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Chemical Analysis of Engine Oils as an Indicator to Estimate The Rate of Wear

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CURRENT research aims to inspect the chemical analysis of engine oils as an indicator of wear in engine. The novelty of work is to test lubricating oil quality and to determine the wear rate in a simple way by taking oil sample of 10 cm^3 and analyzed it in about 5 minutes. This can be done during the operation of equipment without need to stop them, furthermore, this method is a quick indicator of the need to change oil as soon as the initial evidence of wear in the oil molecules. Fresh and used oil samples were chemically analyzed for its elemental analysis for additive elements such as Fe, Cr, pb, Cu, Sn, Al, Ti and Zn, to clarification the wear generation of engine from the contamination present in the lubricating oil. Obtained results showed that increasing percentage of particles of Fe, Cr, pb, Cu, Sn, Al, Ti and Zn metals accompanied by the wear caused in these metals. Height ratio in element Si was not too high this indicated the quality and efficiency of air filters after 100 hours working. Salts such as Na, Ca have increased, but Ba decreased by chemical action at hot temperature of engine.

Keywords: Chemical analysis, Lubricating oil, Viscosity, Additives, Contaminates, Fresh oil, Used oil.

Introduction

Engine oil is any material comprising base oils enhanced with additives, particularly antiwear additive in addition to detergents, dispersants and additives viscosity index enhancement for multi-grade oils. Engine oil is used for lubrication of internal combustion engines with main function of reducing friction and wear on moving parts and to clean the engine from combustion residues. It also neutralizes acids that originate from fuel and from oxidation of the lubricant, improves sealing of piston rings, and cools the engine by carrying heat away from moving parts [1-2].

The friction and wear of metals can be classified according to their mechanisms including: (1) the shaping and cutting of adhesive bonds between asperities of surfaces leading finally to laceration and material transfer and (2) the tilling of a softer material by a harder asperity including plastic distortion and debris formation [3]. About 10–15% of total energy produced by an internal combustion engine is lost due to friction in the piston-cylinder [4], while the piston rings might reason about 70% of the total friction energy losses. Whereas, 33% of the total losses of friction happen in the varied film or boundary film lubrication systems [5], the decrease of friction and wear is of specific importance when such lubrication systems prevail this ratio is correct. Wear volume affects mechano-chemical processes happening on the frictional interaction [6], its intensity depends on the concentration of active additives, oil wear products in their structure and chemical activity.

Lubricants are fabricated to decrease wear on metal surfaces that practice friction through their operation [7] by forming a protective layer between two metal surfaces in contact [8]. Lubricants are used to increase the performance and provide the service life of the engines, moreover, any machinery with rolling elements or ball bearings requires lubrication to prevent the wear and tear of the machinery parts [9].

Engine oils nowadays are mixture using base oils composed of petroleum-based hydrocarbons, organic compounds consisting of carbon and hydrogen, or polyalphaolefins (PAO) or their mixtures in different proportions, sometimes

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with up to 20% by weight of esters [10] for better dissolution of additives. Lubricants contain mostly of minerals or synthetic base oil consisting of hydrocarbons paraffin, naphthenic and, to a lesser extent, aromatic hydrocarbons, to which is added a quantity of chemical additives which content is between 2% and 25% [11]. Chemical additives have diverse properties, such as corrosion, antioxidants, inhibitors and friction modifiers, which control the chemical and physical nature of the oil [12].

Oil analysis is the most vastly accepted form of preventive maintenance [13]; it is an important part of the maintenance strategy for various equipment and is very suitable for equipment that has a lubricating system. Lubricant oil changes unsuitable for its main function due to a loss of its original properties and the presence of pollution [14]. Due to oxidation and pollutions lubricant oils are subjected to chemical change [15], reducing its effectiveness up to a point that no longer encounter quality specifications and requests replacement. The use of second-rate lubricant oils can result in failure and damage of engines. As petroleum products, the lubricating oils and the diesels have high concentrations of GC detectable parts. (20 W-50) oil has a large quantity of heavy components, in which more C34 hydrocarbons almost for 71.6%; although diesel and biodiesel mixture mainly are included of hydrocarbon among C10 and C34 [14]. The determination of thermophysical characteristics for quality control is critical throughout all steps of the lubricant supply chain.

Hydrolytically unbalanced oil compounds have the capability to form acidic pollutants that can cause extreme wear due to surface erosion in tribological equipment [16]. Additionally, hydrolytic decomposition of oil mixtures can be a causative element in the alteration in oil viscosity, which has a noticeable effect on wear because of its relation with film thickness. Thin film lubrication can be defined as a nano-scale of lubrication performance that can be determined by equating physical features of the oil and the interaction between oil molecules and solid surfaces [17].

The maintenance intervals are determined based basically on the anticipated residual useful lifetime of the oil in the engine [18]. The wear has been increased progressively with incremental increasing oil used duration in the engine [19]. Rising temperature leads to reduction of oil viscosity and a thin film of lubrication created by low viscosity. Increasing temperature reasons of lubrication film become less steady and finally to molder.

Explaining the wear generation rate of any engine from the contamination present in the lubricating oil is a way of indirectly estimating the machinery condition [20]. The antioxidants can be used as gauges of oil's quality, meaning that the oil stays functional as long as the antioxidant concentration stays within a safe range of the original concentration.

A direct significance of the viscosity decrease at the whole range of temperature implies a direct decrease in oil film thickness, and this may lead to increased friction at several contacts, and lead to increased wear rates if the oil film thickness changes so thin that permits asperity contacts [21]. This might lead also to a decrease the service life of the engine, thus an increasing in maintenance activities and a reduction in the tribological performance.

The quality of lubricating oil is important to ensure engine operating efficiency [22]. The lubricant oil provides the mechanical power, preserves the cleanliness of the engine, decreases the friction and wear of the moving element, removes particles, and also, saves the engine from oxidation and wear. The lubrication oil can be contaminated with water through weak seals and wetness from ambient sources (including the combustion and condensation in the engines). Lubricants are also vulnerable to oxidation which leads to the creation of low- molecular weight materials, like aldehydes, ketones, acids and alcohols during the start of lubricant degradation processes [23-24].

The aim of this research is to perform chemical analysis of piston, cylinder wall and piston oil-sealing rings as well as samples of fresh and used oil for internal combustion engine as an indicator of the rate of wear occurring in internal engine parts.

Material and Methods

Experimental design

To obtain definitive answers as to why the wear occurs and how it occurs and in which parts may occur, a number of tests on engine's parts and oil have been performed. Fresh and used engine oil samples were chemically analyzed for its elemental analysis for additive elements such as phosphorus, zinc, calcium, magnesium, barium and potassium, to clarification the wear generation rate of engine from the contamination present in the lubricating oil. Thereafter chemical composition analysis of cylinder wall engine and oil-sealing rings and piston was performed.

Material

The experiment was conducted on a sample of cylinder wall engine and oil-sealing rings and piston, in addition to fresh and used oil samples (CO-OP Oil Super SJ 20W/50) (100 hours as working hours), taken from tractor was Russian manufacturing with 90 HP, (Fig. 1), at Agricultural Research and Experiments Station, Fac. of Agric., Cairo Univ. The oil samples were used for 100 hours of operation. Two samples were tested fresh oil (non used) and used oil. The laboratory tests were performed at Tribology, Equipment and Spare parts Center, Faculty of Engineering, Cairo University. Fresh oil (CO-OP Oil Super SJ 20W/50) specifications are illustrated in Table 1.

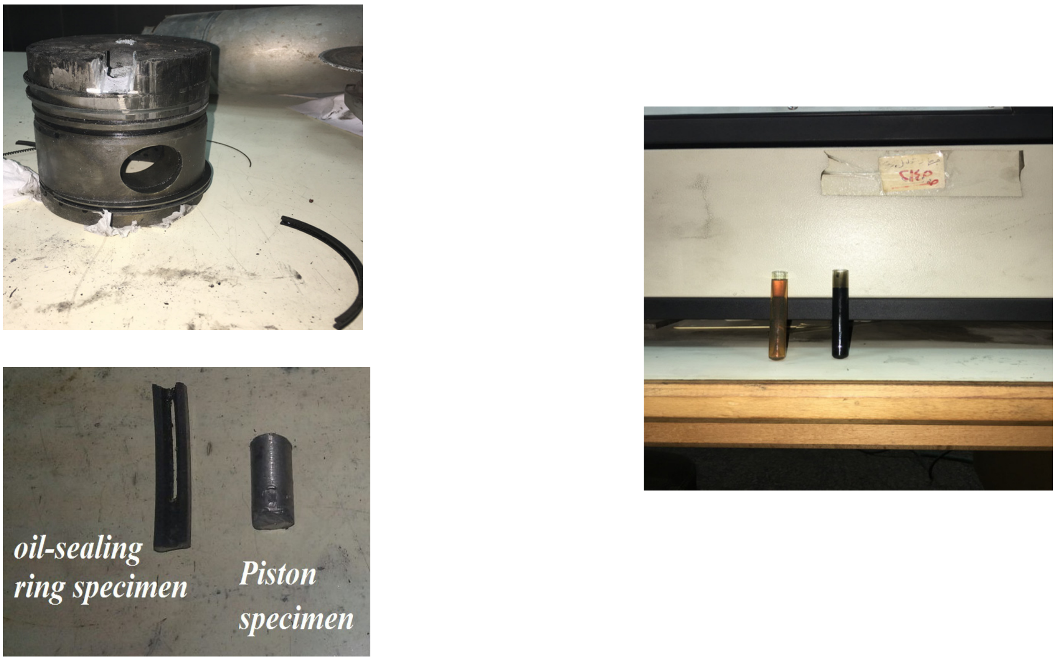

Fig. 1. Tested engine's parts under investigation, (a) the piston with oil-sealing rings, (b) fresh and used engine oil samples.

TABLE 1. Fresh oil (CO-OP Oil Super SJ 20W/50) specifications.

Items	Test Method		Limits
	IP	ASTM	
Specific gravity at 15/15 °C (max)	160	1298	0.9050
Apparent viscosity at –15 °C cP (max)	-	5293	9500
Flashpoint "open" °C (min)	35	-	205
Copper strip corrosion (max)	154	130	1
TBN mg KOH / mg	-	2896	9/12
Pour point °C (max)	15	97	-10
Moisture % vol.	74	95	Nil
Mechanical impurities	Visual		Nil

Oil experimental tests

Oil experimental tests were conducted on the samples to determine the deterioration of the oil condition and estimate the extent of wear in oil due to use in the operation. These tests are:

Determining the engine oil viscosity

Instrument of oil viscosity measurement (Cannon-Fenske "Reverse-Flow" Viscometer for Opaque and Transparent Liquids) has been used to determine the viscosity of fresh and used engine oil samples. This method depends on putting the viscometer into the holder and inserts it into the 50 liter temperature controlled bath. Allow 10 min for the sample to come to bath temperature at 40 ºC and 15 min at 100 ºC. Digital temperature control and an inbuilt cold water cooling coil to provide accurate and stable test temperatures from ambient to 150°C (±0.02°C up to100°C and ±0.05°C between 100 and 150°C).

Chemical analysis of engine oil elements

The oil analysis spectrometer has been used to perform the chemical analysis of engine oil elements. Spectroscopy technique uses the concept in which each element has a unique atomic structure and when it was subjected to the addition of energy, each element emits light of specific wavelengths or colors.

Chemical composition analysis of cylinder wall engine and oil-sealing rings and piston

Energy Dispersive X-ray Fluorescence Spectrometer (EDX Series EDX-720/800HS), has been used to carry out chemical composition analysis of cylinder wall engine and oil-sealing rings and piston. This nondestructive analysis technique depends on fluorescence spectrometer which irradiates a sample with X-rays, after that measures the energy of the generated fluorescent X-rays to determine the type and amount of elements comprising the sample.

Results and Discussion

Illumination the resulted wear rate of engine from the particles present in the lubricating oil is an indirect method to evaluate the engine condition. Moreover, any predicted model for wear rate production would have to take into consideration the lubrication system as well as the concentration of oil elements.

Determination of the Engine oil viscosity

Machine condition monitoring or predictive maintenance is the practice of assessing a machine's condition by periodically collecting data to determine when to perform maintenance. Monitoring and analyzing lubricant oils for characteristics such as contamination, chemical content and viscosity are considered as one of important factor to save engine operating at optimal condition. Oil monitoring, also, may be used to explore the tribological failures which are recognized due to quality variations of the lubricants and wear particles analysis.

The most significant characteristic of oil for lubricating determinations is its viscosity. Viscosity can immediately tell if the wrong grade is present. Viscosity influences tribological behavior [25], high viscosity decreases the coefficient of friction and consequently, the temperature decreases. The hydrolytically unstable oil compounds have the ability to form acidic contaminants [16], which may cause excessive wear due to surface corrosion in tribological systems. Viscosity provides a measure of the impedance of a fluid to shear flow, and may be defined as the shear stress on a plane within the fluid, per unit velocity gradient normal to that plane.

Fresh and used engine oil viscosity was measured at two temperatures, 40 and 100°C. The data are illustrated in Table 2. It was measured at 40°C because it is considered the average temperature for the operation of oils and the measurement was also performed at 100°C as a maximum temperature after which may change significantly specifications of oil lubrication by increasing the temperature (According to ISO/ASTM grades and the SAE (US Society of Automotive Engineers) grades for automotive oils. Moreover, according to engine oil viscosity classifications - SAE J300d, the maximum viscosity at -18º is 5000 cP (mm^2/s) and the minimum viscosity at 100ºC is about 5 cP.

TABLE 2. Viscosity values for both fresh and used engine oil (100 h of working hours).

Test temperature, °C	Viscosity value, (cP)	
	Fresh oil	Used oil (100 working hours)
40	30	25
100	6.5	5

Viscosity of fresh oil was 30 cP at 40°C and decreased to 6.5 cP at 100°C whereas, it was 25 cP at 40°C and decreased to 5 cP at 100°C. The viscosities of all oils decrease speedily with increasing temperature (according to US Society of Automotive Engineers). The drop in oil viscosity is expected, especially when temperatures increase, however, the reduction of used oil viscosity for the fresh oil viscosity can be explained by other considerations.

This result is consistent with the study conducted in Aghaei, et al., study [26], Where they reported that the viscosity decreases as temperature increases. Their experimental data, showed that maximum and minimum relative increase for nanofluid viscosity at a constant temperature by increasing the volume fraction from 0.05 to 1 were 35.52 and 12.92%, which occur at 55 and 15 °C, respectively. They added also, that maximum and minimum nanofluid viscosity decreases by increasing the temperature from 5 to 55 °C were 8.5 and 6.5 times, that occur in the nanoparticle volume fractions of 0.05 and 1, respectively.

A decrease in viscosity may also occur when non-lubricants like solvents and diesel fuel accidently get into the lubricant. If this happens, it is a good time to change the oil. Oil must be periodically changed before its quality gets degraded, with the time, viscosity of the engine oil begins to change [27]. From Table 2 it was shown obviously, the changing of used oil after 100 working hours at which the decreased percent of viscosity [(used oil – fresh oil) / fresh oil] is about 17% only at 40ºC and 23% at100 ºC. That is an extra loss in mechanical economic wise. This result also, is compatible with Andrews et al., [18] who stated that as the oil ages the amount of pollutants increases and some of these pollutants can further accelerate oil degradation and additive depletion. They added also, that usual methods to observe lubricant quality depend on the detection of degradation products volatile acids are recorded as the total acid number (TAN).

Moreover, Yadav et al., [19] stated that low viscosity lubricants tend to create only a thin film, they concluded also, that increasing temperature effected lubrication film to turn into less stable so, the metal-to-metal contact area will increase causing an increase in the wear under high pressure conditions.

Another approach that explains oil lubricant could be losing its viscosity is through the loss or shear down of the viscosity-index improver. A multi-grade engine oil such as a 10W-30, contains an additive known as a viscosity-index improver and during usage, the viscosity-index improvers can sheer down and break apart, causing the viscosity of the oil to decrease. Furthermore, exposure to high temperature is the major factor in causing the sheer of the viscosity-index improver.

In addition to viscosity improvers, those were added to a lubricant, to keep acceptable lubricating abilities at higher temperatures [28]. Whereas, at low temperatures, the viscosity characteristics of the base stock prevail while at high temperatures the viscosity improver maintains the correct viscosity [28].

Chemical analysis of engine oil elements

Salehi et al., [29] stated that oil ageing is a destructive mechanism which can affect its physical and chemical properties and decrease its performance. They showed that the ageing process resulted in the formation of decomposition products and acids; therefore it was necessary to understand the mechanisms of degradation and its impact on the oil properties and performance [29].

The most abundant elements in lubricating oils, Zn, P, Ca and S, were also major elemental constituents in the exhaust. The presence of additive elements such as phosphorus, zinc, calcium, magnesium, barium and potassium, where previous trends indicated trace or no values, is an important indicator of contamination. A raise in values or a change in the quantity or ratio of elements will often point to lubricant mix up. The earlier trend increases dependability in results especially when an oil change in importance is observed. Table 3 demonstrates the typical source of analyzed elements by spectroscopy in fresh and used oil samples.

From Table 3, it can be observed that the chemical analysis of engine oil composition indicates the presence of wear contaminants, viscosity additives and contamination from soot or fuel. Fe, Cr, Pb, Cu, Sn, Al, Ni, Mo, Ag, Ti and V were classified as wear metal elements whereas, Mg, Ca, Ba, P, Zn and B were additives and the contaminats were Si and Na.

TABLE 3. Typical source of elements analyzed by spectroscopy in fresh and used oil samples.

Classification	Element		Tested oil specimens	
			Fresh Oil [ppm]	Used Oil [ppm]
Wear metals	Iron	Fe	162	352
	Chromium	Cr	0.5	12.3
	Lead	Pb	3.5	6.7
	Copper	Cu	9.3	20.7
	Tin	Sn	0.0	8.9
	Aluminum	Al	40.1	78.7
	Nickel	Ni	2.4	1.6
	Molybdenum	Mo	0.7	1.2
	Silver	Ag	0.1	0.1
	Titanium, Not Applicable	Ti	4.4	10.1
	Vanadium	V	1	1
Contaminates	Silicon- Dirt, Seals and Sealants, Coolant Inhibitor	Si	253	279
	Sodium- Salt Water Contamination, Airborne Contaminate	Na	131	170
Additives	Magnesium - Detergent Dispersant Additive, Airborne Contaminant at some sites	Mg	66.7	78.3
	Calcium - Detergent Dispersant Additive, Airborne Contaminant at some sites, Contaminant from Water Detergent	Ca	2949	3263
	Barium Usually an Additive from Synthetic Lubricants	Ba	36.3	22.7
	Phosphorus - Anti wear/ Extra pressure	P	1038	1044
	Zinc - Anti wear	Zn	797	982
	Boron - High Temp Lubrication	B	1.6	1
	Hydrogen	H	5940	5755

Some of these elements have increased in the used oil compared to the fresh oil and others have decreased. Table 4 illustrates the increasing ratio of chemically analyzed elements for both fresh oil and used oil samples.

From Table 4, it can be noted that the increasing ratio ranged between the lowest value of 10 % for Si (Silicon) and the highest value of 2360% for Cr (Chromium). Chromium can be consisted and accumulated at pistons, cylinder liners, exhaust valves, coolant leak from Cr corrosion inhibitor. Silicon is existed inside the engine due to airborne dusts, seals, coolant leak and additives.

A brief review of some of the elements whose values have been increased can be found that Fe (Iron) increasing ratio was 117 %, Fe is most common or wear metals from cylinder liners, valve guides, bearing, crankshaft, camshaft. This result is somewhat compatible with Ahamad et al., study [30], that reported that the oxidation of base oils during use in an engine environment produces corrosive oxidized products. They have approved also, that used oil color was dark, due to carbon from wears. The acid present in engine oil maintains its color but in used oil, the acid is weakened by the neutralization of a base.

TABLE 4. The increasing ratio of chemically analyzed elements for both fresh oil and used oil samples.

Elements	Oil sample		Increasing ratio (%)
	Fresh	Used	
Fe	162	352	117
Cr	0.5	12.3	2360
Cu	9.3	20.7	122
pb	3.5	6.7	91
Sn	0.0	6.9	690
Al	40.1	73.7	83
Si	253	279	10
Zn	797	982	23
Mo	0.7	1.2	71
Ti	4.4	10.1	129

Cu (Copper) increasing ratio was 122 % and it is an oil cooler or oil additive. The increasing ratio of pb (Lead) was 91%, Lead corrosion may be happening in bearing metal and seals. Sn (Tin) increasing ratio was 690 %, Tin may come from corrosion in piston rings or seals. Al (Aluminum) increasing ratio was 83%, the main source of Aluminum is a piston or crankshaft.

Hammami et al., [5] performed a comparison between axle gear oils 75W90-A and 75W90-B after 24 h, under similar tests and operating conditions, they showed that, the Calcium-Zinc based additive package of the candidate (B) oil generated closer internal friction torque and boundary coefficient of friction than the additive package of the reference (A) oil. Though, it promoted higher wear indexes, higher surface roughness at the finish of their tests [5]. So, it can be, strongly, noted that the engine oil reflects the performance of the engine via its properties, even though the condition of lubricant oil can affect the performance of the engine as well. Contaminant added to the lubricant play an important role in wear processes [32], where, hard particle speed up the wear processes while soft particle decreases the wear rate.

Elemental concentration is a good index of lubricants degradation, this result is compatible with that of Andrews et al., [18] who reported that by quantitatively monitoring the concentration of the antioxidant additives and their chemical changes with time one must therefore be able to evaluate the oil's remaining useful life. Whereas, Costa et al., [12] reported that thermal fragmentation of the quaternary ammonium salts produces diagnostic ions that can be used to identify the quaternary amine species even when the molecular ions are not observed. This has been demonstrated for that the corrosion inhibitor additives present in an oil matrix and deposited on steel.

The same behavior can be observed when studying elements whose values have also been underestimated. Table 5 illustrates the decreasing ratio of chemically analyzed elements for both fresh oil and used oil samples.

TABLE 5. The decreasing ratio of chemically analyzed elements for both fresh oil and used oil samples.

Elements	Oil sample		Decreasing ratio (%)
	Fresh	Used	
Ni	2.4	1.6	33%
B	1.6	1.0	37.5%
Ba	36.3	22.7	37%
H	5940	5755	3%

Decreasing ratio of analyzed elements was fairly close; it was 33% for Ni (Nickel), 375 % for B (Boron) 37 % for Ba (Barium) and 3 % for H (Hydrogen). Nickel corrosion comes from bearing metal and valve, Boron is a high temperature lubrication and Barium is a synthetic oil additive.

Chemical analysis of the constituent elements of Cylinder wall, sealing rings and piston

To find out the constituent elements of each part and to make sure that these elements increased as a result of wear. A chemical analysis of the constituent elements of the cylinder wall, sealing rings and piston was performed and its results were tabulated in Table 6. The chemical analysis data show and confirms that the previous results of the oil analysis which in turn proves the real increasing the elements in the oil used as a result of the wear occurring in the engine parts, which is also confirmed by the results of the wear rate.

TABLE 6. The chemical analysis (constituent elements) of engine parts (cylinder wall (Aluminum Alloy A356), sealing rings and piston).

Cylinder Wall (Aluminum Alloy A356)		Sealing rings		Piston	
Elements	%	Elements	%	Elements	%
Al	91.1-93.3	C	0.15-0.21	Al	99.215
Si	6.5-7.5	Si	0.4	Fe	0.432
Mn	0.25-0.45	Mn	0.5-0.9	Hg	0.228
Cu	0.2	Cr	1.5-1.8	Zn	0.087
Ti	0.2	Mo	0.25-0.35	Sn	0.026
I	0.2	Ni	1.4-1.7	Co	0.012
Zn	0.1	Fe	Rest		

Increasing the percentage of particles of Fe, Cr, pb, Cu, Sn, Al, Ti and Zn metals accompanied by the wear caused in these metals during the mechanical process for the equipment. Height ratio in element Si was not too high this indicated the quality and efficiency of air filters after 100 hours working. Some of salts such as Na, Ca have increased, but Ba decreased by chemical action at hot temperature the combustion process and to confirm the results of chemical analysis of oil And verification the elements that have increased their quantities in the used oil has been done (a chemical analysis of the constituent elements of Cylinder wall, sealing rings and piston).

Oils are naturally changed after a predetermined service period and not only when the oil's quality starts to damage. Though the shutdown or maintenance of the engine is expensive, the maintenance activities are recognized based exclusively on the anticipated remaining useful lifetime of the lubricant in the engine. These service periods are set such that the lubricant is changed "too early", i.e. when it still has substantial remaining life; if the service interval is set too long, irreversible engine damage. Wear affects the service life of the engine; when the wear of engine components increases service life of engine decreases and visa versa. Engine performance and its lubricant mutual relation is a significant diagnostic means to evaluate both engine health and performance.

Conclusions

To obtain definitive answers as to why the wear occurs and how it occurs and in which parts may occur, a number of tests on engine's parts and oil have been performed. From the results it can be concluded that according to the analysis of the viscosity of the oil samples, which showed slight differences in the degree of viscosity between fresh oil and used oil, these differences do not represent a significant deterioration for the used oil. It is considered that the oil is suitable for use. Note that this depends solely on the degree of viscosity but after the rest of the tests were applied, the clarity changed when applied chemical analysis of engine oil elements where there is an increase in the particulars of some elements at high rates indicating the presence of wear clearly. This was confirmed through chemical analysis of the constituent elements of the cylinder wall, sealing rings and piston where it was found that components of the components of the cylinder wall, sealing rings and piston are approximately the same as the elements that increased in the oil used, which was a strong indicator of wear in the oil. A good fair oil analysis can monitor engine wear condition, oil contamination and oil degradation simultaneously. Recent method can be done during the operation of equipment without need to stop them, contrary to many tests, which require oil filtration and then perform several procedures to determine wear rate incident by the thickness of impurities in oil.

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التحليل الكيميائي لزيوت المحرك كمؤشر لتقدير معدل التآكل

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يهدف البحث الحالي إلى فحص التحليل الكيميائي لزيوت المحركات كمؤشر على معدل التآكل الحادث في المحرك. تكمن حداثة العمل البحثى في إجراء اختبار جودة زيت التزييت وتحديد معدل التآكل بطريقة بسيطة عن طريق أخذ عينة من الزيت ١٠ سم³ وتحليلها في حوالي ٥ دقائق. ويمكن القيام بذلك أثناء تشغيل المعدات دون الحاجة إلى إيقافها ، علاوة على ذلك ، تعتبر هذه الطريقة مؤشراً سريعاً على مدى الحاجة إلى تغيير الزيت بمجرد ظهور أدلة أولية على التآكل فى جزيئات الزيت. تم تحليل عينات زيت المحرك الجديدة والمستعملة كيميائياً لتحليل العناصر عن العناصر المضافة مثل Fe و Cr و pb و Cu و Sn و Al و Ti و Zn ، لتوضيح كيفية تولد التآكل داخل المحرك وذلك من التلوث الموجود في زيت التزييت. أظهرت النتائج الحصول على نسب مئوية متزايدة من جزيئات الحديد ، الكروم ، الرصاص ، النحاس ، الزنك ، الألمونيوم والقصدير مع التآكل الناتج عن هذه المعادن. ولم تكن نسبة الارتفاع في عنصر السيليكون عالية جدا وهذا يدل على جودة وكفاءة مرشحات الهواء بعد ١٠٠ ساعة من العمل. كما زادت نسب الأملاح مثل الكالسيوم والصوديوم، ولكن انخفضت نسبة عنصر الباريوم وذلك بسبب النشاط الكيميائي عند درجة حرارة المحرك.