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A Lubricating Oil-Based Maintenance for Diesel Engines at the End-user: An Effective Predictive Approach

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Abstract

This study aims to analyze the used lubricating oil of small Diesel engines under different conditions in order to monitor their instant health condition, indicate their useful life, and provide early warnings of failure progress. It is an attempt to monitor different oil properties together with oil contaminants to diagnose the possible failures before occurring and identify their root causes. It is an effective tool in the case where there are no historical data records for the engines. Specifically, used lubricating oil samples from eight Diesel-powered engines are analyzed as an important information source for early failure detection and decision support. Oil properties; kinematic viscosity, density, and total acidic number (TAN) were analyzed. Also, oil contaminants; wear debris particles, soot, and water content were also elucidated in attempting to predict engine health conditions, wear mechanisms, and useful life. Scanning Electron Microscope (SEM) was used to analyze the wear debris particles. The root causes of engine failure were specified using the 5 Why's method, and interviews with specialists, while the results were schematically presented using the Fishbone diagram. The analysis of oil viscosity showed that engines of high capacities performed better at high operating temperatures than small engines. Besides, the large oil imperfections are not directly related to the oil viscosity reduction but to the high oil TAN and the type and concentration of the oil impurities. This work analysis could assist in robust decision-making on the engine health condition, service life, and maintenance activity that should be applied.

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Keywords: Condition-Based Maintenance; Wear debris particles; Viscosity measurement; Industrial Engine; Wear mechanism; Proactive maintenance; Tribology science.

1. Introduction

The effective maintenance management of mechanical systems is of utmost importance in current industrial systems [1]. It plays a vital role in the final product costs, machinery service life, and the quality of the final product [2,3]. This warrants the rapid growth of new technologies and effective maintenance service strategies for controlling maintenance costs, reducing the frequency of failures, and enhancing the quality of operations. Current maintenance management systems have been extensively implemented for large and medium-sized industrial systems where real-time data are available [4-7]. However, small systems at the end-user, such as electrical generators and small engine units, are rarely investigated despite their frequent failures [8-10]. In general, small-size systems involve low-level or no historical records and maintenance facilities. Besides, end-user machines commonly employ no maintenance management systems and often rely on a run-to-failure approach as a maintenance strategy, which is the most primitive, unmanageable, and expensive approach [2,11]. The selection of maintenance approach depends on the nature of operations, equipment complexity, equipment reliability, and critical conditions. To this, it is impracticable to measure the performance of small systems at the end-user using common approaches without historical data records, such as overall equipment effectiveness (OEE), total productive maintenance (TPM), artificial intelligence, or reliability-centered maintenance (RCM) [12-15].

Condition-Based Maintenance (CBM) is at the heart of predictive maintenance, where the failure can be detected early and manipulated [5]. Recently, equipment manufacturers have embedded CBM tools, such as sensors, probes, and cameras to continuously monitor the conditions of equipment, especially those subjected to the continuous deterioration [5-7]. Although these tools instead of additional costs to the initial investment, they provide valuable data to reveal the system's health state, predict the system remaining useful life, and decrease the overall maintenance cost. Therefore, it is the most cost-effective maintenance strategy based on detecting root

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causes through the operational conditions of the assets [11].

CBM has different tools for identifying failure at an early stage [16,17]. Oil-Based Maintenance (OBM) and vibration-based maintenance (VBM) are the most widely applicable techniques in use nowadays [6,7,18]. Although the analysis results of VBM (the process of measuring the vibration of moving parts as an indication of the wear rate [19] and OBM are conforming for continuous monitoring of engines. OBM has several merits over VBM when applied to monitor complicated types of machinery such as internal combustion engines. It provides accurate information on the wear condition, service life, and the severity of failures for entire engine components [5]. Interestingly, it has been inferred that OBM gives approximately 10 times earlier warnings than VBM for predicting machine breakdown [20]. Besides, VBM systems are susceptible to rotational speed, and sensor failures, and need to be built to the engine at the design step [19], making them improper tools for engines at the end-user.

Elemental analysis of used lubricating oil using atomic emission spectrometry has been widely investigated in the literature [16,17,21,22]. It provides accurate elemental analysis of the contaminants of wear debris in the oil. However, such analysis requires accurate data about the manufactured materials for the machine parts that are in contact with oil circulation. That is a compulsory requirement to identify the most stressed engine part.

OBM can be performed based on online and offline systems. In online monitoring mode, the online sensor is carefully installed on the oil passage on a machine during operation[6,7,23]. Many studies in the literature have investigated online monitoring approaches for lubricating oil using online sensors for measuring viscosity [24], dilution [25], oxidation [26], moisture, [27], wear debris [27,6,7], soot [28], and other contaminations [29]. The aforementioned studies dealt with these conditions separately to study their interaction with engine components. In contrast, the offline monitoring mode requires a physical mass of lubricating oil to be analyzed against its properties and contamination in the laboratory far away from the machine [5-7,30]. Frequent offline oil inspection avoids the difficulties associated with dismantling inspection technologies and provides accurate information about the wear condition of oil-lubricated machines, especially those systems that do not have historical maintenance records [18].

Till now, offline methods remain the most predictive tool commonly used for diagnosing oil and machinery conditions [6,7]. It is a proper method for studying different oil parameters altogether since a single parameter analysis provides a meaningless diagnosis [3,5]. A limited number of studies on single-unit systems at the end-user with continuous monitoring have been reported [5,11]. To the best of the researcher's knowledge, no study has monitored various oil properties and contaminants altogether that could assist in robust decision-making on the engine health condition, service life, and maintenance activity that should be applied. The present work aims to analyze the used lubricating oil of 8 Diesel engines of different conditions in order to monitor their instant health condition, indicate their useful life, and provide early warnings of failure progressing. It is an attempt to monitor different oil properties together with oil contaminants to diagnose the possible failures before occurring and identify their root causes.

2. Methods and Experiments

2.1. Oil Properties

Lubrication oil is a viscous fluid in nature that can be considered the life-blood circulation of machinery. When introduced to the engine components, it creates a separating layer between mating surfaces and moving parts to inhibit direct contact between surfaces, decrease wear, and impede the generating of excessive heat [5-7]. Additives are different classes of chemicals used mainly to improve their functionalities, based on the working condition [5]. By comparing the oil analysis results of base and used oils, a maintenance technician can identify the health condition of oil and engine components.

2.2. Data and Samples Collection Procedure

A base lubricating oil of high grade (50w TITAN SAE engine lubricating oil) was used for all engines and then analyzed along with the used oil samples to make the results comparable. Discrete data were collected from different measurement tools and compared with the reading of the base lubricating oil. ASTM standards for each property measurement were carefully followed. Used lubricating oil samples (operated for ~ 150 hours) were collected in 2019 from eight electrical Diesel engines from different customers, with different capacities, and different design considerations. The oil samples were properly agitated for getting homogenous fluid and then a total of one liter of used oil samples was collected from the eight engines and kept for further analysis. **Table 1** shows the engine's name, model, output power, number of cylinders, cooling system, and operating conditions. The oil samples were tabulated in **Table 1** with the following codes; S1, S2… to S8, while the base oil is S0.

Table 1. Characteristics of the selected Diesel operated generators. The used lubricant oil samples were collected from engines after 150 operating hours for each.

Sample Code	Output (KVA)	No. of cylinders	Cooling System	Purchase Date
S1	10	1	water	1991
S2	15	4	water	2016
S3	20	3	air	2013
S4	25	1	water	2018
S5	35	4	water	2013
S6	100	4	air	2017
S7	120	6	water	2014
S8	200	6	Air	2008

2.3. Measurement Devices

Measurements were officially conducted at Yemen Lubricant Manufacturing Co. Ltd., Taiz. All measurement devices were calibrated based on the manufacturer's recommendations and all experiments and measurements for each variable were done by the same person. A basic magnetic stirrer with a heater (IKA IKAMAG RCT) was used for experiments. A portable digital gram lab balance scale (Ohaus Scout Pro SP401) with a capacity of 0.1 – 400 g was used for measurements. A thermometer (± 0.02°C) to measure the temperature of oil samples in the range from 0 to 100°C. The measurements were carried out at room temperature (31°C) and device correcting equations were used to make the results in line with the device readings. Kinematic viscosity was measured using Seta Vis kinematic viscometer (PMT THOMSON), while a glass capillary thermometer (± 0.01 ºC) was used to determine the temperature within the worm bath. The density of oil samples was measured using a Density meter DMA 35 (Paar Scientific Ltd.) working in the range of 0 – 1955 kg.m^{-3} for density measurements and 0 – 40 °C for temperature measurements. Scanning Electron Microscope (SEM, JCM 6000Plus, Jeol, Japan) was used to investigate the debris particle's size, shape, and concentration. MATLAB software was used for image processing and acquisition to calculate the particle features such as size, shape, and wear nature.

2.4. Wear debris measurements

In the first step, 500 ml of an oil sample was diluted with ethanol to enhance the collection procedure of wear debris. A permanent magnet was used to collect the ferric wear debris particles from the sample. In the subsequent step, the magnet was removed from the oil sample, washed several times, and then dried at 60 °C for 2 hours. Finally, the wear particles were then separated from the magnet, weighed, packed, and sent for further characterizations (SEM tool). The above mentioned procedure was repeated for all other samples.

2.5. Water content Measurements

A sensitive measuring tool was used to control the mass of the oil samples to be only 10 ± 0.02 g for each sample. Water content is determined by removing moisture (dehydration up to 250 °C for 2 h.) and then by measuring weight loss. The difference in mass measurements before and after dehydration can be considered the amount of water content, neglecting any other evaporated particulates. A crackle test was also implemented to monitor bubbles in the oil samples.

2.6. Density measurements

The standards of ASTM D1298-12b and API (American Petroleum Institute) for measuring density and relative density are performed at a standard temperature of 60 °F (15 °C) [31]. The procedure could be explained briefly in the following steps: the injection was carefully cleaned and 10 g of oil sample was pumped into the density meter through the entrance slot. As the oil moves from its orifice slot, the density value will be exhibited on the device screen. The same procedure was repeated for all other samples and the results were recorded in turn. A device factor was considered because the device was calibrated at 15 °C [31]. Therefore, the actual density of oil samples will be calculated based on the following equation:

$$\boldsymbol{\rho_{oil}} = (\boldsymbol{T_{amb}} - \mathbf{15}℃) \times \mathbf{0.00061} + \boldsymbol{\rho_{device}} \qquad (1)$$

Where 0.00061 is a device factor, T_{amb} is the ambient temperature at which the experiments were performed, and ρ_{device} is the density measured by the device.

2.7. Kinematic Viscosity measurements

The test is simple and follows the basic standard procedure of ASTM D445-06 standard test of kinematic viscosity [32], while the standard of ASTM D2270 at 40 and 100°C was used to calculate the viscosity index[33]. In brief, the viscometer was first cleaned thoroughly by several rinsing solvents and dried by passing multi-stage filtered air through the instrument to remove the final traces of solvents.10 mL of oil sample was directly charged from the pipette through the tube into the lower reservoir of a calibrated tube in the viscometer. The oil sample was then allowed to settle instantaneously in a warm bath at 40 °C. In the subsequent step, the oil was poured slowly to the tube until it reached the highest line on the right side of the tube. During the process, a stopwatch was used to measure the efflux time, which was then carefully recorded, converted into seconds, and multiplied by a device constant (different for different working temperatures) that is specific for the glass viscosity tube. This simple calculation leads to depict the kinematic viscosity of the oil samples. Furthermore, the whole procedure was then repeated at 100 °C, while other parameters were kept unchanged. For more reliable results, the measurements were repeated twice for each sample and only the average was considered.

2.8. Total Acid Number (TAN) measurements

ASTM D974 is a standard method that is widely used to determine the TAN of an oil [34]. It is a colorimetric method that uses p-naphtholbenzein as a color change pointer to identify the neutralized end-point. For OBM purposes, this test is accurate enough, simple and cost-effective, and exhibited rapid response. In brief, the test was starting with filling the test tube with 20g ± 0.2 of the oil sample. This process was followed by adding 0.098 mol/L of KOH reagent solution slowly to the above solution until the color of the sample was changed. The titrant test tube was precisely marked with graduated regular increments. The difference between the initial states of the oil to the end-point (the point where the oil color was changed) was then measured and converted to TAN units (mg KOH/g of oil) based on the following equation:

$$TAN = \frac{[(V_a - V_b) \times M_c \times M_w]}{w} \qquad (2)$$

Where: V_a and V_b are the volume of KOH in ml at the end and start points on the test tube, respectively; M_c = concentration of KOH solution (0.0980 mole/L); M_w= Molecular weight of KOH (56.1 g/mole)); and w = sample mass (g). The measurement process was conducted for all oil samples twice and the average was recorded accordingly. A control sample of base lubricating oil was also tested in order to make the results comparable.

3. Results and Discussion

3.1. Water Content in lubricating oil

Table 2 shows the quantitative results of water content in oil samples, which were compared with the results of the base oil sample (**S0**). As a matter of fact, less than 0.25 % of water impurities in the lubricating oil indicates the good condition the engine is [27,35]. To this, the results from all oil samples are at abnormal conditions except **S4**

(the engine operated only a few months). Oil samples **S1, S6**, and **S8** have the highest percentage of water contents at 2.2, 2.61, and 3.1 %, respectively. The results of oil samples **S2, S3, S5,** and **S7** showed a moisture ratio in the range of 1.0 – 1.5 %, which indicates that these engines are also at abnormal conditions. Finally, oil sample **S4** exhibited the lowest water content (0.06%), which is in the safe region of normal operation.

Water emulsified in engine oil is annoying contamination even at low concentrations [36]. There are different plausible processes where water can leak into the crankcase oil. Cooling circulation system, rain, condensed humid air from the surrounding, and fuel combustion reactions through piston rings are the most important sources of water in the lubricating oil [27,36]. Once water impurities are emulsified in oil engine, their hazards depend mainly upon oil composition and additives, working conditions and its physiochemical characteristics; leading to a vast change to oil properties and accelerating abrasive wear rate of engine components [27]. Experimental studies indicated that the presence of 1% of the water in engine oil can reduce the life span of journal bearing by 90% [36,37].

During moisture experiments, the observations of oil bubbles at the laboratory level were captured and analyzed. The bubbles' concentration, size, and period of appearance are good indications of the amount of water in the oil samples [38]. By studying the size of the bubbles, a quantitative conclusion was made regarding the water concentration in the oil sample. The results of observation were recorded in which some samples showed negligible or no bubbles and crackles, which mean no free/emulsified water in the oil samples, such as that observed in base oil sample (**S0)** and relatively in **S4**. However, very small bubbles (~0.5 mm) were produced but quickly disappeared like what noticed in **S5**. Another promising finding was that bubbles of ~ 2 mm were initiated, gathered at the center of the oil spot, and then disappear, that exactly what happened in **S3, S6,** and **S7**. In the same way, the results of **S1, S2**, and **S8** showed further novel findings in which higher moisture levels, violent bubbling, and audible crackling were observed. Bubbles start out about 2 - 3 mm and then grew to 4 mm. As we had expected, the bubbles' size and the time until they disappear match well with the water content results.

Table 2. The results of measuring the water content, mass of wear debris particles, soot mass, and density changes of used oil samples and base oil.

Sample Names	Water Content (%)	Net mass of debris particles (g)	mass of soot (g/0.5litre –oil)	Density change %
S0	0.00	--	--	----
S1	2.2	0.17	1.04	1.33
S2	1.13	0.57	0.17	0.00
S3	1.29	0.08	0.97	0.33
S4	0.06	0.13	0.00	0.00
S5	0.984	0.15	0.09	0.44
S6	2.61	0.90	0.93	1.00
S7	1.45	0.85	1.15	0.22
S8	3.101	0.12	0.84	1.22

3.2. Wear Debris Analysis

Table 2 records the results of the mass of debris particles excluding the mass of permanent magnet mass of each magnet. The results showed that **S2**, **S6**, and **S7** samples held bulk quantities of ferrous wear debris particles indicating that these samples need more investigation using microscopic techniques. Furthermore, the results of sludge and soot contents are also reported in **Table 2**, which are good indication to the condition of engines [8]. The results of samples **S1, S3, S6, S7**, and**S8** showed a large yield of soot, indicating imperfect engine combustion and probably frequent and intermittent operation. The poor air/fuel premixing charge and high compression ratios of Diesel engines lead to an increase in the concentration of blow-by gases and then more soot in the lubricant oil. Soot in lubricating oil behaves as an adsorbent to anti-wear additives (ZDDP) and therefore increases the wear rate [28,8].

Figure 1 depicts high and low magnification SEM micrographs of **S2**, **S6**, and **S7** samples. In fact, SEM measurements are useful for identifying the wear mechanism and can avoid the drawbacks of spectroscopy (no detection less than 10 microns) [39] or vibration monitoring (no control at low rotating speeds)[39,40].The obtained SEM images showed a wide-range variety of different sizes and features. A common feature of all particles is their very small thickness, mainly less than 20 µm. Initial analysis of the images showed that the available sizes of particles increase as the engine deteriorated. In addition, the particle edges also seem to become more irregular rather than smooth. In fact, a new engine being in normal operation could show wear debris size typically between 1–20 µm and almost constant concentration. As the engine wears-out, larger debris particles vary between 20–100 µm could be observed and the engine diagnosed to be at abnormal operation[41]. Obviously, the presence of debris particles larger than 100 µm (comparable to the human hair) is a good indication that the engine at catastrophic conditions and requires immediate maintenance action (repair or replacement) [3,6,7,42]. This offline investigation gives an early warning of the machine conditions and helps in decision making.

The features of particles of **S2** shows particles of varied shapes and sizes. Particle range from few microns to about 80 µm was observed. The shape of the particles is irregular with relatively thin dimensions. However, the shape of flake-like debris particles is the dominance morphology as shown in **Fig. 1 (S2)**. The number of generated wear particles with size ≥ 50 µm are less compared to smaller particles. Accordingly, the majority of the particles have a size range of 20 - 40 µm. The mean value and standard deviation of particle size from **S2** images were calculated to be 52.60 µm, and 26.77, respectively. This indicated that the state of the engine started to be in critical condition and requires continuous monitoring. Furthermore, fine particles with the length range from 1µm to several microns are seen. They were produced during the rolling fatigue of mating surfaces within oil passage with random outlines of shape boundary [34,41,42]. Another wear debris in the form of a long chip with a length of ~ 50 µm and width of ~ 5 µm were also observed through the cutting wear process [3,43].

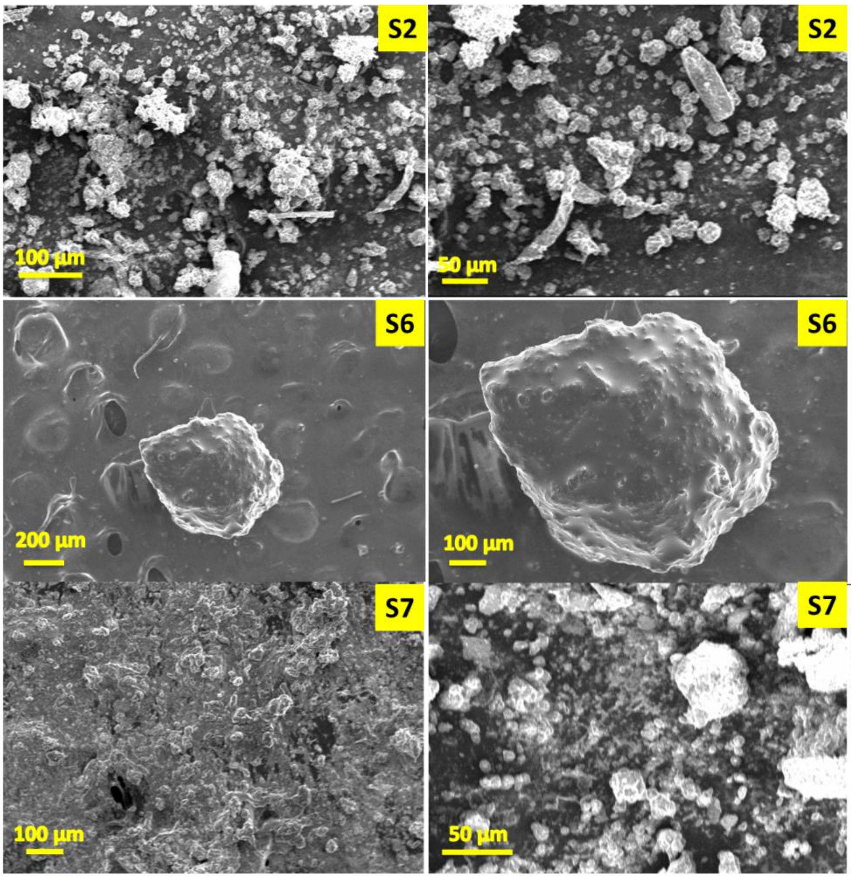

Figure 1. Low and high magnification SEM micrographs and size distribution diagrams of wear debris particles extracted from samples **S2**, **S6**, and **S7**.

Similarly, the information from SEM images of the debris particles of **S6** sample is the largest among other samples. This could be attributed to the bad condition of used oil and perhaps engine design-related problems. The probability of particles with a size of larger than 100 µm is almost high with irregular morphologies and wide size distribution generated plausibly by severe sliding for the internal surfaces. The particle size analysis indicated that the mean value and standard deviation of debris were determined to be 281.25 µm, 45.8, respectively. This quantitative analysis indicated that the debris particles from the**S6** image are greater than the other two samples. However, there is a single particle as shown in the image (**Fig. 1 (S6)),** which is too large. Close observation of this particle inferred that it contains various other small debris particles and other residues in the oil that were agglomerated. Generally, the presence of millimeter size particles is an indication of rapid failure zone often arises from surface fatigue [41].Large quantities of severe sliding wear particles were also found in **S6**, which can create excessive wear of mating surfaces[43].Finally, particles from the **S7** sample are shown in **Fig. 1 (S7)** and had features similar to that of S2 in terms of sizes, shapes, and surface. The particles are of large dimensions and narrowed size distribution. Particles of less than 30 µm sizes are rarely seen in the images but most of the particles are within 10 – 60 µm range but denser and more aggregated.

All in all, the results depicted from the above analysis of **S2, S6**, and **S7** samples provide valuable information about engines' deterioration. They indicate that these engines are working in abnormal conditions. Close observation to **Fig. 2S2, S6** and **S7** indicated the presence of rolled like (rod-like) particles, which are plausibly initiated as flat platelets subjected to rolling process due to the high operating temperatures [3,41]. Similarly, the presence of small spheres (< 20µm) is clearly shown in the three samples. These spheres are of normal nature, generated often in bearing fatigue cracks due to one or a combination of cavitation, rolling, grinding, welding processes under high operating temperatures [3,41-43].As a conclusion, the engines corresponding to **S2** and S7 are in abnormal condition and require focused maintenance. However, the condition of engine matching with oil sample **S6** is at catastrophic failure and needs immediate action either for replacing or overhaul maintenance.

3.3. Density measurements and Interpretations

Table 2 shows the results depicted from density measurements at ambient temperature (31± 0.1°C) for all samples, and a device factor was implemented as per ***Equation 1***. The results of the reduction of oil density indicated that all samples exhibited a reduction of oil density from that of base oil except samples **S2**, and **S4**, which showed almost zero change of oil density. Furthermore, oil samples **S1**, **S6**, and **S8** are the most oil samples with a percentage reduction in density ≥ 1.00 %, which are identical results with moisture content in the same oil samples.

3.4. Kinematics Viscosity

Table 3 depicts the results of Kinematic viscosities at 40 °C and 100 °C in centistoke units and viscosity index (VI). In fact, VI is essential to determine oil shear forces or resistance to motion between oil layers and mating parts [44]. An increase of VI value is an indication of the stability of oil viscosity under temperature change [44,45]. The large increase of VI suggests that the engine is able to operate at higher temperatures effectively[45]. The VI of the base oil (**S0**) was measured to be 96.41 and kept as a reference for other oil samples. Besides, the results of VI of used oil samples fluctuates above and below the VI of base oil. Samples **S2** and **S4** showed a negligible change to the VI, indicating, and not necessarily, the good conditions of the corresponding engines. Besides, Oil samples **S1**, and **S3** are the only samples that exhibit a dramatic decrease of VI at 54.88, and 71.28, respectively. A decrease in VI indicates a dramatic change in the viscosity as temperature increases and may cause excessive wear to the engine components and rapid oil deterioration rates [46]. The reduction of oil VI could be attributed to the high level of fuel dilution and invalidity of the base oil used as per the manufacturers' recommendations [45]. In contrast, oil samples **S5, S6, S7,** and **S8** showed an increase in VI. Interestingly, the results of VI from oil samples showed that as engine output power increases the values of VI also increase, plausibly due to design considerations.

Table 3 shows also the percentage change of viscosity of the used oil samples and interesting results were elucidated. It is worth mentioning that a reduction of 20% of oil viscosity is a critical baseline for predictive maintenance [44]. The reduction of oil viscosity of**S1**and **S8** is the most worsening sample with a reduction of 64.36%, and 62.2%, respectively. Similarly, their reductions at high operating temperatures are also alarming. The viscosity result of S1 is in coordination with the results of VI of the same sample. Samples **S2** and **S4** showed the smallest change of oil viscosity among all other samples, indicating the good working condition of those engines and the results are in-line with the results of VI. Similarly, oil samples **S5** and **S7**showed that the viscosity reduction is slightly around the 20% baseline with improved performance at high operating temperatures (100 °C).Finally, Samples **S3** and **S6** showed also relatively alarming reduction of oil viscosity with better performance for S6 at high operating temperatures.

All in all, keep in mind that viscosity is the most important physiochemical property of a lubricant and the analysis of the kinematic viscosity change (%) and VI of oil samples provides precious investigation to the deterioration of engine components. The results of the VI are more specific. All the calculated VI of used oil samples **(Table 3)** are below the recommended VI value (above 150) for good operations[45]. We found that the rate of increase of VI is correlated well to the engine's output. This suggests that larger engines perform better at higher operating temperatures than small engines, as the science of the rmodynamics also claimed.

3.5. Total Acid Number (TAN)

Table 3 shows the results of the Total Acid Number (TAN) measured based on ASTM 974 standard test [34]. TAN results are given as the number of milligrams of KOH required to neutralize 1 g of oil. The higher the TAN value is, the higher the acidity of the oil [46]. The results showed that all used oil samples are at acidic medium, which means that these oil samples more susceptible to physiochemical reactions than those at neutral mediums. Therefore, the oil samples with large TAN numbers ($\geq$1.0) are plausibly exposed to higher oxidation and wear reactions.

The results showed that the base oil sample (S0) gives the minimum value at 0.244 mg-KOH/g-Oil. In fact, ideal fresh oil is assumed to give zero TAN (pH = 7). All samples of used lubricating oil showed TAN numbers above 1 mg-KOH/g-Oil, indicating plausible oil degradation and excessive wear[34,41,42]. Samples **S3**,**S6,** and **S7** exhibited the highest TAN values at 3.29, 3.19, and 3.24 mg-KOH/g-Oil, respectively. These high values imply high oxidation rate and the high degradation level of corresponding engines. In contrast, sample**S4**demonstrated the lowest TAN values at 1.11mg-KOH/g-Oil. The remaining samples have high TAN numbers in the range of 1.5 – 2.2. These results need to be interpreted with the results of other parameters, such as viscosity, water content, and density to support robust decision making on the engine's deterioration rates.

Table 3. K. Viscosity, Viscosity index (VI), and TAN measurement results of the used oil samples and base oil sample (S0).

Parameter/Sample code	S0	S1	S2	S3	S4	S5	S6	S7	S8
K. Viscosity @ 40°C	268.5	95.69	263.71	175.98	268.23	215.9	151.5	203.14	101.46
K. Viscosity @ 100°C	21.58	9.06	21.17	14.2	21.12	19.34	16.71	19.15	12.00
Viscosity index (VI)	96.41	54.88	95.42	71.28	94.734	101.25	117.97	106.43	108.33
Vis. Change (%) @ 40 °C	0.00	64.36	1.784	34.45	0.1	19.6	43.57	24.34	62.2
Vis. Change (%) @ 100 °C	0.00	58.0	1.9	34.29	2.13	10.38	22.54	9.82	44.39
TAN (mg of KOH/g of oil)	0.25	1.53	1.80	3.29	1.11	2.2	3.19	3.24	1.83

4. Failure modes Analysis

In this section, the failure mode analysis is performed for all engines under study. It employs visiting the place of engines, meeting with maintenance technicians, reading manuals, and asking the questions that possibly indicates the root causes of the dramatic changes in oil properties. Analysis tools such as 5 Why technique and fishbone diagram were implemented whenever they required. This section aims to interpret the results for each engine, investigate the root causes of failure and their effects. Also, its goal is to elucidate technical and managerial recommendations to the owners of those engines.

4.1. Low Capacity Engines (< 50 KVA)

Table 4 summarizes the test results of used lubricant oil samples of low capacity engines. The engine related to **S1** is a Diesel engine (Single cylinder, 10KVA, in service since 1991) belongs to a small business shop in the city. The engine shows the worst results in terms of reduction of kinematic viscosity and VI, plausibly due to the high water and fuel dilution. This was supported by the high water content in the oil at 2.2%, presumably due to the aging of the water circulation system and low combustion efficiency. The high reduction of density (1.33%) also supports that high fuel dilution (low density and viscosity than oil).The high contents of the solid residual in oil (1.04 g/0.5 liter-oil) is another confirmation of the low combustion efficiency. There is excessive wear in engine rings and bearing that assist in fuel dilution. The investigation from the owner of the engine indicated that it works at short periods (4 hours daily) and irregularly, indicating that the engine exposed to large start-up and end-up frequency as another indication to fuel dilution and incomplete combustion[28]. The high frequency of failure in this engine can be explained due to its long-period in service. As a conclusion, this engine is at a catastrophic condition, and over-aged. Our recommendation goes to immediate replacement with a new engine for reliable performance and cost saving.

The engine related to **S2** is a Diesel engine (4 cylinders, 15 KVA, in service since 2012) belongs to a small business shop in the city. The engine operates with short and irregular periods and light loads; hence the time span to change the oil is long. The results of oil properties and contamination (**Table 4**) showed that the engine is currently operated at abnormal conditions. The analysis of wear debris particles shows that almost all particle sizes are below 70 µm indicating that the engine is in the abnormal working area[41]. The analysis of kinematic viscosity showed that almost no change to the oil viscosities even at high temperature working conditions while VI results showed that it has a value close to that of base oil as shown in **Table 4**. The good results of oil viscosity and contamination after 150 working hours are good signs of the health condition of this engine. The above results could be supported by the zero change in oil density. The high value of TAN number (1.802) indicates that the oil is at acidic conditions, which presumably the reason behind yielding bulk quantity of debris particles (0.57 g). The low soot residue in the oil (0.17 g) indicated that the engine combustion efficiency is relatively good and our suggestions to follow strict guidance offered by the manufacturer to enhance its performance and lengthen its service life.

The engine related to sample**S3**is a Diesel engine (3 cylinders, 20 KVA, in service since 2013) belongs to a small enterprise in the city. The analysis of viscosity reduction (34%) and VI (71.73) indicated the abnormal condition of the engine, especially at high operating temperatures (**Table 4**). The high reduction in viscosity could be understood with the high water content (1.33%) and possibly high oxidation arises from extremely high TAN number. The results of high acidity of oil (TAN = 3.29)are alarming since acidic mediums excite the physiochemical reactions of oil constituents. The low reduction of oil density (0.33%) could possibly be explained as the balance between water and fuel dilution, high oxidation reaction, and soot. This engine requires immediate extensive maintenance and follows strict instructions made by the maker.

The engine related to **S4** is a Diesel engine (4 cylinders, 25 KVA, in service since 2018) belongs to a workshop in the city. This engine is like a new engine and only a few months since it was brought to the service. All measurements are close to the new one (**Table 4**). It was inserted in this work for more reliability measurements.

The engine related to **S5** is a Diesel engine (4 cylinders, 3٦ KVA, in service since 2013) belongs to a cancer center, a public authority in Taiz city. The oil viscosity reduction was recorded in the range (< 20%) with improved properties at high temperatures. This could be supported with the increase of VI (101.25) than that of base oil (96.42). Its water content (0.984 %), soot concentration (0.09 g/0.5 liter-oil), and density reduction (0.44%) are relatively low as compared to other samples, plausibly due to its low service. The only alarming parameter is TAN number at2.2, indicating the acidic medium of oil and then the oil constituents and engine components in contact with the oil will be prone to high oxidation. This parameter should be monitored continuously by following instructions from the maker to ensure its proper operating.

Table 4. A summarization of the measured oil properties of low capacity engines (< 50 KVA).

S. No.	Debris particles (µm)	Vis. Red. (%)@40 °C	Vis. Red. (%)@100 °C	Vis. Index (VI)	Water in oil %	Density Red. %	TAN	Soot (g)	Engine Condition
S0	------	0.0	0.0	96.41	0.0	0.0	0.25	-----	----------
S1	-------	64.36	58.0	54.88	2.2	1.33	1.527	1.04	catastrophic
S2	20-70	1.784	1.9	95.42	1.13	0.00	1.8	0.17	average
S3	-------	34.45	34.2	71.73	1.29	0.33	3.29	0.97	very critical
S4	-------	0.1	2.13	94.73	0.06	0.00	1.109	0.00	very good
S5	--------	19.6	10.38	101.25	0.984	0.44	2.2	0.09	Need more monitoring

4.2. Large Capacity Engines (100-200 KVA)

The engine related to **S6** is a Diesel engine (4 cylinders, 100 KVA, in service since 2017) belongs to an internet shop in the city. Although this engine worked for almost one year only, it is working under heavy loads and continuous work for about 18 hours daily. Microscopic analysis of wear debris particles showed alarming results with particle sizes > 150 µm. This finding could be the first indication of the catastrophic condition of the engine.

The results of viscosity reduction (**Table 5**) showed un ultimately high reduction (43.57%) as compared to about 20 % of normal reduction [44]. The measurement of viscosity reduction at high temperature (100 °C) showed an average reduction (22.54%), which indicates that the engine is designed to sustain high-temperature conditions. This finding could be supported by the results of VI (117.97), which is the highest VI for all studied oil samples. The result of water content (2.6% as compared to ~0.25% permitted percentage) in the oil is also alarming [35,36]. During visiting this engine, our observation indicated that the engine was not protected against rains and humid air and was installed in free space and even beside the rain channels to assist the air cooling system. The density of oil was also reduced by ~ 1.0% due to the high water content and plausibly fuel dilution (lighter contaminants). The high yield of soot (0.93 g/0.5 liter-oil) is an indication of the incomplete combustion, high oxidation reactions, and wear rate. The above investigation could be verified using the result of TAN value (3.19) (**Table 5**), which is extremely alarming, indicating that the oil is at highly acidic and then excessive oxidation reactions and wear rates are plausibly the case. What is more, the engine follows a careless maintenance management system, despite its short-period in service. The engine useful life was shorten promptly due to the bad maintenance and overload. The fishbone diagram (**Figure 2**) summarizes the root causes of deterioration and their effects. The analysis classifies the base problems to the bad working environments, unskilled technicians, bad management, and old maintenance techniques. Our investigation has proved that the frequency of engine main time to failure is high. The long hours operating (> 16 hours daily), heavy loading, incorrect place, and the bad maintenance are the main causes of rapid deterioration of this engine. Our recommendation to purchase another unit with the same characterization to allow each unit to work short time and apply strict maintenance schedules.

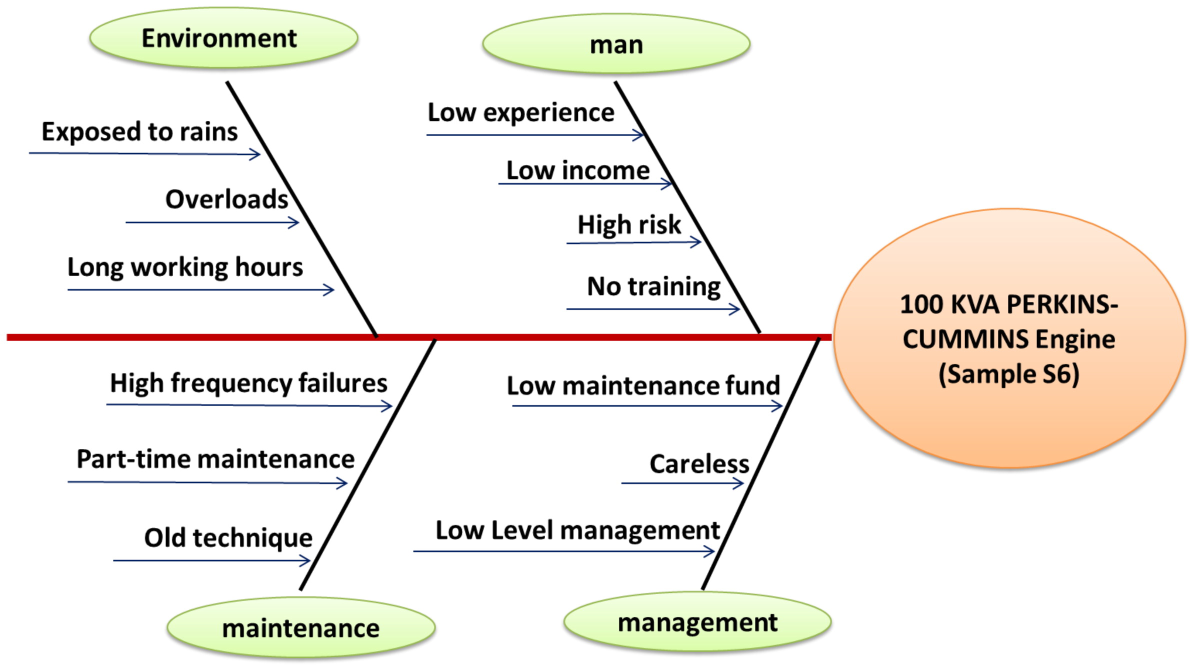

Figure 2. Fishbone diagram Cause-Effect analysis of the engine matching with oil sample S6.

The engine related to **S7** is a Diesel engine (6 cylinders, 120 KVA, in service since 2014) belongs to a public Health Authority in the city. The microscopic analysis of wear debris particles of this engine showed a variety of particle sizes and shapes in the range of 10 -600 µm, which are in abnormal operation [41]. The analysis of kinematic viscosity showed a pronounced reduction (24.34%), which is close to the world standard of 20% reduction [44]. The reduction of viscosity at high temperature showed in-range reduction (9.82%), which indicated that the engine performance at high-temperature condition is good. These findings are in-line with the results of VI which showed an increase than that of base oil. The results of density reduction showed only 0.22%, which could be understood as a balance between high and low-density contaminants and degradation products. The high value of TAN (3.24) (**Table 7**) is another approve of excessive oxidation and abrasive wear reactions. The results of water content tests are relatively high at 1.45%, but not as high as other engines.

5 Whys' technique was implemented to investigate the failure mode for this engine. Our inspection depicts that this engine follows a quit good routine maintenance. It works 11 hours a day and the lubricating oil changed as per routine schedule. What is more, the engine was installed at the right place where it protected from rains and exposed to open air. However, there are some management problems such as slow response to failure signs and they attribute that to the lack of maintenance funds. We observed that the oil quantity slightly decreases with time, plausibly due to evaporating at high operating temperatures close to the combustion chamber and high oil degradation raised from excessive acidic medium (high measured TAN value).The research team observation and inquiry from maintenance technicians have detected a water leakage to the engine combustion case through engine head plausibly due to fitting problems and aged engine. Although the engine viscosity and VI are not bad, the large debris particles could be attributed to the ultimately high TAN (3.24 mg of KOH/g oil). The low reduction of viscosity could be explained as a balance between high wear products, high soot and other residue (1.15 g/0.5 liter-oil), and water and fuel dilution. There fore,this engine is at catastrophic condition due to the presence of large impurities on its oil. The maintenance management is bad and the engine requires overhaul maintenance to retain its efficiency.

The engine matching with the **S8** oil sample is a Diesel engine (6 cylinders, 200 KVA/160 W, in service since 2008) belongs to a public Engineering college in the city. Fishbone diagram is selected to investigate the failure causes and effects of this engine with the help of staff interviews. The research team observation and inquiry from maintenance technician depict that his engine follows bad routine maintenance and management. Different technicians dealt with this engine for a short time without any training and experience. The team has also observed that the engine was installed in an open atmosphere and exposed to rains and humid air. This engine is operated only 4 hours for only two days weekly (a total of 8 hours in the week) with irregular nature. Therefore, the time span to change the oil takes long months, considering it the longest duration among all other engines.

The results showed the second-worst kinematic viscosity reduction among all other engines at low and high-temperature tests at 62.2% and 44.39%, respectively. This ultimate reduction in kinematic viscosity is questionable. We can explain it in terms of the high-frequency starting and shutdown of this engine, which derives the condensed water and fuel dilution processes [27] and then the excessive reduction in oil viscosity. From a scientific view, a rich fuel/air ratio takes place at starting and shutdown leading to incomplete combustion and then fuel dilution [28]. The above scenario could be supported by the high reduction of oil density (1.22%) of this engine [47]. What is more, the high water contamination (3.1%), high TAN (1.83), and large soot (0.84 g) offer a proper environment to the corrosion and oxidation reactions to propagate and accelerate with more than five folds [48], resulting in dramatic changes to the oil properties and engine deteriorations.

To this, in spite of engine low useful life (10 years since the installation), light loads, and low-frequency operations, the aforementioned catastrophic conditions of this engine and the analysis of Fishbone Diagram (**Fig. 3**) drive an immediate decision to make an urgent action towards overhaul maintenance followed by building a strict regulation to follow the manufacturer routine maintenance, relocate the current place of the engine to be in a safe mode against all unwanted environmental conditions, apply a suitable maintenance management system, train the operation and maintenance staff, and change filters and oils as scheduled.

Table 5. A summarization of the measured oil properties and impurities of large capacity engines (> 50 KVA).

S. No.	Debris particles (µm)	Vis. Red. (%)@40 °C	Vis. Red. (%)@100 °C	Vis. Index (VI)	Water in oil %	Density Red. %	TAN	Soot (g)	Engine Condition
S0	------	0.0	0.0	96.41	0.0	0.0	0.25	-----	----------
S6	> 150	43.57	22.54	117.97	2.6	1.00	3.19	0.93	catastrophic
S7	40-130	24.34	9.82	106.43	1.45	0.22	3.24	1.15	very critical
S8	-------	62.2	44.39	108.33	3.101	1.22	1.83	0.84	catastrophic

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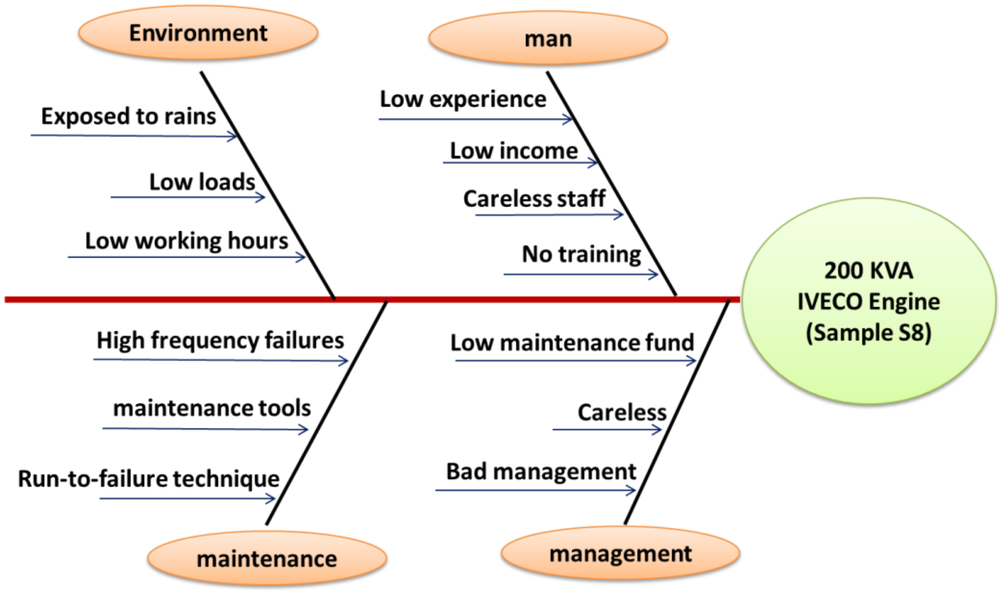

Figure 3. Fishbone diagram failure (causes-effect) analysis of the engine related to sample S8.

5. Conclusions and Recommendations

This study investigated the health conditions of small unit engines at the end-user, which are rarely reviewed in the literature. The absence of failure records, clear maintenance plans, and maintenance funds for small-unit engines are the major dominating causes of the rapid degradation of engine. Therefore, the analysis of used oil properties and contaminants is an optimum option for predicting health conditions. Failure analysis investigated the root causes of engine failure could be traced to (1) Wear debris particle features are the most reliable offline diagnosed technology for small unit engines, (2) irregular and frequent startup of the engines are one cause of rapid degradation of engines, (3) bad working conditions and incorrect installation are plausible causes of early deterioration of engines, (4) Continuous monitoring of oil viscosity is an effective tool for early detection of failures in small-unit engines, (5) more contaminants in the engine oil are an indication of deteriorating engines, (6) large capacity engines performs better than small engines in term of viscosity degradation and wear rate propagation, and (7) the type of oil, and oil working hours before replacing influence the quality of lubricating oil and engines.

This study recommends including oil lubricant analysis as a major source of the maintenance routines. The management should implement CBM systems regularly to monitor operating conditions and invest sufficient funds to extend the useful life of engines. Also, the technical work should be assigned to skilled and experienced technicians for performing maintenance duties effectively. The engine technicians should monitor lubricating oil levels, oil filters, oil working hours, and oil type as per the manufacturer's recommendations. Furthermore, the engine should be placed in suitable environments; far away from the rain with a suitable ventilation system. Finally, an offline oil analysis needs to be taken frequently for maintenance.

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