Chromatic Parameters in the Condition Monitoring of Synthetic Hydraulic Oils

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Abstract: Chromatic device was developed using light emitting diodes, optic fibers and photodiodes. Chromatic ratio and total contamination parameters based on transmitted light intensity in Red, Green, and Blue wavelengths were used for oil chemical and particulate contamination assessment. Chromatic ratio criterion was found independent of the particulate contamination of oil; but depended on chemical degradation, being more sensitive for synthetic than mineral hydraulic oil. Total contamination index of the sensor depended on both the chemical degradation and particulate contamination of the oil, being most sensitive in blue wavelength, and least in the red. Test results for synthetic hydraulic oils monitored corroborated with results of other tests such as viscosity, total acid number, elemental optical emission spectroscopy, particulate counts and UV-VIS photospectrometry. Chromatic ratio showed a clearer indication of oil degradation, compared to key monitoring parameters such as total acid number, viscosity and particle counts. The results showed that these parameters are effective criteria for the condition monitoring of synthetic hydraulic oils.

Keywords: Chromatic ratio, total contamination index, color sensor, oil degradation

1. Introduction

1.1. Detecting changes in lubricating oils condition

Oil is degraded by many factors such as temperature rise, oxidation, water, aeration and exposure to light, among others. Oil contamination could be both chemical (oxidative and thermal degradation, dissolved and emulsified water, etc) and physical (wear particulate matter, free water and air, etc). Oftentimes, oil contamination is nearly always associated with color change; hence change in light absorbance. As oil degrades in service chemical and physical changes occur which manifest as change in acidity due to oxidation and additive depletion, change in viscosity due to formation of higher molecular weight components, increased interfacial wear of mating pairs giving rise to higher wear-particulate counts. Some of these changes in oil properties lead to reduced load carrying capacity, pressure losses, wear, leakages, and reduced lubricity, among others. These changes are detected by different methods like TAN and Viscosity measurements, mass spectrometry, UV-VIS spectrometry, etc. These methods are not without some short comings, hence the need for other techniques for specific applications. Hence, some condition monitoring techniques have been proposed and implemented as follows.

Kumar et al. [1] developed an online optical color sensor which could transform engine oil darkness in the course of degradation into electrical resistance. Light is passed through the oil film from one end and its intensity is recorded at the opposite end. Change in the oil transparency derived from

degradation was detected as change in light absorbance intensity which was converted to electrical resistance. According to them, the sensor device can prove to be of great value to users of internal combustion engines. Similarly, Turner and Austin [2] also proposed an electrical technique for online condition monitoring of lubricating oils. Khandaker et al. [3] used chromatic modulation technique to detect change oil condition not by detecting intensity changes at particular wavelengths but by monitoring the sum of the contributions of relative changes at all wavelengths within a spectral power distribution. Kanavouras and Coutelieris [4] studied the factors that influence oil oxidation (such as light, oxygen and temperature) and found that exposure of package olive oil to light in continuous or alternating pattern should be avoided as since, even for a short time, it could significantly stimulate the oxidative degradation caused only by elevated temperatures and presence of oxygen.

It is known that oil color becomes darker with usage, specifically brownish except in diesel engines oils where it becomes black due to soot; hence there is a color shift to long wavelength range of the optical spectrum in the course of oxidative and thermal degradation of mineral oils. Therefore, experience has shown that while it is relatively easier to detect early degradation of mineral hydraulic and engine oils by inspection, the same is not always true of synthetic hydraulic oils. This is due to the presence of color pigments in them which obscures early color change. These color pigments appear as microparticles less than 5 μm size in particulate counters, giving ambiguous picture of particle contamination especially for synthetic hydraulic oils. Hence, there is the need for a device which can detect early oxidative and thermal degradation of synthetic hydraulic oils.

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1.2. Device Measurement Principle

The proposed oil degradation sensor [5] measures chromatic ratio as a parameter of oil oxidative and thermal degradation, and oil optical density at three wavelength ranges as parameters of total contamination of the oil. Chromatic ratio (CR) is ratio of light intensity transmitted through oil in the red-wavelength to intensity transmitted through oil in green-wavelength. CR is determined using Red (U_R) and Green (U_G) color sensor outputs as follows.

$$CR = \frac{\Delta I_R}{\Delta I_G} = \frac{U_R}{U_G}. \tag{4}$$

The longer oil service time the higher CR, that is, lower contribution of intensity in green-wavelength and higher contribution of intensity in red-wavelength of oil. The device also measures second oil condition parameter - total contamination. Total oil contaminations which depends on content of oxidation and aging products, dust and wear debris in oil as well as water is estimated by change of optical density of the used in comparison with a fresh one. The change of optical density of oil is evaluated in three wavelengths - Red (DD_R), Green (DD_G) and Blue (DD_B) according to formula:

$$TCI_R = \Delta D_R = D_{R,used} - D_{R,fresh} = \ln\frac{U_{R,fresh}}{U_{R,used}}, \tag{5}$$

$$TCI_G = \Delta D_G = D_{G,used} - D_{G,fresh} = \ln\frac{U_{G,fresh}}{U_{G,used}}, \tag{6}$$

$$TCI_B = \Delta D_B = D_{B,used} - D_{B,fresh} = \ln\frac{U_{B,fresh}}{U_{B,used}}, \tag{7}$$

where

$D_{R,fresh}, D_{G,fresh}, D_{B,fresh}$: optical density of fresh oil in Red, Green and Blue wavelength, correspondingly;

$D_{R,used}, D_{G,used}, D_{B,used}$: optical density of used oil in Red, Green and Blue wavelength, correspondingly;

$U_{R,fresh}, U_{G,fresh}, U_{B,fresh}$: output signal of fresh oil in Red, Green and Blue wavelength, correspondingly;

$U_{R,used}, U_{G,used}, U_{B,used}$: output signal of used oil in Red, Green and Blue wavelength, correspondingly.

1.3. Description of device

The design of the CR-device is shown in Fig. 1. Optical radiation from the white light emitter (1) enters into the oil column thickness through the optical window (3), and incident on a three-element color sensor (2) through the optical window (4). Feedback photodiode (5) is used to stabilize the optical power of the emitter. The emitter and color sensor are mounted on a housing (8) and connected to a preamplifier PCB under cover (11) by electrical wires (10). The entire sensor probe is connected to a microcontroller by cable (12). Protective mesh (9) is also mounted on the housing to isolate air bubbles present in oil and secure the optical windows from mechanical damage. The color sensor provides the measurement of luminous intensity in three RGB (red, green, blue) wavelengths. CR and TCI are therefore evaluated based on color sensor output in the
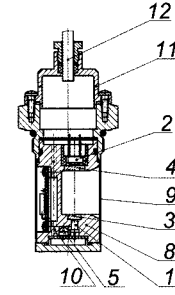

Fig. 1. Probe for chromatic parameter device.

Detector Probe with Preamplifier

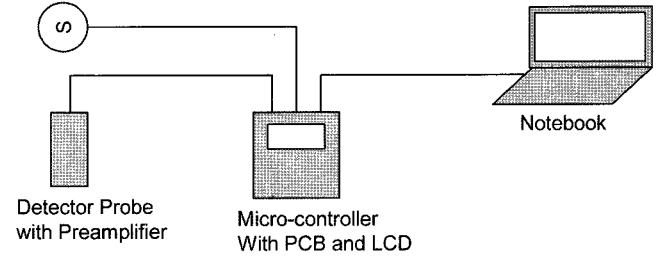Micro-controller With PCB and LCD

Notebook

Fig. 2. Instrumentation for CR-detector application.

different wavelengths using equations 4-7 and displayed on the LCD of the microcontroller or displayed on a notebook monitor as in Fig. 2.

2. Materials and Methods

Different samples of four synthetic hydraulic oils from industry machines were used to test the newly developed sensor, as well as an artificially or laboratory degraded mineral oil MHD-1. All the in-service degraded oils were obtained from the hydraulic systems of a steel plant (POSCO, Korea), Paper Mill (Hansol, Korea) and Lubricant plant (SK, Korea) with bulk oil operational temperature of 20-30°C and 50-65°C in winter and summer respectively. Artificial particulate contaminations were performed by ferrous particle inclusion using carbonyl Iron particles Grade-L, mean particle size 7.6 μm in T100-sample. And artificial thermal degradation was performed by adopting ASTM D2070 procedure in an electric gravity oven.

Viscosity tests were performed using Cannon viscometer tube 300-series and 450-series in a SETA KV-8 viscometer bath, TAN tests were performed using kittiwake (FG-K25196-KW & FG-K2-006-KW) kits to ASTM D974 and ASTM D664 standards. Elemental optical emission Spectroscopy tests were performed using *spectroil-M* and UV-VIS spectrometer tests were performed with *Opron-3000* spectrometer. HIAC/ ROYCO/HRLD particle counter was used for particulate-count tests with ACFTD calibration.

Firstly, Detector is connected-up as in Fig. 2 after cleaning, then power is turned on and sensor window is immersed in oil sample contained in a vessel. Chromatic ratio (CR), Total contamination index (TCI) in the Red, Green and Blue wavelengths, as well as temperature and water content (%RS) were read on the LCD panel.
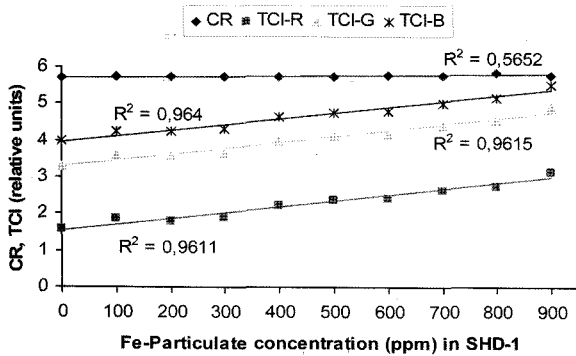
Fig. 3. Chromatic parameters variation with Fe-particle contaminants in SHD-1 oil.
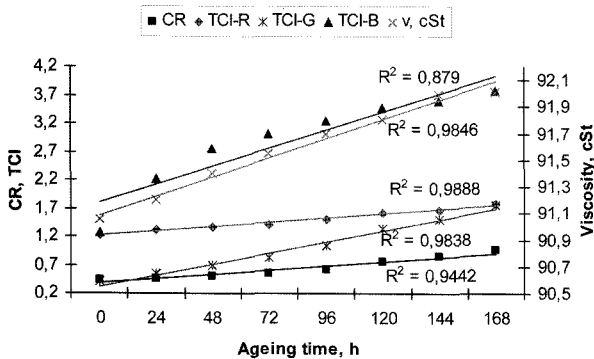

Fig. 4. Chromatic Parameters Variation with Artificial Ageing of T100 Oil.

Fig. 5. UV-VIS Optical Absorbance Spectra of the T100 oil with different ageing.

3. Results and Discussions

3.1. Artificially degraded oils

3.1.1. Chromatic Ratio (CR) and Total Contamination Index (TCI)

In particle contaminated SHD-1 oil CR-values were practically constant and independent of particle concentration as shown in Fig. 3, which indicates that CR was dependent on chemical rather than physical degradation. Sample was purely a Fe-particle/oil mixture, without chemical reaction. TCI linearly regressed with particle concentration in SHD-1 samples with $R^2 = 0.9611$, 0.9615 and 0.9640 in the red, green and blue wavelengths respectively. Using a one-tail t-distribution, the p-value of this regression was p-value $= 3.165*10^{-7}$, $3.062*10^{-7}$ and $2.319*10^{-7}$ for the red, green and blue wavelengths respectively; that is a statistical significance of $3.165*10^{-5}\%$, $3.062*10^{-5}\%$ and $2.319*10^{-5}\%$ correspondingly. Hence, the null hypothesis of TCI independence on physical or particulate contamination in oil is therefore rejected based on less than 0.001% statistical significance or more than 99.999% confidence interval.

In the thermally degraded T100 oil (though, a mineral hydraulic oil) samples, TCI increased with increase in ageing as in Fig. 4 following a linear model, within the time and temperature limits tested.
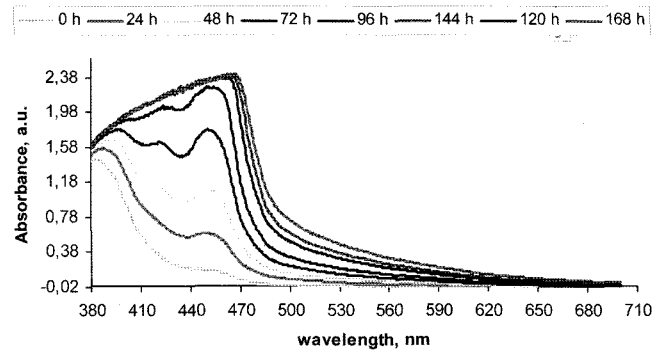
3.1.2. Viscosity and total acid number (TAN)

Viscosity (Fig. 4 and Table-1) of the thermally degraded oil in this study increased linearly with ageing hours, due to the build-up of insolubles and evaporative loss of more volatile components. This linear variation of viscosity with ageing agrees with the results of Singh et al. (2006). However, a decrease in the viscosity of a lubricant with respect to degradation is due to loss of shear stability of the polymeric components, like polymers used as viscosity index improvers.

The TAN-values showed little change during thermal degradation, decreasing from 0.20 to 0.15 mgKOH/g after 168 h probably due to the depletion either by evaporative loss or decomposition of organic acidic-additive in the oil, verifiable by molecular spectroscopy.

3.1.3. UV-VIS spectroscopy

The UV-VIS photospectrometry of the artificially degraded samples shown in Fig. 5 indicate a steady increase in optical absorbance and a decrease in transmittance with ageing; as well as a spectral shift from short to longer wavelength. Optical absorbance-peak of samples and its wavelength of occurrence also increased with ageing. Hence, the shift in the transmittance spectra is associated with a shift in absorbance-peak wavelength from short to longer wavelength. The results of Figs. 5 provide good background support for the measurement principle of the CR detector.
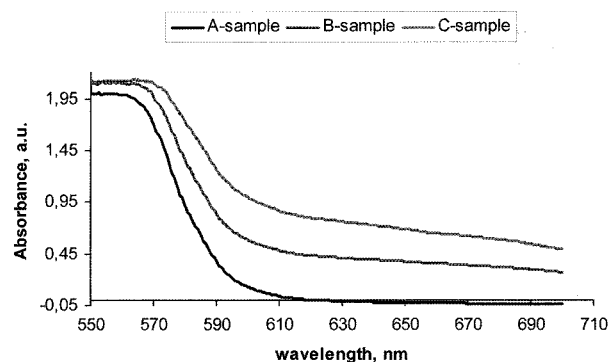
3.2. In-Service degraded oils

3.2.1. Chromatic Ratio and Total Contamination Index

From Figs. 6, 7 and Table-1, similar to the artificially degraded oil samples, the chromatic parameters of the in-service degraded oils varied uniformly with oil chemical degradation and particulate contamination. As the oil degraded, the CR and TCI increased. TCI was most sensitive in the blue wavelength, and least in red. CR was the parameter most sensitive to degradation, even more sensitive than the viscosity of the oils samples (Fig. 6). This better sensitivity of chromatic parameters to degradation is derived from the color pigments present in synthetic oils.

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Table 1. Chromatic parameters, TAN and viscosity tests results

Samples	Chromatic parameters				Viscosity, v	TAN
	CR	TCI-R	TCI-G	TCI-B	40°C, cSt	mgKOH/g
SHD-1						
A-sample	5.69	1.57	3.30	3.98	55.93	0.96
B-sample	7.24	1.98	3.97	4.46	58.55	1.44
C-sample	9.01	2.39	4.59	4.89	61.33	1.84
D-sample	10.70	2.75	5.13	5.27	62.43	2.38
E-sample	12.13	3.10	5.59	5.58	67.56	2.76
SHD-2						
A-sample	4.53	1.91	3.43	4.33	202.36	0.52
B-sample	4.68	2.22	3.76	4.57	220.38	0.48
C-sample	5.27	2.36	4.02	4.77	220.99	0.52
D-sample	6.13	2.67	4.48	5.06	221.66	0.44
E-sample	6.69	2.92	4.83	5.31	224.90	0.40
SHD-3						
A-sample	6.65	1.59	3.49	4.00	31.76	0.22
B-sample	7.95	3.29	5.37	5.67	31.84	0.32
C-sample	10.57	4.22	6.58	6.57	32.12	0.44
SHD-4						
A-sample	7.88	1.67	3.74	4.12	32.10	0.22
B-sample	8.59	2.15	4.30	4.60	32.78	0.24
C-sample	10.75	2.48	4.85	4.97	33.43	0.28
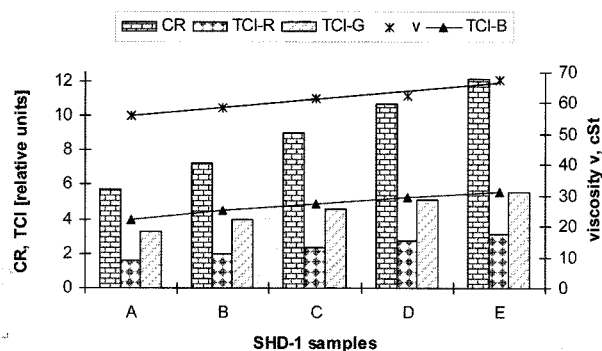
Fig. 6. Chromatic Parameters and viscosity variation with degradation for SHD-1 oil.

Fig. 8. UV-VIS Photospectrometry of SHD-3 Oil.
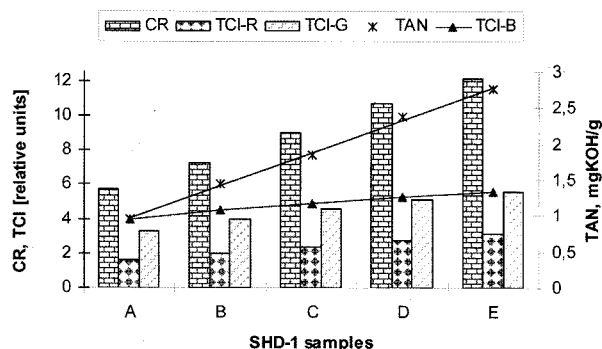
**Fig. 7. Chromatic Parameters and TAN variation with degradation for SHD-1 oil.**

3.2.2. Viscosity and total acid number (TAN)

Viscosity increased with ageing for all in-service degraded oils

samples. From Figs. 6, 7 CR and TCI correlated well with TAN, viscosity and degradation of in-service synthetic hydraulic oils, with TCI being most sensitive in the blue wavelength and least in red. It is worth noting that CR is sensitive to chemical degradation for all samples unlike TAN which is often recognized as a key parameter to evaluate the oil additive-acidity and chemical degradation (Figs. 6, Fig. 7, and Table-1). In SHD-2 sample, TAN decreased with degradation unlike others which showed a direct variation. This inverse relationship for SHD-2 is due to the depleting effect of additive acidity. This could be explained by previous works of KOCITI [6] and Wurzbarch [7] indicating that lubricants with high Phosphorus-based additives exhibit an initial decrease in TAN with increase in degradation before complete additive depletion. However, the TAN rise of oils is due to oxidative degradation.

Table 2. RDE elemental spectrometry and particulate count tests results

Sample	Elemental RDE-spectrometry											ISO Grade
	Fe	Pb	Cu	Si	B	Na	Ca	P	Zn	Ba	Ti	
SHD-1												
A-sample	0.33	0.00	0.11	3.86	0.04	0.00	0.06	222	0.18	0.01	0.00	20/15/14
B-sample	4.11	0.35	2.25	3.30	0.35	0.17	0.17	229	2.94	0.04	0.00	-
C-sample	8.10	1.59	3.93	3.74	0.59	0.30	0.20	227	5.07	0.12	0.00	20/15/12
D-sample	12.3	2.77	5.70	3.25	0.92	0.60	0.19	226	7.36	0.18	0.00	-
E-sample	16.0	3.50	7.50	4.93	1.14	0.87	0.28	217	8.87	0.25	0.00	20/15/13
SHD-2												
A-sample	0.70	0.00	0.23	5.69	0.00	3.01	0.30	1484	0.40	0.03	0.00	25/23/20
B-sample	14.0	0.00	0.19	9.72	0.01	2.68	0.58	1533	0.50	0.05	0.88	-
C-sample	24.3	0.00	0.15	10.90	0.25	2.72	0.75	1459	0.97	0.11	1.64	26/25/20
D-sample	42.6	0.00	0.26	13.20	0.03	2.10	1.53	1465	1.40	0.13	3.39	-
E-sample	56.4	0.00	0.31	16.20	0.04	1.73	1.73	1441	1.38	0.15	4.76	25/25/22
SHD-3												
A-sample	0.10	0.00	0.00	2.25	50.6	1.35		208	266	0.04	0.02	0.00	24/20/15
B-sample	0.23	0.00	1.24	2.44	49.6	1.39		205	265	0.15	0.00	0.00	24/20/16
C-sample	0.11	0.00	2.55	3.16	49.8	1.54		206	266	0.30	0.03	0.00	23/19/17
SHD-4												
A-sample	0.00	0.00	0.00	0.00	63.4	0.06		109	77.0	0.00	0.02	0.00	22/19/15
B-sample	0.19	0.00	11.9	0.96	57.3	0.08		110	79.8	0.43	0.02	0.00	23/20/17
C-sample	0.09	0.00	22.9	1.88	53.5	0.09		115	88.9	0.66	0.02	0.00	23/20/17
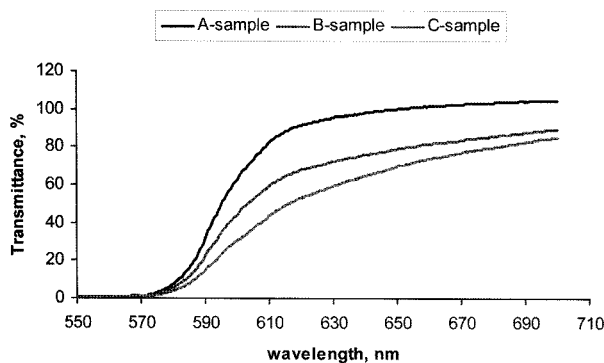
Fig. 9. UV-VIS Photospectrometry of SHD-4 Oil sample.
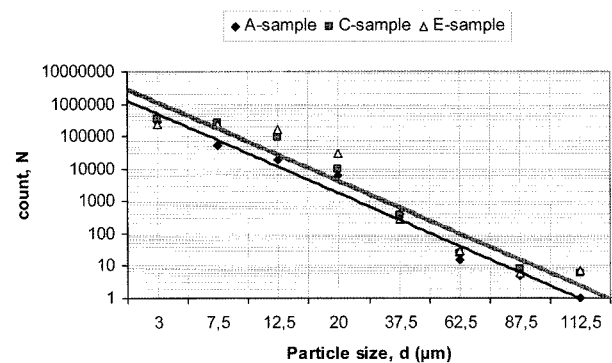
Fig. 10. Coles plot of the Particulate counts for SHD-2 oil.

3.2.3. UV-VIS spectroscopy

Optical absorbance intensity and peak-value increased with increasing degradation (for both in-service and artificially degraded) synthetic hydraulic oils. The converse was true for the transmittance spectra (Fig. 8). Also a spectral shift from short to longer wavelength was observed for all synthetic hydraulic oil (both artificially and in-service degraded) samples as shown in Fig. 5. This corroborated with the work of Vanhanen et al. [8]. As low absorbance synthetic oil degrades, they absorb more and transmit less light, hence the oil appears darker or brownish to the eyes. From the absorbance spectra, the mineral hydraulic oil approached peak-value in a leptokurtic (conical) manner (Fig. 5), while synthetic samples exhibited a platykurtic (flat-top) approach as in Figs. 7, 8.

3.2.4. Elemental Optical Emission Spectrometry and Particulate Counts

From Table-2, high particulate counts were observed in A-samples of synthetic oils. This due to color pigments in oil, a phenomenon that could be misleading, especially in hydraulic oils where fine particles attract attention. However, the elemental spectrometry results still showed that A-samples were least degraded than B, C, D, E-samples (in that order). Wear particles were progressively generated as oil degraded in service, without appreciable additive element depletion.

In Fig. 10, though the C and E-samples showed wear particle contamination compared to the F-sample, their particulate counts versus particle size trends is almost inseparable from each other. This obscures the levels of degradation in the used

samples in contrast to a clear distinction observed using chromatic parameters. However, the SHD-2 samples showed mean particles sizes of 4.524, 6.186 and 7.714 μm at a standard deviation of 3.507, 3.789 and 4.608 for A, C, and E-samples respectively. This indicates that as lubricating oil degraded, interfacial wear of mating pairs continued unabated within the oil sampling period. The same trend of mean wear particulate sizes increasing with service period was observed in the other in-service degraded oil samples.

4. Conclusion

Chromatic ratio parameter was found independent of the particulate contamination of oil; but depended on chemical degradation, being more sensitive for synthetic than mineral hydraulic oil. Total contamination index of the sensor depended on both the chemical degradation and particulate contamination of the oil, being most sensitive in blue wavelength, and least in the red. Test results for synthetic hydraulic oils monitored corroborated with results of other tests such as viscosity, total acid number, elemental optical emission spectroscopy, particulate counts and UV-VIS photospectrometry. Chromatic ratio showed a clearer indication of oil degradation, compared to key monitoring parameters such as total acid number, viscosity and particle counts. The results showed that these parameters are effective criteria for the condition monitoring of synthetic hydraulic oils.

Nomenclature

CR: Chromatic Ratio
D: Optical Density
I: Otical light intensity
TAN: Total Acid Number
TCI: Total Contamination Index
U: Color Sensor Output
ΔD: Change in Optical Density
μ: Kinematic Viscosity
R, G, B: Red, Blue, Green accordingly.

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