, but also there are no standardized tests for estimation of NGEO working performances. On the other end, engine manufacturers generally have widely various requirements, therefore oil approvals are only granted upon successful completion of field trials. Fuel and engine oil condition monitoring, including engine inspection are required during a trial. However, SAE (*Society of Automotive*

Engineers) and ASTM (*American Society for Testing and Materials*) together with engine manufacturers and oil and additive companies have formed a taskforce to develop natural gas engine oil performance categories [9]:

- NG1: Stoichiometric engines,
- NG2: Lean-burn engines,
- NG3: Automotive gas engines.

IMPORTANT PROPERTIES OF NATURAL GAS ENGINE OILS

One of the most important requirements of NG engine manufacturers, is the use of engine oils with low content of sulfated ash. As mentioned before, sulfated ash is residue which remains after the oil is burned during operation. This ash residue is made up of metal sulphates from such additives as barium, calcium, phosphorus, zinc, magnesium and boron. It was found that sulfated ash significantly contributes to the formation of deposites. The deposits prevent heat transfer and cause local temperature rise. When the temperature exceeds a critical limit, deposits act as "hot spots" causing premature fuel ignition and throbbing engine operation. Also, ash deposits cause ring sticking or breaking, plug fouling and valve burning. Therefore, NG engine manufacturers, accurately determine the allowed sulfated ash content in the oil, which corresponds to a gas engine model, such as specification Cummins CES 20074 (max allowed content 0.6 %wt) or Mercedes-Benz MB 229.51 (max allowed content 0.8 %wt) etc. Diesel engines are more sensitive to presence of sulfated ash, especially emission control systems. Sulfated ash causes reduction of their activity or, in extreme cases, block them totally. For example, filters as part of emission control systems, are especially susceptible to particulate matter. According to the ash content (which is measured with DIN 51575 or ASTM D874), engine oils are classified as [10]:

- ashless oils < 0.1 %wt,
- oils with low sulfated ash content 0.1 - 0.5 %wt,
- oils with middle sulfated ash content 0.5 - 1.5 %wt,
- oils with high sulfated ash content > 1.5 %wt.

In accordance with the aforementioned, it is common for NGE oils to belong to, in the worst case, the group of oils with medium containing sulfated ash.

In addition to sulfated ash, it is very important, that these oils should have a low concentration of sulfur. Sulfur has a very negative effect on the catalytic converter, because it quickly adheres to catalytic converter working surfaces, thus reducing the ability of converter to work properly. Nonetheless, sulfur with oxygen builds SO_2 (sulfur-dioxide) which (beside nitrogen-oxide) is the major cause of sulfuric acid formation. Also, the amount of sulfur in the engine depends a lot on the quality of fuel (see Table 2). However, due to the increase of quality of gasoline and diesel fuels, sulfur content in the engine oil comes forward. Future engine emission regulations will have huge impact on engine oil content. Natural gas as an engine fuel, has an average sulfur content about 5.5 mg/m^3 [5] which is 0.0055 ppm, where the most part of sulfur is added as odor additive.

Table 2. Amount of sulfur in unleaded gasoline and diesel fuel [11]

Category	Sulfur amount for unleaded gasoline (ppm)	Sulfur amount for diesel (ppm)
I Category	1000	2000
II Category	150	300
III Category	30	50
IV Category	10	10
V Category	10	10

The engine oil includes sulfur as additive which improves antiwear properties, detergent properties, to inhibit corrosion, as wear modifier and antioxidant. The largest source of sulfur in engine oil are the base oil, antiwear and detergent additives. However, one should be very cautious here, because too low sulfur content may cause the poor antiwear properties of the engine oil. Therefore, optimal sulfur content in engine oils must be carefully determined and examined.

Phosphorus is another element that is limited in oils, primarily because it has a very strong negative impact on the proper functioning of the catalytic converter [12]. Phosphorus can blind over the catalytic reaction sites in the converter, making it less efficient in turning carbon monoxide into carbon dioxide. It is contained in the engine oil as a part of antiwear and antioxidant additives, and especially in ZDDP (zinc-dialkyldithiophosphate) which is very important ingredient of lubricating oil. Current API/ILSAC/ACEA specifications impose 0.06 to 0.08% (600 – 800 ppm) limit on phosphorus. Its replacement is possible with antiwear additives based on sulfur, however, their price is higher and efficiency is at lower level.

Next important parameter for natural gas engine oil is volatility or NOACK value. The NOACK volatility test (ASTM D-5800 or DIN 51581) determines how much weight loss an oil experiences through volatilization. The more engine oil vaporizes, the thicker and heavier it becomes, contributing to poor circulation, reduced fuel economy and increased oil consumption, wear and emissions. Low viscosity oils burn easier (have higher volatility), which may result in higher oil consumption. On the other end, low viscosity oils contribute to higher fuel economy, lower emission of CO_2, CO, HC, NOx and particulate matter. However, with time, light molecules in oil tend to evaporate as the oil is heated, which leading to an increase in the oil's viscosity. This occurence is more evident with mineral base oils compared to synthetic oils. Some of the NOACK values required by API, ILSAC and ACEA specifications are given in the following Table 3.

Table 3. Required NOACK values for engine oils according to API and ACEA specifications [13, 14]

Specification	API SN and GF-5	API CJ-4	ACEA A1/B1-A4/B4	ACEA C1(12)-C3(12)	ACEA C4(12)	ACEA E4,E6,E7 and E9(12)
NOAK value	Max 15%	Max 13% (for SAE 10W-30)	Max ≤ 13%	Max ≤ 13%	Max ≤ 11%	Max ≤ 13%
Used test	ASTM D5800	ASTM D5800	CEC L-040-93	CEC L-040-93	CEC L-040-93	CEC L-040-93

Oil volatility and thermal resistance are important parameters for NGE oils because natural gas combusts at much higher temperatures than diesel fuel. Higher temperatures encountered in natural gas engines trigger the formation of nitrogen-oxide (NOx) that further reacts with engine oil. This process is well known as nitration and can be quite severe, depending upon air-to-fuel ratio, oil operating temperature as well as engine speed (RPM), spark timing, load, ambient air conditions and aftercooling. Nitrogen-oxides enter the engine oil through exhaust gas recirculation (EGR) system and normal blow-by when the explosion that occurs in engine's combustion chamber causes fuel, air and moisture to be forced past the piston rings into the crankcase.

Nitration and oxidation of engine oil leads to:

- Viscosity increase in engine oil due to polymerization,
- Increase of oil acidity,
- Corrosive wear through nitration,
- Engine deposits in the form of varnish in hot areas of the engine, and sludge in cooler areas of the engine which may lead to ring sticking and filter plugging, respectively,
- Filter blockage due to sludge.

The effects of these degradation processes are visible on lubricant parameters such as viscosity, rise in acid number, drop in base number, infrared analysis of used oil, and on engine parameters such as engine cleanliness and bearing corrosion.

4. CONCLUSIONS

Despite some known disadvantages, natural gas vehicles are on a rising implementation trend, especially for applications, such as public transportation, vocational trucks, heavy-haul transport. The main reasons are the following:

- Natural gas is less expensive than gasoline or diesel fuel,
- Natural gas is more abundant than other automotive fossil fuels,
- Natural gas vehicles are far more environmentally friendly than other fossil fuel vehicles.

Clean burning fuels have a direct impact on extending the useful life of the engine's lubricating oil. In conventionally fueled vehicles, engine oil degrades as a result of soot and other impurities from the combustion process that get absorbed into the oil. A cleaner-burning fuel like natural gas, produces less soot, so the oil in natural gas engines should last longer and save a significant portion of planned preventive maintenance funds.

Engine oil formulation is of critical importance for satisfaction of all requirements in order to achieve reliable, economical and as much as possible cleaner engine performance. Therefore, the complexity of the problems that lubricants are trying to solve is at a very high level. At the time of formulating a natural gas engine oil, the following factors are to be considered:

- High resistance to oxidation and nitration,
- Good valve wear performance,
- Low combustion chamber deposites,
- No spark plug fouling,
- Good piston deposits control,
- Good anti-wear and anti-scuff properties,
- Optimized ash content,
- Quality of natural gas,
- The oil sump capacity and quantity of oil consumption,
- The operating parameters and metalurgy of engine components.

Note

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