Experimental Study on the Effect of Marine Engine Lubricant Degradation on Tribological Performance of Cylinder Liner and Piston Rings Contact Using a Tuning Fork Technology Based Oil Sensor

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Synopsis

An investigation was carried out to study the effect of changes in oil quality on its tribological performance using a tuning fork technology based oil sensor. In this research, a tribological testing system was commissioned, to simulate the piston ring-cylinder liner sliding contact, and to measure the lubricant condition in real-time using an oil sensor. Tribological contact between cylinder liners and piston rings in marine engines is the most affected region due to excessive thermo-mechanical stresses. At top dead centre, the effect of such stresses is at a maximum where piston-sliding speed is lowest, while the temperature is high due to fuel combustion, and radial load behind the piston rings compressing against the cylinder liner surface is at a maximum due to gas pressure and the compression fit of piston rings within the cylinder liner. At bottom dead centre, this effect is less severe due to a reduction in temperature and gas pressure on the piston rings, as the piston is positioned away from the combustion chamber. These two regions experience boundary lubrication conditions, where anti-wear and anti-friction additives are responsible for forming a protective lubricious film on sliding surfaces. At mid-stroke, piston-sliding speed is maximum, therefore, a full hydrodynamic film is formed in this region separating the piston rings and cylinder liner. The formation of oil film depends upon, the physical properties of oil (such as viscosity and density) under hydrodynamic lubrication conditions, and the oil chemistry (such as presence of additives in oil) under mixed or boundary lubrication conditions. Lubricants in marine engines undergo intense degradation in quality due to contamination with wear particles, water, soot, un-burnt fuel, coolant, and additives depletion. Such degradation of lubricants leads to a reduction in their capability to form a minimum thickness of oil film between two moving engine components to avoid direct metal-to-metal contact, which may cause wear. Therefore, monitoring the condition of marine

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engine lubricants is vital in order to predict any significant change in its quality. The results obtained from tribology testing and oil condition monitoring in the current research showed a good correlation and are useful to understand the performance of lubricants for piston ring-liner contacts.

Keywords — Condition Monitoring, Engine Lubricants, Oil Properties, Cylinder Liner, Piston Rings, Tribological Performance

1. Introduction

The top compression piston ring experiences the most complicated tribological contact against the cylinder liner walls due to complex variations of load, speed, temperature and the presence of lubricant. Although, the larger part of the piston ring – cylinder liner interaction area in the engine experiences hydrodynamic lubrication during each piston stroke (Rizvi, 1999), but at Top Dead Centre (TDC) near the top piston ring reversal point boundary lubrication is prevalent. High wear takes place in this region due to extremely high friction forces, which are directly proportional to excessive combustion gas pressure and relatively slow piston speed, which prevent the hydrodynamic lubricant film from building up (Li et al., 1983). Major factors responsible for disrupting the oil film thickness are cylinder bore distortion (mainly due to wear), piston speed, lubricant viscosity, top ring face profile, ring flexibility, boundary conditions and surface roughness characteristics (Bhatt et al., 2009). The wear protection for the cylinder liner and piston assembly surfaces is mainly provided by the chemical film formed by anti-wear additives present in the lubricant.

Extended oil change periods cause degradation of the lubricant physical and chemical properties (Tung et al., 2004). Oil drain intervals, therefore, need to be managed and planned efficiently otherwise it may cause severe consequences for engine wear. Condition monitoring of oil can help to overcome this problem. This can be achieved while oil is in-service and provides real-time information of oil condition. Condition-based drain intervals not only reduce oil consumption and maintenance costs but provide incremental vehicle and equipment protection through the immediate detection of contaminants infiltrating lubricants and oils. Contaminants like soot, water, ethylene glycol coolant and fuel in engine oil are easily detected by their impact on the viscosity, density and dielectric constant of oil. Oil oxidation also changes these properties in a detectable manner (Bernasconi et al., 2019)

In this research, the authors have performed the numerical and experimental analysis to evaluate the effects of oil quality on its capability to form an oil film for piston ring and cylinder liner tribological contact. Such that the effect of change in oil viscosity on the minimum oil film thickness under varying piston ring sliding speed of piston ring and oil temperature in actual engine was studied. Experiments were performed to analyze the change in oil chemistry using a tuning fork technology based oil sensor in real-time in terms of dielectric constant. Standard laboratory based oil tests and tribo-tests were performed to verify that the data obtained from the oil sensor reflects the oil chemical behavior.

2. Experimental Details

2.1 Experimental Test Set-Up

Experiments were performed to analyze the quality of oil using a tuning fork technology based oil sensor in real-time. Figure 1 shows the experimental test set-up that involves the use of the oil sensor in line with tribo-testing machine. Figure 2 shows the individual components used in the commissioning of the oil condition monitoring test set-up. The oil sensor used is capable of measuring oil properties such as viscosity, density, dielectric constant and bulk temperature of the oil. However, due to the erratic nature of results for viscosity and density, only data for dielectric constant is considered for analysis. The data is recorded by the oil sensor every 30 seconds for the complete test duration. For the benefit of detailed analysis, the data was interpolated to obtain a value at 1-second intervals for the complete test duration of 3 hours.

The test chamber in the tribo-test machine contained the simulated environment of the piston ring and cylinder liner tribological contact. The test chamber was filled with lubricating oil such that the sliding flat sample (representing the cylinder liner) is submerged in oil. The piston ring was held in a holder and its running face was pressed against the sliding flat sample. The oil in test chamber was then circulated through silicone (neoprene) tubes capable of transfering engine oils at 100 ºC. The tubing was also wrapped with a sheet of foam for insulation and to avoid heat loss from the oil to the

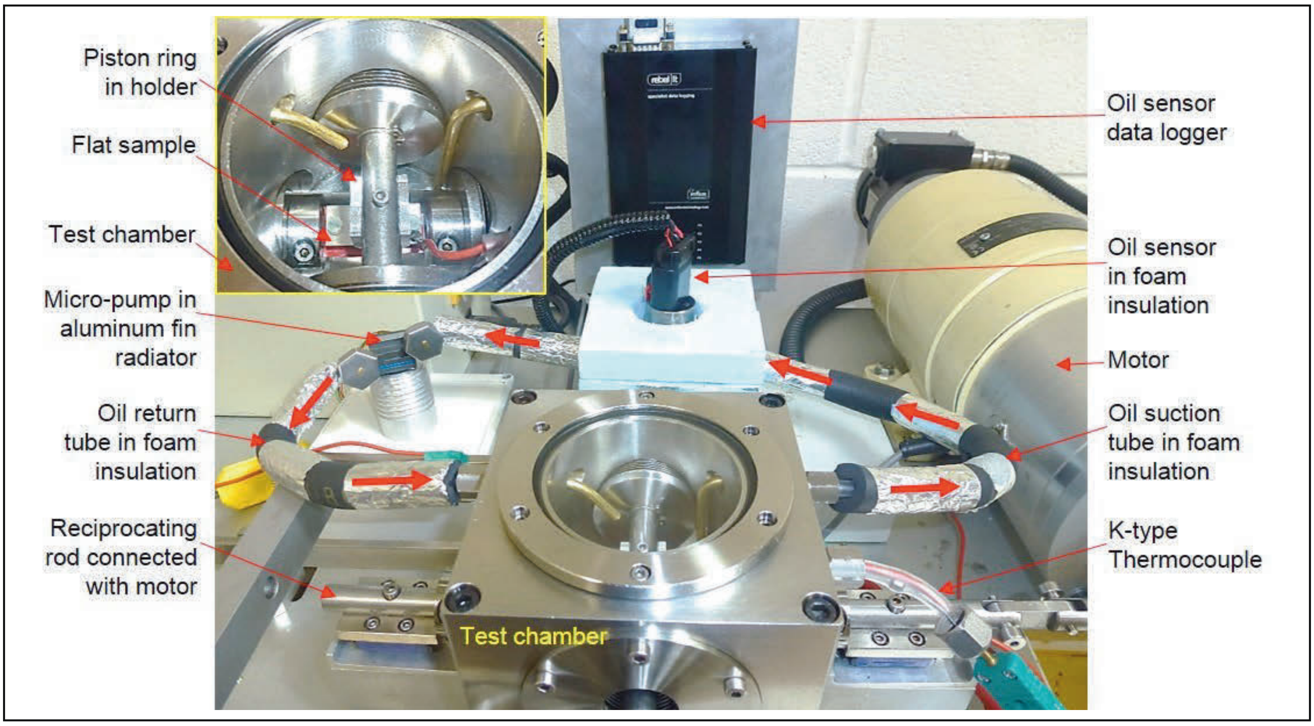

Figure 1: Illustration of experimental test set-up showing oil sensor connected with tribometer

surrounding environment. A micro-pump was used to maintain the required oil flow rate of 0.2 m/s for the optimum measurements by the oil sensor. Tribo-tests were performed using the test conditions as mentioned in authors' previous work (Anand et al., 2015). White light interferometry was used to analyse the wear scar on the flat plate samples after the tribo-tests.

2.2. Oil Samples and Analysis

Engine lubricating oil at three different stages of its servicing in an actual marine diesel engine was used for numerical and experimental analysis. The samples were collected using the oil-suction pump into oil sampling bottles at different service intervals such as 135h (refer as Sample 2) and 196h (refer as Sample 3) which represent the in-service condition of the lubricating oil. Fresh engine oil (refer as Sample 1) is also employed in experiments for performance comparison and was supplied in a sealed container by the RNLI (UK). In order to verify the experimental results obtained from the Tuning fork technology based oil sensor, the standard laboratory based tests were also

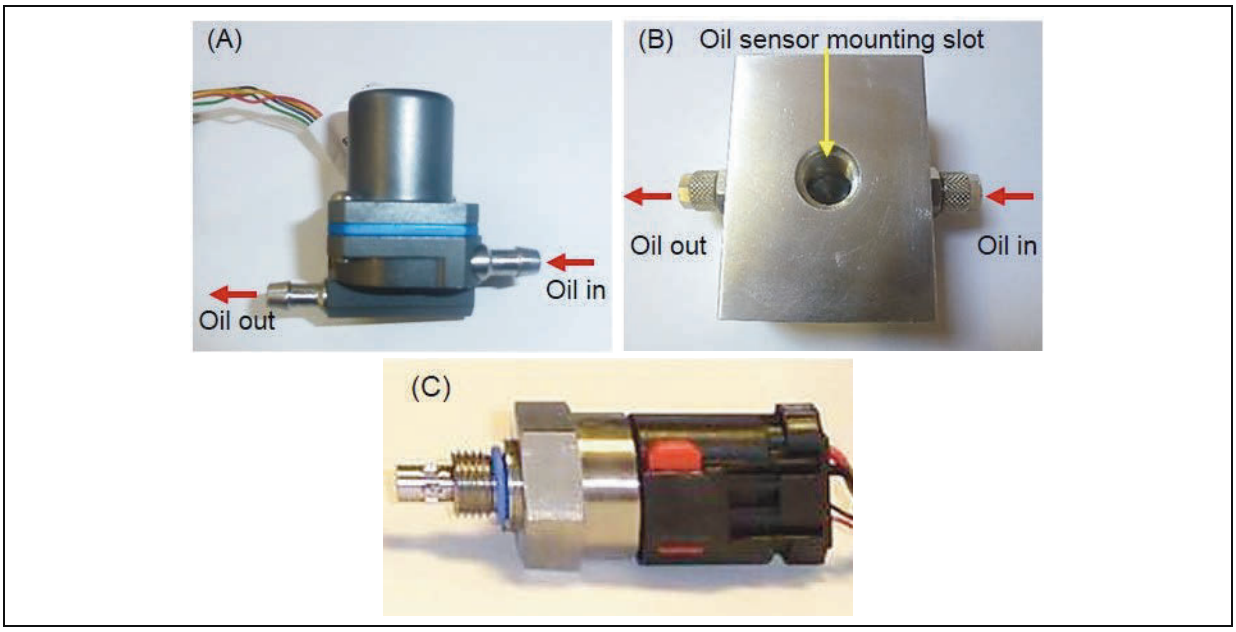

Figure 2: Equipment used in experimental test set-up as (A) Micro-pump, (B) Oil sensor mount and (C) Tuning fork technology based oil sensor

conducted on these oil samples to evaluate the chemical properties of the lubricating oil. Oil viscosity was measured by performing the ASTM D445 test method (ASTM D445-19, 2019). Water content of oil was measured using the ASTM D6304 (Coulometric Karl Fischer Titration) test method C (ASTM D6304-16e1, 2016). Soot, oxidation, nitration and sulfate contents of oil were measured using Fourier transform infrared (FTIR) spectroscopy (ASTM E2412-10, 2018).

3. Results and Discussion

3.1 Minimum Oil Film Thickness

The change in the sliding speed of reciprocating piston rings (or piston) affects the capability of the engine lubricating oil to form a thick film at the contact interface between piston ring's running face and cylinder liner to avoid direct metal-to-metal contact. Such that when the piston is at mid-stroke position, the sliding speed is highest and it is expected for oil film thickness to be at its maximum. Whereas, at top and bottom dead centre positions, the sliding speed approaches to zero, therefore, the oil film thickness is expected to be minimum.

It was envisaged that in order to understand the effect of oil quality of three lubricating oil samples on piston ring – cylinder liner contact, it is important to analyze the capability of the concerned oil to form hydrodynamic film at different sliding speeds across the complete piston stroke length. For this purpose, the 4-stroke MAN D2840LE401 marine engine was used. At the maximum engine operating speed (revolution per minute) of this engine, the piston rings (or piston) slides on cylinder liner at the speed from 0 to 10.83 m/s, between top and bottom dead centre positions with respect to crank angle, as calculated using equation (1).

$$U = r\omega(\sin\varphi + \frac{\lambda}{2}\sin 2\,\varphi) \tag{1}$$

Where, r is crank radius of 45 mm, l is conrod length of 256 mm, λ is conrod ratio (i.e. r/l) of 0.176, ω is crank angular velocity of 240.73 rad/s, φ is crank angle and U is instantaneous piston speed.

Minimum oil film thickness for the three oil samples was calculated for the given range of instantaneous piston rings sliding speed (i.e. 0 to 10.83 m/s), using the elliptical point contact equation (2) by Chittenden et al. as mentioned by D. Dowson in his review article (Dowson, 1995).

$$\frac{h_{min}}{R} = 3.68\,\{2\alpha E^*\}^{0.49}\left\{\frac{U\eta_o}{2E^*R}\right\}^{0.68}\left\{\frac{W}{2E^*RL}\right\}^{-0.073}\{1 - \exp[-0.67\left(\frac{Rs}{Re}\right)^{2/3}]\} \tag{2}$$

Known Parameters	Values			SI Units
		@ 40 ºC	@ 100 ºC	
η_0 = Dynamic viscosity of lubricant	Sample 1	9.38E-02	1.34E-06	s-N/m^2
	Sample 2	8.87E-02	1.21E-06	
	Sample 3	9.04E-02	1.25E-06	
α = Pressure-viscosity constant	1.15E-08			m^2/N
v_1 = Poisson ratio for piston ring	0.30			-
v_2 = Poisson ratio for cylinder liner	0.29			-
E_1 = Modulus of Elasticity for piston ring	2.89E+11			N/m^2
E_2 = Modulus of Elasticity for cylinder liner	9.0E+10			N/m^2
E* = Reduced Young's Modulus for the materials of contacting surfaces	7.5E+10			N/m^2
R = Reduced Radius of Curvature	0.01195			m
L = Length of contact	0.0035			m
W = Applied load	2419.56			N

Table 1: Known data for minimum oil film thickness calculations

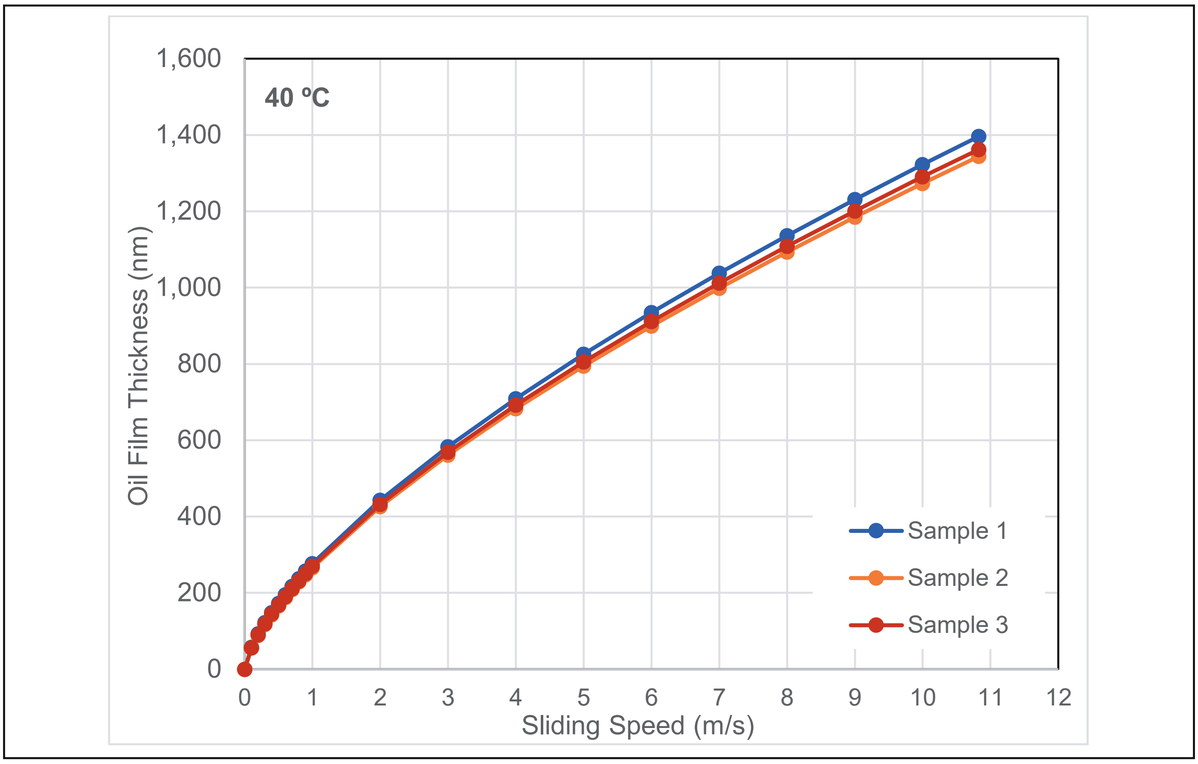

Figure 3: Minimum oil film thickness formed by three lubricating oil samples at 40 ºC

Where,

$2\alpha E^*$ is a dimensionless Material Parameter,

$\frac{U\,\eta_o}{2E^*R}$ is a dimensionless Speed Parameter, and

$\frac{W}{2E^*RL}$ is a dimensionless Load Parameter.

The above oil film thickness equation (2) incorporates the oil viscosity, which is affected by the change in temperature. Therefore, the values of the minimum oil film thickness (hmin) were calculated for oil viscosities at 40 ºC and 100 ºC for the three lubricating oil samples using equation (2) and the known data in Table 1.

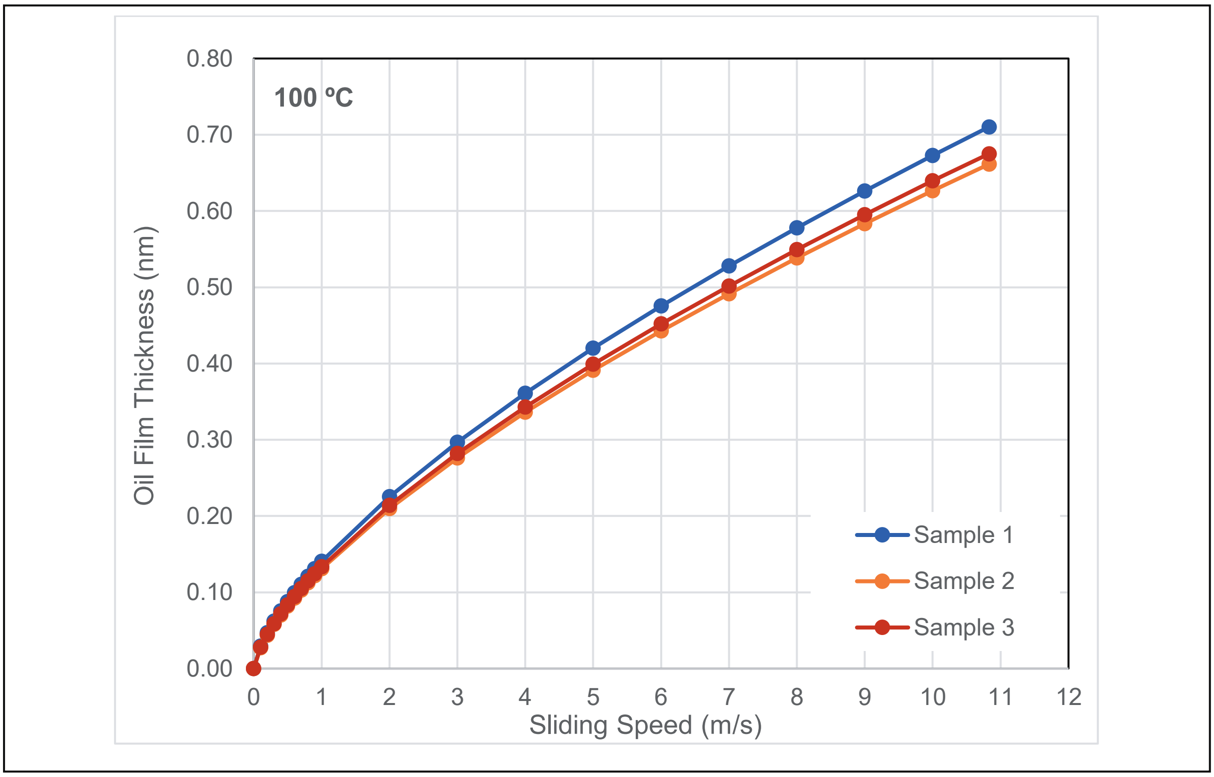

Figure 4: Minimum oil film thickness formed by three lubricating oil samples at 100 ºC

The obtained oil film thickness results (in nanometer, nm) were plotted against piston rings sliding speed for two different temperatures, i.e. 40 ºC and 100 ºC, as shown in Figure 3 and Figure 4, respectively.

Clearly, as the sliding speed reaches its maximum 10.83 m/s), the oil film thickness is also maximum and the film thickness reduces as speed reduces, as expected. This relation is the same at both temperatures. However, at the lower temperature, the film thickness increases by an order of magnitude after 4 m/s sliding speed (Figure 3). The same effect is not visible at the higher temperature even for the speed of 10.83 m/s (Figure 4). In addition, there is a significant difference in the oil film thickness at both temperatures for all three oil samples. These observations indicate that thicker oil film is formed as engine starts due to higher oil viscosity and as engine runs for a while and oil gets hotter, the thickness of oil film reduces due to the reduction in oil viscosity.

Secondly, there is a clear difference in the oil film forming capability of sample 1 and the other two used oil samples, at both low and high temperatures. However, this difference is negligible at lower speeds and only starts to become clear after roughly 4 m/s and 1 m/s sliding speeds at 40 ºC and 100 ºC, respectively. These observations suggest that the viscosity of oil does not play any meaningful role in forming an oil film at the lower sliding speed range, irrespective of the oil temperature. This means the physical condition of the lubricating oil is immaterial at lower sliding speeds. On the contrary, the change in oil viscosity mainly affects its oil film forming capability at higher sliding speed range.

3.2 Oil Condition Monitoring

In order to study the effects of oil quality at lower sliding speeds, one must investigate the chemical condition of the oil, which influences its capability to form a lubricous chemical film on the sliding surfaces and is independent of any viscous effects. One of the quick and easy way to analyze oil quality is to evaluate the dielectric constant of oil, which is an indicator of oil additives depletion, excessive oil oxidation or the presence of moisture or contaminants such as wear debris.

Therefore, an oil condition monitoring system was commissioned to measure the lubricant condition in real-time. A tuning fork technology based oil sensor was installed in the tribo-test machine and the piston ring - cylinder liner sliding environment was simulated, as shown earlier in Figure 2.

Lubricating Oil	Mean Value	Standard Deviation
Sample 1	2.39	0.058
Sample 2	2.60	0.014
Sample 3	2.74	0.026

Table 2: Data of dielectric constant for three oil samples. Each test was repeated at least two times.

The typical representative curves along with the mean and the standard deviation of dielectric constant values for three oil samples measured using the oil sensor are shown in Figure 5 and Table 2, respectively.

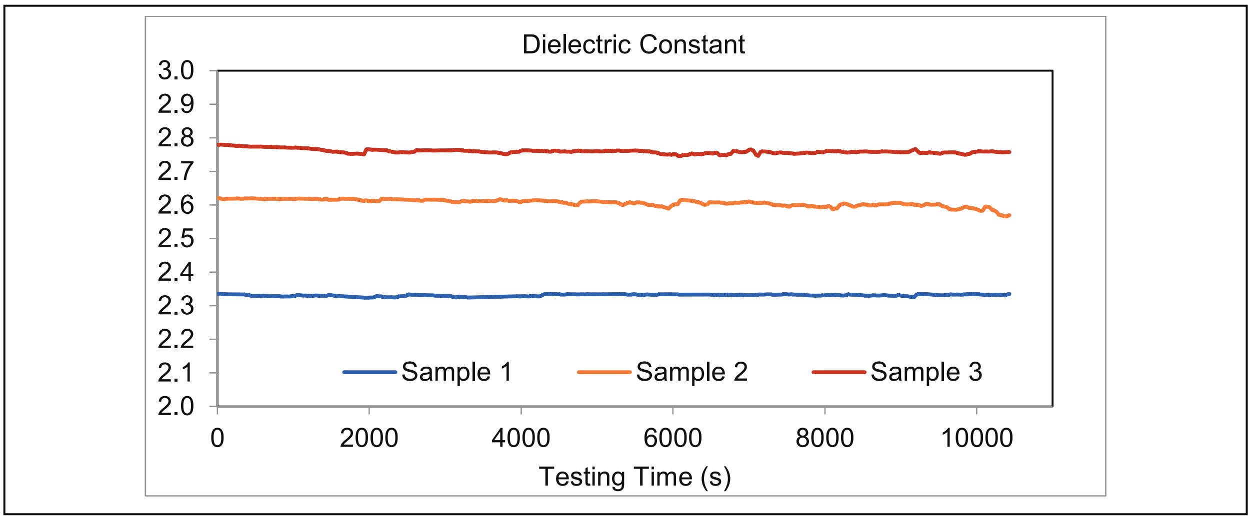

Figure 5: Typical representative curves of dielectric constant vs time for three oil samples measured using oil sensor

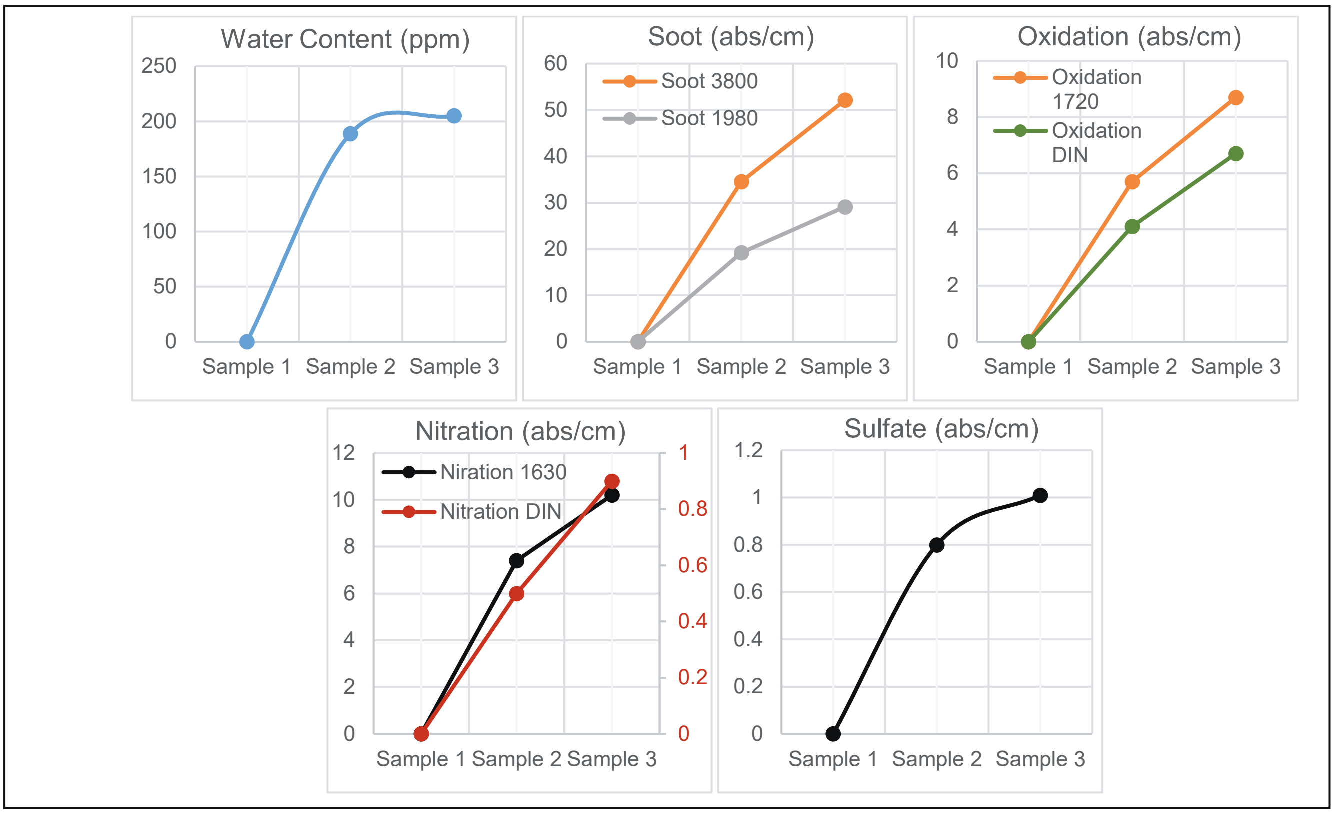

Figure 6: Different oil properties of three oil samples measured using standard laboratory based techniques

Since the viscosity of the oil at 40 ºC was considerably higher, therefore an oil flow rate of 0.2 m/s was difficult to obtain. This flow rate is necessary for the optimum measurements accuracy for the oil sensor used. Therefore, the measurements of dielectric constant were only made at 100 ^{0}C this is also the average oil temperature in an actual diesel engine.

From Figure 5, it can be seen that there is a clear distinction in dielectric constant values of the three oil sample correlating with their service time in engine. A higher dielectric constant of oil samples 2 and 3 compared to sample 1 gives indication of either contamination or a change in the oil chemistry of the former two oil samples. These results also correlate with the presence of contaminants such as water content, soot, oxidation, nitration and sulfate contents of oil, as shown in Figure 6. This therefore verifies the dielectric constant results of three oil samples with those of the oil properties obtained from the standard laboratory based oil tests.

Both Figure 5 and Figure 6, suggest that the chemical nature of the oil has deteriorated over time, which results in a reduction of the oil capability to form a tenacious and lubricous chemical surface film, affecting its tribological performance. Therefore, the dielectric constant can be used to observe a change in oil quality if it is monitored in real time and data is benchmarked

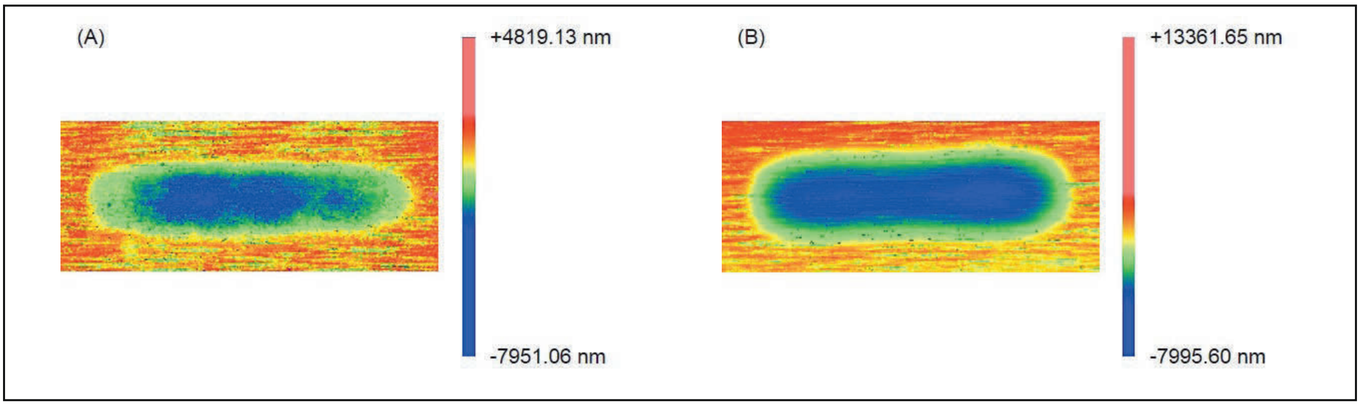

Figure 7: Wear scar on flat plate samples after tribo-testing with (A) oil sample 2 and (B) oil sample 3

against new oil, by looking for an unusual and sudden change in the measurements. Also, it is simple, easy and quick method of providing immediate evaluation of the oil condition.

Figure 7 shows that white light interferometry images of the wear scar formed on the flat sample after the tribo-testing carried out using lubricating oil samples 2 and 3. Clearly, the width and depth of scar is larger for Sample 3 than Sample 2. This indicates that the oil sample 3 could not form as effective a tribo-film to separate the two mating surface during the sliding process resulting in higher wear (Figure 7B). This can be attributed to the deterioration in quality of both oil samples in the actual marine engine before being used for this research. This therefore suggests that the oil chemical condition captured by the oil sensor and standard laboratory based tests are in line with the tribo-testing results.

4. Conclusion

Numerical and experimental analysis of oil quality was performed. The effect of changes in oil viscosity on the minimum oil film thickness under varying piston ring sliding speeds of piston ring and oil temperature in real-world engine were studied. Experiments were performed to analyze the change in oil chemistry using a tuning fork technology based oil sensor in real-time. Dielectric constant values were measured by the oil sensor and verified against the results obtained from the standard laboratory based oil tests and tribo-tests performed on the same oil samples. Results suggested that oil viscosity does not affect the oil film formation at lower sliding speeds, irrespective of the oil temperature. The effect is only visible at the higher sliding speed range. In addition, the oil sensor can be used to analyse the change in the chemical nature of the oil due to its deterioration in the marine engine environment.

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