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RESEARCH

Determination of Oil Drain Period in Naval Ship Diesel Engine

The performance requirement of lubricating oils is rising continuously in terms of oil drain intervals, reduced friction and wear of the components in internal combustion engines. The oil drain capability of the engines must be considered to properly estimate oil drain intervals for the equipment in economic point of view. The primary goal of this research study is to determinate the useful lifetime of the lubrication oil in the Diesel engine. Firstly, the chemical and physical analysis of used mineral crankcase oil is studied to predict the condition of the lubricant and engine wear components during continuous operation by using analysis methods and techniques. Secondly, the optimum oil drain period is determined according to the calculations of cost analysis and iron wear element concentration value during engine overhaul period results of oil sample analysis. Examined oil samples were taken from a ship main Diesel engine belonging to the naval forces in Turkey. Lubricant samples were examined approximately every 40 hours for deterioration of the lubricant and evidence of wear of the engine components. Finally, the optimum oil drain interval for the mineral SAE 30 oil is found as 775 hours in this experimental study. As the oil drain interval is 300 operating hours instead of 775 operating hours, the extra cost paid for the lubricant is 3357.49 EUR. In case that there is an average of two oil changes per year for one ship, this cost increases to 6714.98 EUR for one ship.

Keywords: Marine ship Diesel engines, oil analysis, optimum oil drain period, economic analysis

Introduction

The engine environment causes chemical degradation of oil over a period of time. Oil is contaminated by internal and external factors which change chemical structure of the lubricant. Undesirable changes in the oil property may affect performance and may lead to failure of the mechanical components. It is therefore, essential to have a periodic monitoring of the lubricant properties. The lubricant analysis is therefore, an essential tool in the industry for optimisation of lubricant uses as well as condition monitoring of equipment [1].

Lubricating oil in combustion engines during its operation undergoes various environmental stresses and leads to thermo-oxidative degradation of its base stock. Initially the degradation rate is slow due to protective action of additives; however, the rate dramatically increases as soon as the additive package gets depleted. This is normally reflected in abrupt changes in the oils various physical and chemical properties, and also in the system performance indicating the end of useful life oil. The oil change periodicity is a function of many parameters including operating and environmental conditions. This periodicity is recommended by the manufacturer and is generally too safe. Discarding oil before the end of its

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complete useful life is highly undesirable in the context of cost. So that the recommended oil change periodicity is desirable to determine according to the engine's reliability [2]. Engine oil degrades in quality during its use and after certain period of time the oil needs to be changed depending upon its condition. So that oil deterioration is subdivided into two main categories:

(1) Ageing which causes physical and chemical changes to occur in the oil as a result of oxidation,

(2) Ageing related to adverse external conditions such as sand dust, dirt, fuel, water, blow-by gases and metallic particles being introduced into the oil [3, 4].

Mineral lubrication oils deteriorate when they oxidize or react chemically with dissolved atmospheric oxygen. [5]. In the presence of oxygen at elevated temperatures, organic peroxides are formed by the removal of hydrogen atoms from the lubricant hydrocarbon chain, which results in the formation of free radicals, which then react with the oxygen to form peroxy radicals [6]. Oxidative by-products are generally characterized as insoluble resins, varnishes and sludges or soluble organic acids and peroxides [7]. This raises oil acidity and encourages varnish formation as the surface deposits. Lubricant makers add oxidation inhibitors as additive to help breakdown peroxides and hydroperoxides that form during the initial oxidation step [5]. High temperatures and pressures during combustion result in the production of nitrogen oxides which in combination with water, generate nitric and nitrous acids. Additionally, the combustion of sulphur containing fuel produces sulphur oxides which condense to form sulphur acids in the presence of water vapour [8].

The service life of a lubricant tends to proportional to the degree of oxidation. The rate of oxidation is accelerated by high temperatures and the presence contaminants. Oil contamination is the single most important cause of oil related machinery damage. Moreover, the wear damage initiated by most oil contaminants progresses at much higher rate than the equivalent wear damage due to normal speed and load conditions. The most common oil contaminants can be broadly categorized as particulate and chemical (such as dirt-soot, process materials, wear metals, water-glycol, fuel dilution, process chemicals, wrong oil contamination) and are usually associated with ingress from the environment or other machine systems. This contaminants promote degradation, consume additives, impair lubricant properties and cause tribological damage to machinery parts [7]. Other contaminants include metallic particles, unburnt fuel and lubricant combustion. The presence of even small quantities of metallic debris such as iron, copper, lead can act as oxidation catalysts which will degrade the lubricant. Wear rates arising from the presence of particulate contaminants increase rapidly when the size of particles exceeds running clearances between sliding surfaces [6].

OIL ANALYSIS TECHNIQUES

Oil analysis is a widely used monitoring technique in which information on the performance or condition of a machine is determined from the degree of contamination or degradation of its lubrication oil. Several methods are described in the literature for condition assessment of oil in simulated laboratories. Viscosity, oil insolubles, total acid or base number (TAN/TBN), water content, wear debris and metal particle analysis and spectroscopic methods etc. are some of the test or techniques which have been exploited for health monitoring of the oil systems. Samples should be taken from the operating equipment according to an established schedule based on hours of operating or miles of service [2].

Total Base and Acid Number (TBN/TAN)

Total Acid Number (TAN) and Total Base Number (TBN) are very important in terms of quality control of lubricants during the manufacturing processes as well as for determining the condition of lubricants during use and for prediction of the period for replacement with new lubricant. The sum of acidic and basic compounds in the lubricants is referred to as (TAN) and (TBN), respectively, which are defined as number of milligrams of potassium hydroxide corresponding to the acidic and basic compounds [9].

(TBN) is a measure of the buffering capacity of engine oil and its ability to maintain the alkalinity of the oil. A high (TBN) value indicates the absence of strong acid forms. The acceleration of acids during the combustion leads to a reduction in the (TBN) of the oil. The capacity of oil to resist this reduction in (TBN) is a property, which is therefore desirable and is a required property for modern lubricants [8]. (TAN) is a direct indication of oil oxidation since acids generated during oil oxidation are directly estimated by titrating with base [2].

The (TAN) and (TBN) are measured by titration method. The acidic concentration (TAN) of lubricant is generally expressed as the quantity in milligrams of potassium hydroxide (KOH) required neutralizing all the acidic by-products in one gram of lubricant sample. The alkalinity (TBN) is the quantity in milligrams of acid, expressed in equivalent milligrams of potassium hydroxide (KOH) and required to neutralize all basic constituents in lubricant sample [7]. There is a widely held view that in applications, oil should be changed when its TBN falls to 50 per cent of the original level (ASTM D445/89) [4].

Viscosity

Viscosity is a measure of lubricant's internal friction, or resistance to flow. It is also referred to as the ratio of shear stress to shear rate. In a given machine, the thin film separating the moving surfaces can be maintained only if the operational viscosity range is correct. Consequently, viscosity is the most important property of a lubricant specification. There are two types of viscosity: kinematic and dynamic (or absolute). Kinematic viscosity is derived from the measurement of the time taken for lubricant at a specific temperature to flow a given distance through a capillary tube under the influence of gravity. The unit of measurement of kinematic viscosity is the Stoke. A Stoke is equal to one square centimetre per second. For most lubricant applications, the Stoke is an inconveniently large and smaller unit, is preferred. The most common test for kinematic viscosity is the ASTM D445/89 method [7]. It can show a rise due to oxidation, nitration or contamination or a fall caused by dilution of the oil by fuel. A useful rule is that a rise or fall of 25 percent in viscosity is the maximum acceptable limit value [4].

Flash point

One traditional technique used to determine fuel dilution is flash point testing which determines the reduction in the flash point temperature due to the presence of lighter hydrocarbon of fuel components [10]. The Flash point of a lubricant is the measure of the fluid's volatility and flammability. It refers to the minimum temperature at which there is sufficient vapour to cause a flash of the vapour/air mixture in the presence of an open flame. The main concern is to assess the potential for explosion or fire under the anticipated conditions of operation. Contamination by more volatile fluids, such as the dilution of an engine lubricant by fuel, greatly increases the potential for damage due to explosion and/or fire. If the flash point of oil is significantly 25% lower than the original value, this indicates contamination by fuel. (ASTM D93) [7].

Insoluble Contents

Many soluble oxidation by-products are precipitated out of a used-oil as insolubles held in suspension such as resins, dirt, soot and metals. The insoluble products tend to raise the oil viscosity and generate deposits on component surfaces, reducing lubrication and cooling performance. In worst case, insoluble loading can plug oil passages and filters, leading to severe equipment damage. Insolubles in the oil tend to increase the oxidation rate and promote corrosion of metal parts. The presence of pentane helps to settle out insolubles held in suspension, such as resins, dirt, soot and metals. Precipitates that are separated from the oil by pentane solution are called Pentane Insolubles. The degree of Pentane Insolubles contamination of a lubricant is usually determined by the ASTM D893 centrifuge or micro filtration method [7]. Precipitates that are separated from the oil by a pentane solution are Pentane Insolubles. The oils of lower dispersancy may be unsuitable for service at about 2 per cent insolubles, whereas the higher performance grades can tolerate 5 per cent or more [4].

Metal contents

Metal concentrations are normally low and increase slowly with longer operating periods. A sudden upward change in the concentration of any metallic element, such as copper, lead or iron suggests an increased wear rate and possibly abnormal operating conditions [11].

Metal contents in the oil are divided into three broad categories:

1) Wear metals, such as iron from liner-gears,
2) Contaminants, such as lithium, which indicate presence of grease,
3) Oil additives, like phosphorus, which is found in extreme pressure and antiwear additives.

Inductively coupled plasma (ICP) spectroscopy is the most important and useful test in used-oil analysis. ICP spectroscopy measures light in the visible and ultraviolet regions of the spectrum. It is an atomic emission procedure whereby the diluted oil passed through argon gas plasma which is maintained at a temperature of 8000 °C. In the upper region of the plasma, acquired energy is released as a result of the electronic transitions, and characteristic light emissions occur. Different elements produce different frequencies or colours. The intensity of the light emitted is directly proportional to the concentration of the element. ICP spectroscopy is used to measure the concentration of different elements in the oil [12].

EXPERIMENTAL WORK

The I.C. ship Diesel engine used for this work was manufactured by MTU (Motoren und Turbinen Union Friedrichshafen GmBH) and this ship belongs to Naval Turkish Forces that oil drain period is every 300 operating hours. The name of the ship is withheld for reasons of confidentiality. This ship has four main similar Diesel engines. Detailed specification of one of the test engine is given in Tab.1. Tab.2 shows the properties of tested oil.

Tab.1: The test engine characteristics

Particulars of Diesel Engine	Four stroke, turbocharged, water cooled, 20 cylinder, 232.6 litres
Maximum Power and Speed	9924 H.P. at 1350 rpm and 27 knot
Block Type	60° - V
Compression Ratio	9.75
Bore x Stroke	230 mm x 280 mm
Injection Pressure	300-350 Bar

Tab.2: Some properties of mineral extra turbocharged oil used in the test program

Performance grade
API CH-4/CG-4/CF-4/SL/SJ, MTU type 2
Physical characteristics
Viscosity grade SAE 30
Viscosity 12.02 cSt specs at 100 °C
Viscosity 100.6 cSt specs at 40 °C
Flash point 225 °C
Viscosity index 100 min.
TBN, 13.3 mgKOH/gr
Category 2

The test process started at the end of the ship's overhaul which was made at every 9000 operating hours. The schedule of this test program is planned for a sevenmonth period. At the beginning of the test, new oil filters were installed and engine was flushed with new oil. Afterwards, the samples were collected at every 40 operating hours. The oil temperature was maintained at 80 °C during engine operation.

Experimental results of iron wear debris concentration were taken as the basic determination for oil drain period. This is due to the fact that most engines are made of cast iron and the additives compounds with iron, such as iron phosphate and iron sulphide [11]. The costs for the lubricant and the overhaul work were calculated, and then the changes of the total costs were interpreted. Tab.3 shows the maximum concentration limits for different elements of wear in engines.

Tab.3: Maximum concentration limits for different elements of wear in engines [11].

Metal	**Content (ppm)**
Lead	5 to 40
Silicon	10 to 20
Iron	40 to 200
Chromium	30
Aluminium	15 to 40
Copper	5 to 40
Tin	5 to 15
Silver	5 to 10

DETERMINATION OF THE OPTIMUM OIL DRAIN POINT

According to engine tests by MTU, engine life is represented as 9000 operating hours that is overhaul period for engines type 20V1163 [13]. During this overhaul period, oil drain period is every 500 hours for SAE 30 marine Diesel lubricant (produced by Petrol Ofisi Company in Turkey) approved by MTU as category 2 [14]. Based on the used oil analysis, iron wear debris was 35 ppm at 390 operating hour for one of the four main Diesel ship engines. The following calculations were used to determine the optimum oil drain point [11].

Cost of engine wear for test duration (EUR/ppm) :

$$\text{Eq (1)} \quad \frac{\text{Overhaul engine cost (EUR)}}{\text{Iron wear debris extrapolation value (ppm)}}$$

Overhaul engine cost/h for any interval (EUR /h) :

$$\text{Eq (2)} \quad \frac{\text{Eq (1) x measured iron wear debris (ppm)}}{\text{Engine overhaul operating hours (h)}}$$

Oil cost per hour for any interval (EUR /h) :

Eq (3) Oil price (EUR) / Oil change interval (h)

Total engine cost for any interval (EUR /h) :

Eq (4) = Eq (2) + Eq (3)

Tab.4: Viscosity, total base number, flash point and insolubles data of the engine.

Operating Hours	100 °C Viscosity (cSt)	40 °C Viscosity (cSt)	Viscosity Index	TBN (mgKOH/g)	Flash point (°C)	Insolubles (%)
0	12.02	100.6	113	13.3	225	0.045
50	11,9	97,12	114	12,9	198	0.066
100	11,79	96,05	114	12,73	194	0.1
150	11,7	94,39	115	12,41	196	0.118
190	11,61	93,42	115	11,98	197	0.167
230	11,5	92,35	115	11,71	198	0.171
270	11,41	90,9	116	11,07	197	0.173
310	11,3	90,01	116	10,9	196	0.182
350	11,2	89,15	117	10,38	195	0.25
390	11,1	88,12	117	10,01	194	0.312

RESULTS

Viscosity, total base number, flash point and insolubles data of the engine are given in Tab.4. Viscosities (40 °C and 100 °C), TBN and flash point values show that the oil kept its service performance up until the end of the 390 operating hour (Tab.4). It is found that all of the data which are achieved at the end of the test duration are in an acceptable level.

That which there is a wide range of iron concentration intervals reported between 40 and 200 ppm is indicated in Tab.3. Tab.5 gives the properties of measured wear metallic contents (in ppm). Fig.1 shows the iron concentration in this work during test period.

Tab.5: The measured wear metallic contents (in ppm) of the used SAE 30 mineral oil.

Op. Hours	Fe	Cu	Si	Cr	Al
0	2	0	2	0	2
50	5	3	4	1	2
100	8	3	6	1	2
150	12	4	6	2	2
190	14	5	8	2	2
230	17	6	9	2	2
270	24	14	10	3	2
310	26	16	11	4	2
350	31	20	12	5	3
390	35	25	13	6	4

Tab.6: Linear and Quadratic Functions.

Extrapolation type	Function
Linear Function	f(x) = 0,09005.x – 1,3
Quadratic (or Second-Degree) Function	f(x) = 10 -4 .x 2 + 0,0475.x + 2,2779

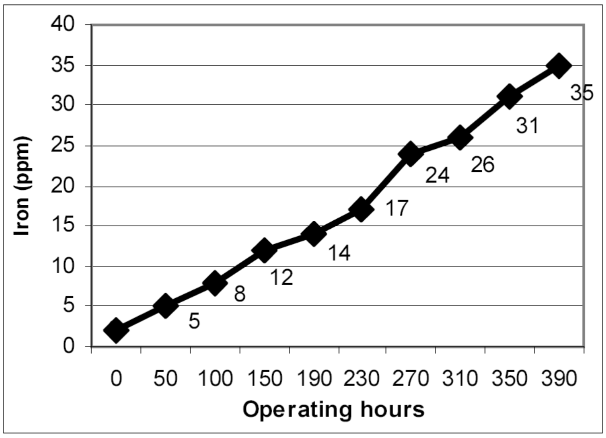

Fig 1: Iron wear debris concentration and operating hours profile.

According to the data of iron concentration, it is calculated the quantity of the iron (Fe as metallic wear debris) all along 9000 operating hours (overhaul hour for the engine [13]). This is the most important criterion for calculating the number of oil changes, the engine overhaul hour and their relative costs during the life of the engine [4]. This calculation is made by using extrapolation methods at MATLAB that is a numerical programming language.

Linear and quadratic (or second-degree) function types are compared with each other for error analysis (Tab.6, Tab.7).

Tab.7: Error analysis comparison of the functions.

Error analysis	SSE	R-Square
Linear Function	15,81	0,9818
Quadratic (or Second-Degree) Function	6,367	0,9927

Consequently, it is found that quadratic (or seconddegree) polynomial function is the most correct forecasting function type for the extrapolation. Iron wear debris extrapolation value that is used at Eq.1 is found as 8221.168 ppm (Tab.8). All of the obtained results of iron concentration extrapolation calculations are showed Fig.2 and Tab.8. Polynomial functions are showed on related figures.

Tab.8: Function values of iron (ppm) at the result of extrapolation analysis between 50 h and 9000 h.

Hour	Function values of iron (ppm)	Hour	Function values of iron (ppm)
50	4,8934	1000	145,968
100	7,9899	2000	482,038
150	11,5672	3000	1010,488
190	14,7754	4000	1731,318
230	18,2914	5000	2644,528
270	22,1152	6000	3750,118
310	26,2468	7000	5048,088
350	30,6862	8000	6538,438
390	35,4334	9000	8221,168
500	50,0755		

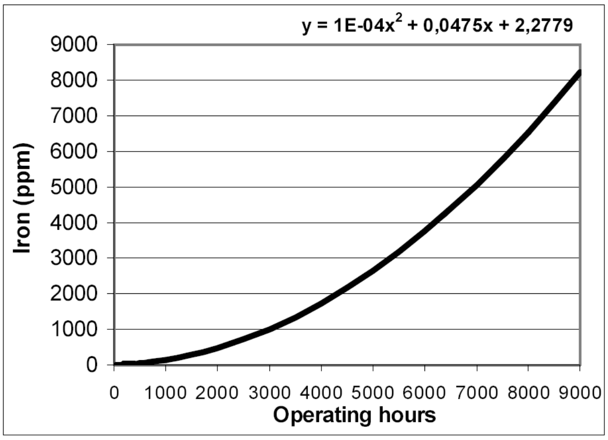

Fig 2: Iron wear debris concentration extrapolation analysis.

Tab.9 shows the overhaul engine cost per operating hours for any interval (Eq.2), the oil cost per operating hours (Eq.3) and the total engine cost for any interval (Eq.4). Fig.3 shows the plots of overhaul engine and oil costs per interval as a function of operating hours. It is to be noted that as the operating hours increases, the overhaul engine cost per interval increases and oil costs per interval decreases. This is due to increasing wear in the engine as the oil life is extended in the engine.

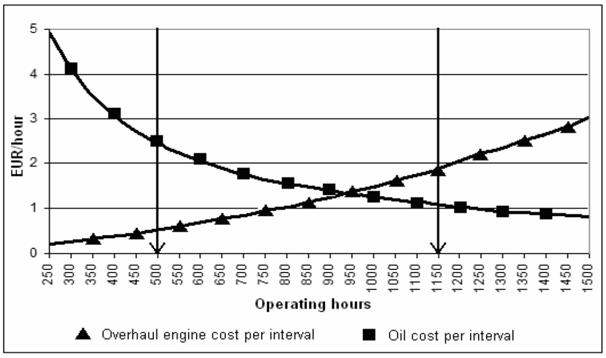

Fig.3: Overhaul engine and oil costs per interval and operating hours profile in engine

Fig.4 and Fig.5 shows the total engine cost per interval as a function of operating hours. As seen in the Fig.5, the lowest total cost is 775 operating hours. It can be seen that lowest cost interval lies between operating hours of about 500 and 1150 operating hours. This interval presents the economical oil change interval. Similar calculations were also made for the second main Diesel engine. As seen in Fig.6, the lowest cost interval was found between operating hours of about 500 and 1075 operating hours and the lowest total cost was found 769 operating hours for the second main Diesel engine. Both results are highly compatible.

It is examined that operating hours are the critical ones for the limit values of the iron, viscosity (40°C and 100°C), total base number and flash point data by using the extrapolation functions at MATLAB programming language. As a result, the limit values of iron, viscosity (40 and 100 °C), total base number and flash point data of the engine was found between operating hours of about 780 and 1260 operating hours (Fig.7, Fig.8, Fig.9, Fig.10, Fig.11). It can be seen that this results are plugcompatible and still in use with the results of total cost calculations (500 and 1150 operating hours).

Oil drain interval is generally applied as 300 operating hours in this ship. According to this, as oil drain interval is 300 operating hours instead of 775 hours, the extra cost for the lubricant is paid 3357.49 EUR. In case that there is an average of 2 oil changes per year for one ship, the extra cost would be 6714.98 EUR. Because of that, there are four ships at the same class, the total extra cost increases to the value of 26859.92 EUR

Tab.9: The overhaul engine cost, oil cost and total engine costs per operating hours

Operating hours	Overhaul engine cost per interval (EUR/hour)	Oil cost per interval (EUR/hour)	Total engine cost per interval (EUR/ hour)
50	0.050909	24.6	24.65091
100	0.083122	12.3	12.38312
150	0.120339	8.2	8.320339
190	0.153714	6.473684	6.627399
230	0.190293	5.347826	5.538119
270	0.230073	4.555556	4.785628
300	0.26201	4.1	4.36201
350	0.31924	3.514286	3.833526
390	0.368627	3.153846	3.522474
500	0.520953	2.46	2.980953
600	0.680446	2.05	2.730446
700	1.757143	2.617096	1.757143
750	1.64	2.597212	1.64
760	1.618421	2.595685	1.618421
770	0.997516	1.597403	2.594919
775	1.007718	1.587097	2.594814
780	1.017969	1.576923	2.594892
790	1.038621	1.556962	2.595583
800	1.059474	1.5375	2.596974
900	1.279009	1.366667	2.645676
1000	1.518558	1.23	2.748558
2000	5.014815	0.615	5.629815
3000	10.51247	0.41	10.92247
4000	18.01153	0.3075	18.31903
5000	27.51198	0.246	27.75798
6000	39.01383	0.205	39.21883
7000	52.51708	0.175714	52.6928
8000	68.02173	0.15375	68.17548
9000	85.52778	0.136667	85.66444

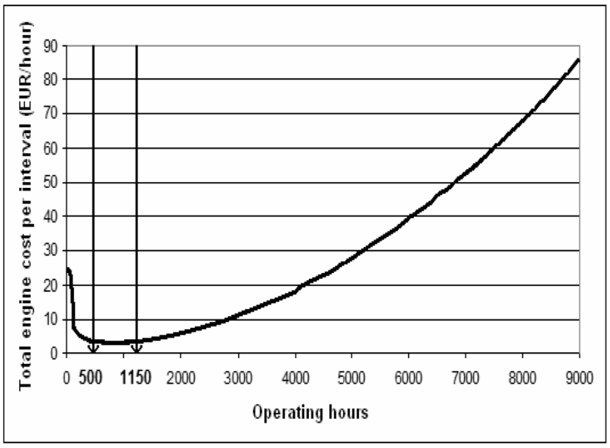

Fig.4: Total engine cost per interval and operating hours profile

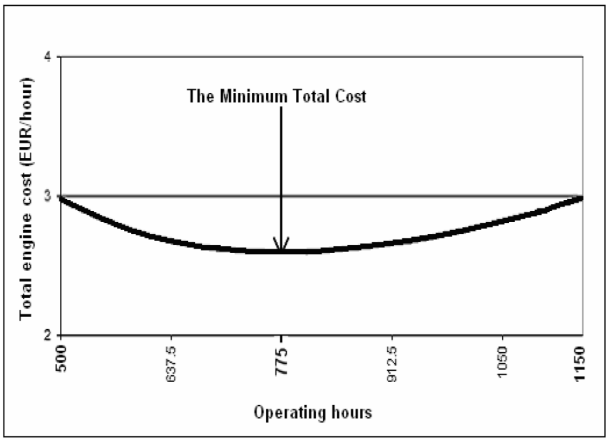

Fig.5: Total engine cost per interval for an optimum oil change point in engine.

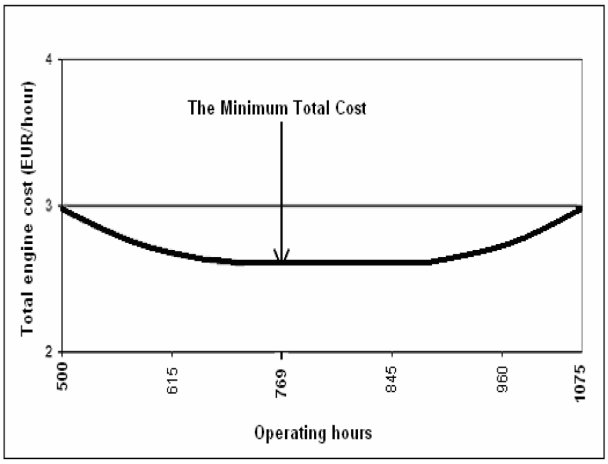

Fig.6: Total engine cost per interval for an optimum oil change point in the second main Diesel engine.

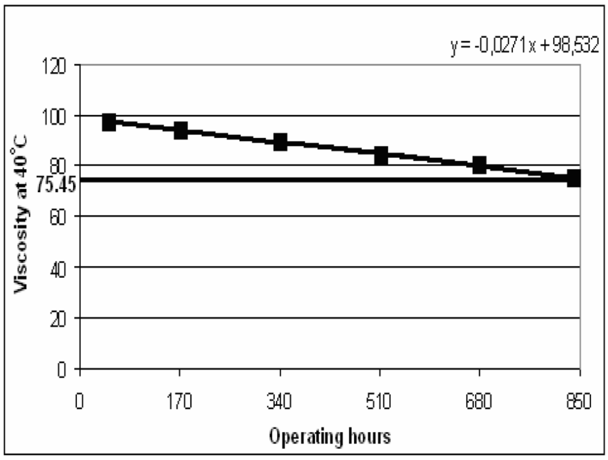

Fig.9: Extrapolation analysis result and limit value of Viscosity (40°C)

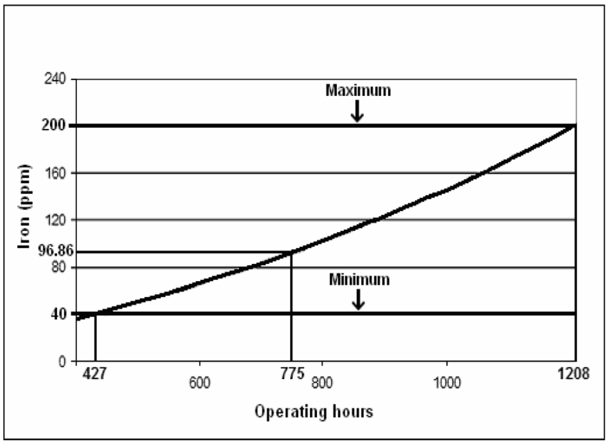

Fig.7: Extrapolation analysis result and limit values of Iron (Fe)

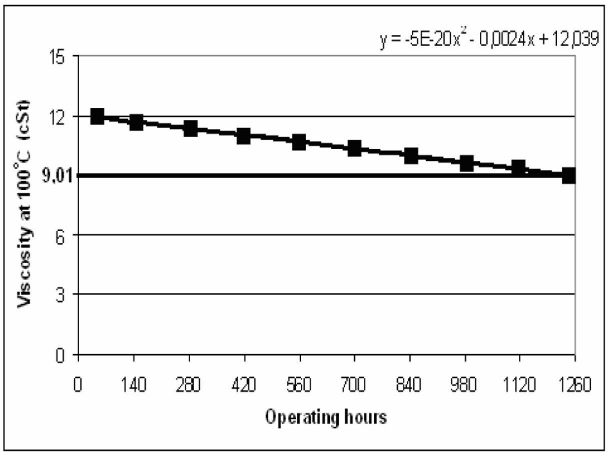

Fig.10: Extrapolation analysis result and limit value of Viscosity (100°C)

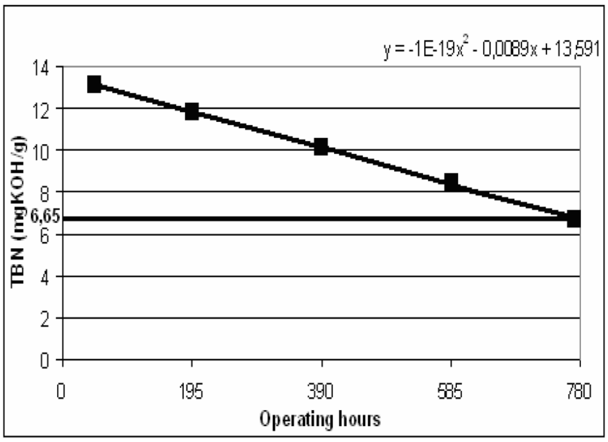

Fig.8: Extrapolation analysis result and limit value of Total Base Number (TBN)

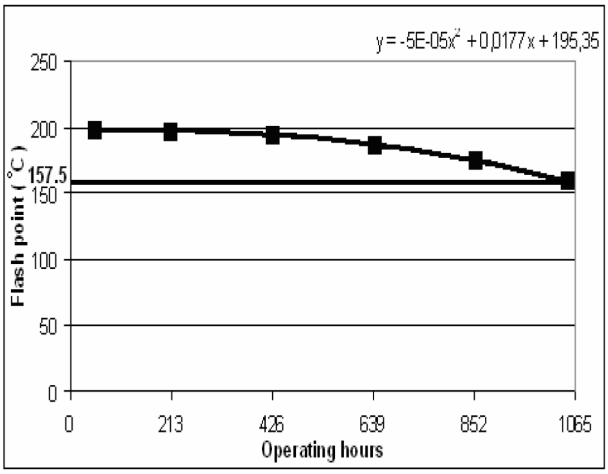

Fig.11: Extrapolation analysis result and limit value of Flash Point

DISCUSSIONS and CONCLUSIONS

Internal combustion engines, such as Diesel engines, are the most stressful on lubrication oil. In this environment, high temperatures and stresses promote thermal and mechanical degradation of the lubricant base stock and consume additive. The lubricant is also exposed to hot combustion products and other contaminants which promote reactions with oxygen, nitrogen, sulphur and result in the formation of acidic by products [7].

Modern oils have many different additives to reduce wear and enhance life, but eventually the oil must be replaced. The oil also becomes gradually contaminated with combustion by-products such as soot and acidic compounds, which if left to build up, could damage the engine. Replacing the oil on a time or distance basis is wasteful and environmentally damaging since the oil may still have useful life [15].

The deterioration in the condition of lubricating oil over a period of time leads to change of the engine oil and charging of fresh oil. Every cycle of this change over, costs the user. The longer the period of change over, the lesser is the cost on the user. Therefore, it is absolutely necessary to get an idea about the correct change over time beforehand so that the use of oil is optimum. For oil analysis of mobile machineries, for example, automobile or naval engine components, laboratory analysis is definitely a viable solution [3].

The primary goal of used oil analysis is to determine oil and machine condition so that required maintenance can be performed at a minimal cost and before substantial secondary damage occurs to machine parts [7].

1) The optimum oil drain period is between 500 and 1150 operating hours, with 775 operating hours being an optimum value for the tested ship Diesel engine in this work.
2) When the oil drain interval is reduced, the total cost increases but the overhaul cost per operating hours is reduced. When the oil drain interval is increased, the oil cost decreases but the overhaul cost per operating hours increases.
3) As the oil drain interval is 300 operating hours instead of 775 hours, the extra total cost for the lubricant would be paid 26859.92 EUR in Turkey.

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