DEVELOPMENT OF DIELECTRIC SENSOR TO MONITOR THE ENGINE LUBRICATING OIL DEGRADATION

by

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Present day practice of following fixed schedules of oil change intervals could result in loss for the equipment owner, as the oil is not utilized up-to its maximum useful life. Similarly, the extended use of engine oil beyond maximum useful life is of high risk, which could lead irreversible and catastrophic damages to engine parts. Engine oil condition indicates the condition of engine parts, in any application. Therefore, monitoring the condition of the oil in real time is of paramount importance. Researchers had established that the engine oil degradation correlates with change in dielectric property of the engine oil. The important factor to realize the on-line real time monitoring of the changes in dielectric property of the engine oil is, the cost of dielectric sensor within affordable limit for an operator. Current work aims at developing such a low cost affordable dielectric sensor and engine oil samples (SAE 15W40 grade) were collected from durability test engines used in engine test rig and on-road vehicles. These samples were tested for physical and chemical properties. Any changes in the properties, of engine oil monitored,indicate that it undergoes degradation due to usage. A prototype of capacitive type sensor was developed and validated with reference fluids. The dielectric values measured using proto type sensor in the used oil samples show a correlation with change in physical properties. This trend and thresholds of dielectric provides effective plat form to monitor the engine oil degradation. The sensor could be coupled to a suitable warning device by incorporating specific algorithms.

Key words: *engine oil, degradation, dielectric constant*

Introduction

Engine manufacturers normally define the oil change intervals rather than specifying the maximum useful life of oil. The oil change period basically derived based on application related considerations such as different operating speeds and loads, operating environment, and different duty cycles. The *light duty cycle* and *severe duty cycle* are the two extreme conditions under which the same oil is used. The change period, thus prescribed does not indicate the actual condition of the specific engine oil. The change in chemical or physical properties of the used oil can be tested in regular intervals to monitor the remaining useful life, in a laboratory. This includes measuring degradation in chemical or physical properties, soot percentage (particularly in Diesel engines), wear debris and contamination due to fuel or water dilution. This method is a tedious, extremely difficult, expensive, and not so practical process as it involves frequent sam-

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pling and testing at laboratory. Major drawback of such procedure is that it fails to provide the prior warning to the operator about exact end of useful life, which is of fundamental need, if the oil has to be utilized to its maximum useful life. Therefore, monitoring the condition of the oil, on actual real time operation is therefore of paramount importance to avoid discarding the oil much before its maximum use full life as well as to avoid the risk of using degraded oil.

Many researchers reported about capacitance sensors to measure the dielectric constant of the engine lubricating oil in order to monitor the engine oil degradation. The capacitor sensor has capable to measure the degradation detection due to oxidation, water contamination and wear particle [1]. The grid capacitive sensor also used to compute the dielectric constant of the lubricating oil contamination and found that the value of dielectric constant varied from 6.5 to 10 pF in relation to the input frequency [2]. Agostin *et al*. used leaved-disc capacitor to measure the dielectric constant then correlated it with viscosity of the engine lubricating oil [3]. The researcher designed a wireless sending system, which transmits lubricating oil capacitance information and energy between sensor and reader for automobiles with a capacitive sensor [4].

Liu *et al*. conducted experimental validation on permittivity as a method of measuring oil degradation and confirmed the change in trend between the permittivity and acid value, iron content, moisture [5]. The effect of temperature on dielectric constant of lubricating oil was studied by Torrents and Areny [6]. They have showed that in the lower frequency range, the temperature coefficient of the dielectric constant depends on whether the oil is new or it has been used. Apart from previously mentioned sensors, some commercially available sensors are also capable of online oil quality detection by way of interpreting lubricating oil dielectric property but they are costly. In this research work, an attempt is made to develop affordable dielectric sensor to monitor the engine oil condition.

Engine oil degradation process

As lubricants ages, they become less capable of delivering expected performance largely due to the progressive dump of high amounts of sludge and insoluble compounds into the oil sump. The primary driver for this problem is oxidation. Oxidation is a general term used to describe a complex and series of chemical reactions, which disturbs the chemical stability of the liquid and encourages formation of new unwelcome molecular species within a lubricant sump. Initially, oxidation was characterized as a chemical reaction involving oxygen. The definition has been expanded to include any reactions involving electron transfer. Craft [7] described the lubricant oxidation as a three-stage process: Initiation, propagation, and termination [7].

Initiation stage involved with the formation of a free radical, an atom or molecule fragment with one or more unpaired electrons. The biggest contributor of free radicals is the oxygen itself. Contaminants those are rich with oxygen (air, water) feeds oxygen to the system. Free radicals are highly reactive and un-stable, quickly combining with HC components to form alkyl radicals and hydroperoxi-radicals. The propagation stage occurs when hydroperoxi (peroxide) radicals react with the base oil or additives to regenerate an alkyl-radical (or generate an alcohol and water) and restart the cycle. When high temperatures exist, the peroxide radicals split and sustain the chemical reaction. When wear debris is present, peroxides may catalytically split to sustain the reaction, even at low temperatures. The propagation stage becomes autocatalytic, with the chemical reactions themselves providing the feedstock to start the next cycle.

The termination stage occurs when the designated oxidation inhibitor (antioxidant) performs its function. All the three stages of engine oil degradation lead to formation of acidic components, which affect the dielectric constant of lubricating oil as shown in fig. 1.

Fresh lubricating oil properties

Table 1 shows fresh oil properties of SAE 15W-40 grade lubricating oil. The typical value of kinematic viscosity at 100 °C ranges from 14.5 to 15.7. The base number value is 9.6 initially and decreases as degradation takes place. When the lower value of base number equals acid content, it shows end of oil life. The soot level below 4% is desirable.

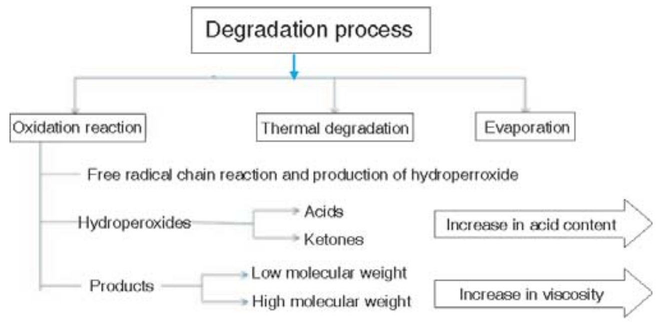

Figure 1. Degradation process of engine oil

Table 1. Fresh oil properties

Properties	Oil 1	Oil 2
	Values	Values
Grade	15W-40	15W-40
Density, [kgm^{-3}]	881	875
Viscosity at 100 °C, [cSt]	15.7	14.5
Viscosity index	131	135
Pour point, [°C]	–30°	–27
Flash point, [°C]	204	230
Sulphur, [wt.%]	0.32	Not traceable
Base number	9.6	10.1
Sulphated ash. [wt.%]	1	1.3
Phosphorous, [wt.%]	0.12	Not traceable
Zinc, [wt.%]	0.13	Not traceable

Engine oil sampling and lab testing

Engine oil samples were collected from engines from test bed and on road vehicles (diesel powered vehicles) at regular intervals. These samples were tested as per ASTM procedure and test results were compared with threshold limits. The analysis of collected test samples aimed at prognostic of the engine oil brings out interesting facts that the SAE 15W-40 grade of oil used in different engines does not behave the same way. Moreover, the life of the oil does not depend on a single property or factor under consideration. Instead, any property that overshoots its limit first, determines the end of life though other properties might be still within their limits. tab. 2 gives summary on lab test results of the samples collected from Engine test bench. It is observed that the useful life of oil varies in the samples depending on various factors. Table 3 gives summary on lab test results of samples collected from fleet vehicles. It is observed that the maximum useful life of oil varies in the samples depending on the various factors.

Such variation in physio-chemical properties of samples, collected exactly in same drain period, depends on factors like operating temperature, load cycles, speed cycles, wear ma-

Table 2. Oil analysis of samples from test bench engines at regular intervals

Engine no.	Test duration [h]	Sampling frequency [h]	Condition of oil	Max life [h]	Max life limited based on
1	350	50	Degraded	250	Viscosity beyond 18.5 cSt and soot beyond 4%
2	500	50	Degraded	500	Silica reached max level of 40 ppm

Table 3. Summary of oil analysis of samples from on road fleet of vehicles

Samples collected from	Test duration [km]	Sampling frequency [km]	Condition of oil	Max life [km]	Reason for limiting max life
Fleet 1	60000	30000	Good	60000	Oil condition checked up to 60000 only
Fleet 2	60000	30000	Degraded	60000	Total base number reaches lower limit of 5 mg KOH/g
Fleet 3	60000	30000	Good	60000	Oil condition checked up to 6000 only
Fleet 4	60000	20000	Good	60000	

terials, condition of piston rings/liners/valve seats/valve guides, injector spray patterns, injector pressure, air cleaner efficiency, and so on. As such, the fixed change schedule prescribed in the vehicle does not truly reflect the entire life, considering safe situation depending on operating parameters. Hence, it could be a risk in either way to permit the engine to run for the prescribed duration of oil change period, due to the following reasons:

– the oil might have lost its life before the prescribed period (under more severe operating conditions, which were not considered by the equipment manufacturer while validation), and
– the oil has been discarded much before the end of useful life.

The degraded oil could lead to costly failures such as journal bearing seizure, piston ring seizure, cam bush wear, *etc*.

Development, validation and testing of dielectric sensor proto type

The dielectric sensor has two co-axial cylinders, as electrodes, which separated by space or medium and works on the principle of capacitance. The medium has certain dielectric constant. The dielectric constant is the measure of a material's influence on the electric field. The net capacitance will increase or decrease depending on the type of dielectric material. Permittivity relates to a material's ability to transmit an electric field. In the capacitors, an increased permittivity allows the same charge to be stored with a smaller electric field, leading to an increased capacitance. The value of capacitance is measured by using LCR meter. The capacitance can be stated in terms of the dielectric constant by Carey [8] and Baxter [9]. A coaxial type sensor with inner and outer electrode is developed as shown in fig. 2. The dielectric constant was measured in reference fluids like toluene and coconut oil. Initial error of 4-5% was observed as shown in tab. 4.

Figure 2. Protot type dielectric sensor

Table 4. Validation result of sensor

Fluid	Measured [pF]	Measured dielectric	Reference dielectric	Error
Toluene	78.66	2.18	2.3	5%
Coconut oil	108.46	3.004	2.9	4%

$$\varepsilon_{\rm r} = \frac{C}{C_0}$$

where $\varepsilon_{\rm r}$ is the dielectric constant, C – the capacitance in farads with dielectric between plates, and C_0 is the capacitance in the absence of dielectric.

Figure 3. Exploded view of modified sensor parts

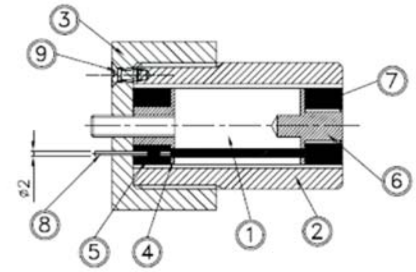

Figure 4. Assembly view of modified sensor parts
1 – inner electrode, 2 – outer electrode, 3 – top cover – Nylon, 5 – top sleeve, 6 – bottom Bush – Nylon, 7 – bottom sleeve, 8 – ground terminal, 9 – negative terminal

The error observed was due to fringe & spacing effects. A ground terminal was introduced to reduce fringe effect. A small rifle hole of 2 mm diameter in inner electrode and lead through it was introduced to reduce the lead effect. Diametric clearance was reduced from 4mm to 2 mm between the electrodes to reduce spacing error. Nylon bushing in sleeves was introduced to reduce stray capacitance. The modifications were done in order to reduce errors due to fringe effect, lead effect and spacing effects [10]. With the modified sensor, the error was reduced from 4 % to 1%. The modified sensor is shown in figs. 3 and 4.

The capacitance was measured for fresh lubricating oil using a LCR meter coupled to the sensor ground terminal as shown in fig. 5. Table 5 shows the variations observed with optimized proto type sensor output after improvement (1% max).

Figure 5. Test set-up for measuring dielectric constant

Table 5. Validation result of modified sensor

Reference fluid	Dielectric constant (measured dielectric)	Dielectric constant (standard value)	Error [%]
Toluene	2.319	2.3	1
Coconut oil	2.934	2.9	1

Table 6. Fresh oil properties

Fluid	Capacitance [pF]	Measured dielectric constant
Fresh lubricating oil (SAE 15W-40)	46.36	2.03

Results and discussion

The dielectric constant value measured in the fresh SAE 15W-40 engine lubricating oil is given in tab. 6. Further, the used oil samples collected at various kilometers per hours interval from bench test engines and fleet vehicles were tested, using the sensor. The measurement results of dielectric constant and trend analysis of the changes in dielectric constant with respect to the changes in physical properties (Viscosity, TBN, TAN, soot) as the oil undergoes degradation, is given in tab. 7, and plotted in subsequent figures.

Table 7. Dielectric constant of vehicle oil samples

Vehicle 1			
Oil [km]	0	30000	60000
Kinematic viscosity at 100 °C, cSt.	14.43	12.75	12.61
TBN, mg KOH/g oil	9.64	7.6	6.24
TAN, mg KOH/g oil	2.27	3.13	3.43
Dielectric constant	2.155	2.298	2.433
Vehicle 2			
Oil [km]	0	30000	60000
Kinematic viscosity at 100 °C, cSt.	14.52	13.07	12.57
TBN, mg KOH/g oil	9.79	6.79	5.41
TAN, mg KOH/g oil	2.29	4.06	4.17
Dielectric constant	2.13	2.832	3.326
Vehicle 3			
Oil [km]	0	30000	60000
Kinematic viscosity at 100 °C, cSt.	14.45	13.59	13.55
TBN, mg KOH/g oil	10.09	8.01	7.14
TAN, mg KOH/g oil	2.48	3.51	3.26
Dielectric constant	2.178	2.251	2.355
Vehicle 4			
Oil [km]	0	30000	60000
Kinematic viscosity at 100 °C, cSt.	14.19	14.98	14.59
TBN, mg KOH/g oil	10.3	7.92	7.07
TAN, mg KOH/g oil	2.87	3.08	3.71
Dielectric constant	2.5	2.484	2.481

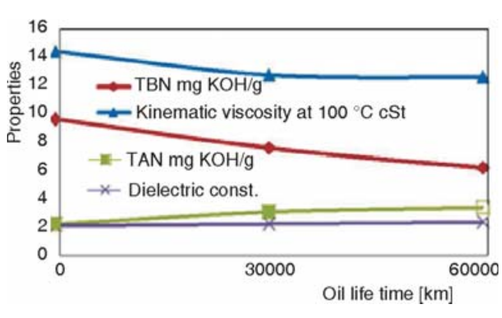

Figure 6. Change in TBN, TAN, viscosity, and dielectric constant with respect to oil life (oil sample from vehicle 1)

The correlation trend graph of dielectric constant with respect to viscosity, total base number (TBN) and total acid number (TAN) are shown in figs. 6-9. Figure 6, represents the dielectric value of 2.433 when viscosity, TBN and TAN are within limits. This trend shows the remaining useful life oil at 60000 km. Figure 7 shows the depletion of TBN and increase in acid content, both meeting at 5 mg KOH/g, which indicates the end of useful life of oil. Kinematic viscosity and wear materials are still within limits. The dielectric constant increases from 2.13 to 3.32 in a correlation at the end of useful life oil. Figure 8 represents the dielectric constant

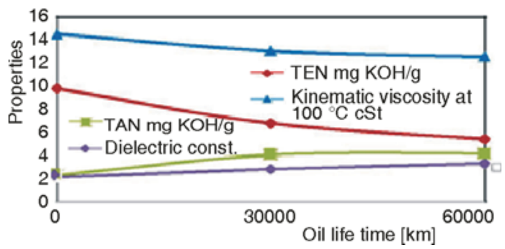

Figure 7. Change in TBN, TAN, viscosity and dielectric constant with respect to oil life (oil sample from vehicle 2)

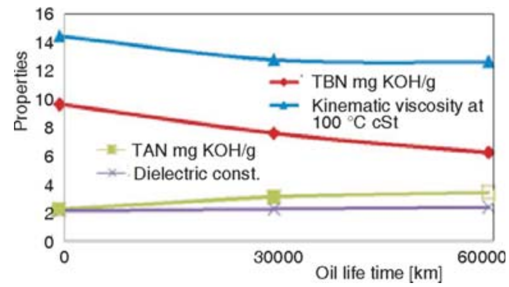

Figure 8. Change in TBN, TAN, viscosity and dielectric constant with respect to oil life (oil sample from vehicle 3)

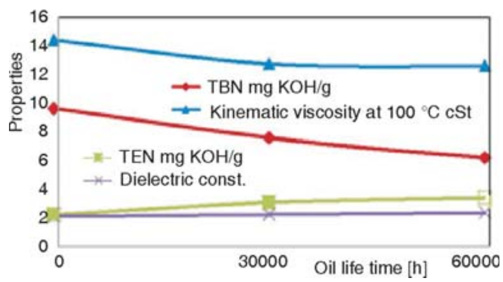

Figure 9. Change in TBN, TAN, viscosity and dielectric constant with respect to oil life (oil sample from vehicle 4)

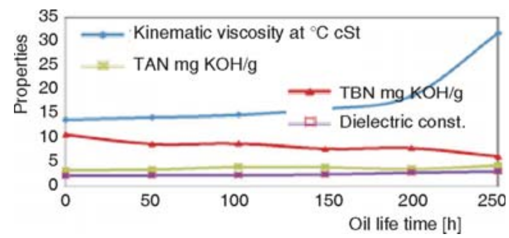

Figure 10. Measurement of TBN, TAN, viscosity and dielectric constant from oil sample of engine 1

value of 2.355 and the viscosity, TBN and TAN values are within limit. This shows a remaining useful life of oil at 60000 km.

Figure 9 shows that the TBN, TAN, and kinematic viscosity are within limits, and the oil has still remaining useful life at the end of trial. The dielectric constant correlation remains in the range of 2.5, while acid content and base number are within limits.

The used oil samples collected from test engines were tested. The measurement results of dielectric constant and trend analysis of the changes in dielectric constant with respect to the changes in physical properties (viscosity, TBN, TAN, soot) as the oil undergoes degradation, is given in tab. 8 and plotted in figs. 10-13. The trend analysis of dielectric constant with respect to viscosity, TBN, TAN, and soot are shown in figs. 10-13. Figure 13 shows that silica content has almost reached the allowable limit of 40 ppm at 450 hours, while viscosity, TBN, and TAN was

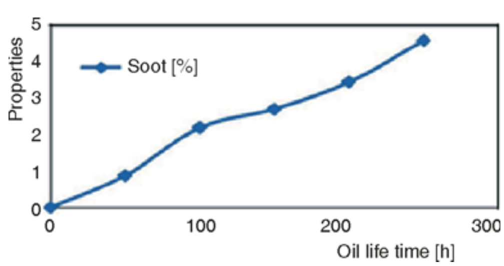

Figure 11. Change in soot [%] in oil sample from engine 1

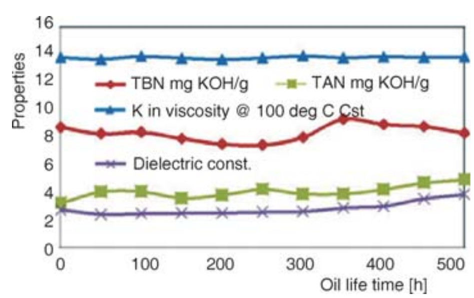

Figure 12. Measurement of TBN, TAN, viscosity and dielectric constant from oil sample of engine 2

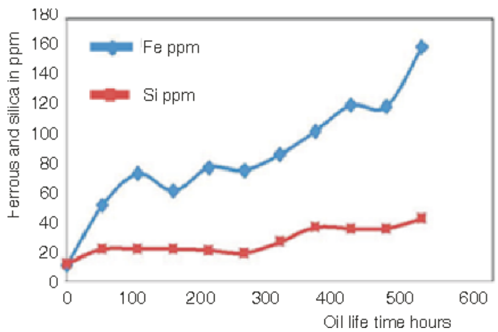

Figure 13. Wear debris in ol samle (silica and ferrous) from engine 2

within limits. The dielectric constant increases from 2.72 to 3.88 in relation with the end of useful life of oil.

Conclusions

An extensive oil analysis was done based on Tribology & Lubricant technology guide on SAE 15W-40 oil with diesel engines. The 12 individual samples were taken from two test engines and 12 individual samples from four on road fleet vehicles. These samples were tested for physio-chemical properties in laboratory. The analysis showed that the lifetime is varying for each operation depends on different degradation levels of properties such as viscosity, total base number, total acid number, soot and contaminants. A proto type sensor was initially developed and validated in reference fluids. An error of 4% was observed. The sensor was modified with reduced gap between the electrodes and with nylon inserts. The modified proto type sensor was validated with reference fluids and tested in fresh engine lubricating oil. It was used to measure the dielectric constant of used oil samples and correlation of dielectric constant with respect to changes in physical/chemical properties was studied. The dielectric constant is an effective electrical property to monitor the engine oil degradation.

Table 8. TAN, TBN, kinematic viscosity and dielectric constant of used oil samples from test bench engine 1 and 2

Engine 1: oil hours	0	50	100	150	200	250
Kinematic viscosity at 100 °C, cSt.	13.87	14.27	14.8	16	18.65	31.73
TBN, mg KOH/g	10.74	8.79	8.95	7.81	7.96	6.21
TAN mg KOH/g	3.34	3.52	4.04	3.98	3.65	4.36
Soot, [%] FT-IR	0	0.87	2.19	2.7	3.44	4.57
Dielectric constant	2.2	2.28	2.32	2.5	2.83	3.11
Engine 2: oil hrs.	0	100	200	300	400	500
Kinematic viscosity at 100 °C, cSt.	13.82	13.89	13.66	13.93	13.88	13.86
TBN, mg KOH/g	8.75	8.39	7.53	8.02	8.95	8.32
TAN mg KOH/g	3.24	4.08	3.82	3.89	4.23	4.94
Dielectric constant	2.75	2.468	2.512	2.622	3.01	3.88

A low cost sensor of this type can measure the dielectric property in real time situation as well as give warning signal before the useful life of oil ends. Future scope of work is in this direction to have it fitted in Engines with suitable circuits and warning devices to realize the potential of providing real time indication of engine oil life.

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