Appendix-A

Calculation of film thickness and Hertzian diameter in case of four-ball tester

Film Thickness

Considering hard EHL,

$$\frac{h_{min}}{R_x} = 3.63\, U^{0.68}\, G^{0.49}\, W^{-0.073}(1 - e^{-0.68k}) \quad \text{......(i)}$$

$$\frac{h_{min}}{R_x} = 3.63\, \left[\frac{v\eta_0}{E'R_x}\right]^{0.68} [\xi E']^{0.49} \left[\frac{w}{E'R_x^2}\right]^{-0.073} (1 - e^{-0.68k}) \quad \text{......(ii)}$$

Where, h_{min}: film thickness; *U, G and W*: dimensionless speed, material and load parameter, respectively; *k*: ellipticity parameter ; R_x: effective radii in x-direction (i.e. $\frac{1}{R_x} = \frac{1}{R_{ax}} + \frac{1}{R_{bx}}$) ; ν: top ball speed; η_0 : dynamic viscosity of oil (for castor oil 0.28 PaS); *E'*: effective young's modulus; ξ: pressure-viscosity coefficient; w: load (392 N in case of antiwear test as per ASTM standard)

$$v = Friction\ radius * \frac{2\pi*1200}{60} = 0.00367 * \frac{2\pi*1200}{60} = 0.46\ m/s$$

$$R_x = \frac{R_{ax}*R_{bx}}{R_{ax}+R_{bx}} = \frac{6.35 * 6.35}{6.35 + 6.35} = 3.175\ mm = 3.175\ X\ 10^{-3}m$$

$$R_x^2 = 10.08 * 10^{-6}\ m^2$$

$$\xi = (0.6+0.965\log_{10} \eta_0)\ x10^{-8} = (0.6+0.965\log_{10}0.28)\ x10^{-8} = 6.6507\ x10^{-10}\ m^2/N$$

For similar balls young's modulus and poisson's ratio will same i.e. E_1=E_2= 204 GPa and υ_1=υ_2= 0.3, thus

$$E' = \frac{2E_1E_2}{E_2(1-\upsilon_1^2)+E_1(1-\upsilon_2^2)} = 226.37*10^9\ N/m^2$$

k = 1 (for similar balls in contact)

From equation (ii)

$$\frac{h_{min}}{R_x} = 3.63\left[\frac{0.46 * 0.28}{226.37 * 10^9 * 3.175 * 10^{-3}}\right]^{0.68}[6.6507 * 10^{-10} * 226.37 * 10^9]^{0.49}\left[\frac{392}{226.37 * 10^9 * 10.08 * 10^{-6}}\right]^{-0.073}(1 - e^{-0.68})$$

$$\frac{h_{min}}{R_x} = 9.263 * 10^{-6}$$

$h_{min} = 9.263*10^{-6} *3.175*10^{-3}$ m $= 29.41*10^{-9}$ m $= 0.029$ µm

Similarly, for epoxidized castor, epoxidized rapeseed, epoxidized sunflower, cottonseed, sesame, neemseed, olive, rapeseed and sunflower oil the film thickness was calculated and summarized in Table A.1:

Table A.1: Summary of calculated film thickness for modified and unmodified biolubricants.

Oil	**Calculated film thickness (µm)**
Castor	0.029
Epoxidized castor oil (ECO)	0.093
Epoxidized rapeseed oil (ERO)	0.0324
Epoxidized sunflower oil (ESO)	0.0257
Cottonseed	0.030
Sesame	0.031
Neemseed	0.023
Olive	0.032
Rapeseed	0.033
Sunflower	0.0319
CO+0.5%w/v CeO_2	0.031
ECO+0.5%w/v CeO_2	0.094

Since, the value of film thickness is less than 0.1 μm, hence system is working in the boundary lubrication.

Hertzian Contact Diameter

For sphere on sphere contact,

The Hertzian contact radius "a" = $\sqrt[3]{\frac{3w(\frac{1-\upsilon_1^2}{E_1}+\frac{1-\upsilon_2^2}{E_2})}{4(\frac{1}{R_1}+\frac{1}{R_2})}}$

Here, w = 392N, E_1=E_2= 204 GPa and υ_1= υ_2= 0.3

$$a = \sqrt[3]{\frac{3*392*(\frac{1-0.3^2}{204*10^3}+\frac{1-0.3^2}{204*10^3})}{4(\frac{1}{6.35}+\frac{1}{6.35})}}$$

a = 0.2027 mm i.e. 202.7 μm

Hertzian contact diameter = 2a = 2* 202.7 = 405.4 μm

Appendix-B

Calculation of Friction Factor and Sommerfeld Number

Friction Factor is calculated by

$$f = \frac{Torque}{Radius\ of\ the\ ball * Applied\ load} = \frac{T}{r * w}$$

Sommerfeld Number calculated by

$$z = \frac{Viscosity * Sliding\ velocity * Ball\ radius}{Applied\ load} = \frac{\eta_0 * v * r}{w}$$

Since, sliding velocity (v) = 0.46 m/s, w = 392 N, r = 6.35 mm

Table B.1: List of calculated Friction factor and Sommerfeld number for different oils.

Base oil	**Viscosity (N-s/m^2)**	**Torque (N-m)**	**Friction factor (f)**	**Sommerfeld number (z)**
CO	0.28	0.138	0.055	2.08x10^{-6}
SO	0.076	0.108	0.043	0.5 x10^{-6}
RO	0.089	0.115	0.046	0.66 x10^{-6}
OO	0.087	0.135	0.054	0.65 x10^{-6}
NO	0.033	0.140	0.056	0.24 x10^{-6}
SSO	0.063	0.144	0.058	0.47 x10^{-6}
CTO	0.065	0.154	0.062	0.48 x10^{-6}
ERO	0.153	0.050	0.020	1.14 x10^{-6}
ESO	0.196	0.051	0.021	1.46 x10^{-6}
ECO	0.502	0.095	0.039	3.74 x10^{-6}
CO+0.5%w/v CeO_2	0.285	0.101	0.041	2.12 x10^{-6}
ECO+0.5%w/v CeO_2	0.505	0.132	0.053	3.76 x10^{-6}

Table B.1 and Figure B.1 have shown that the friction factor values were much higher than the limiting value i.e. 0.01 (dashed pink line) with the variation in Sommerfeld number, thus system may consider in boundary lubrication (Unsworth et al., 2005).

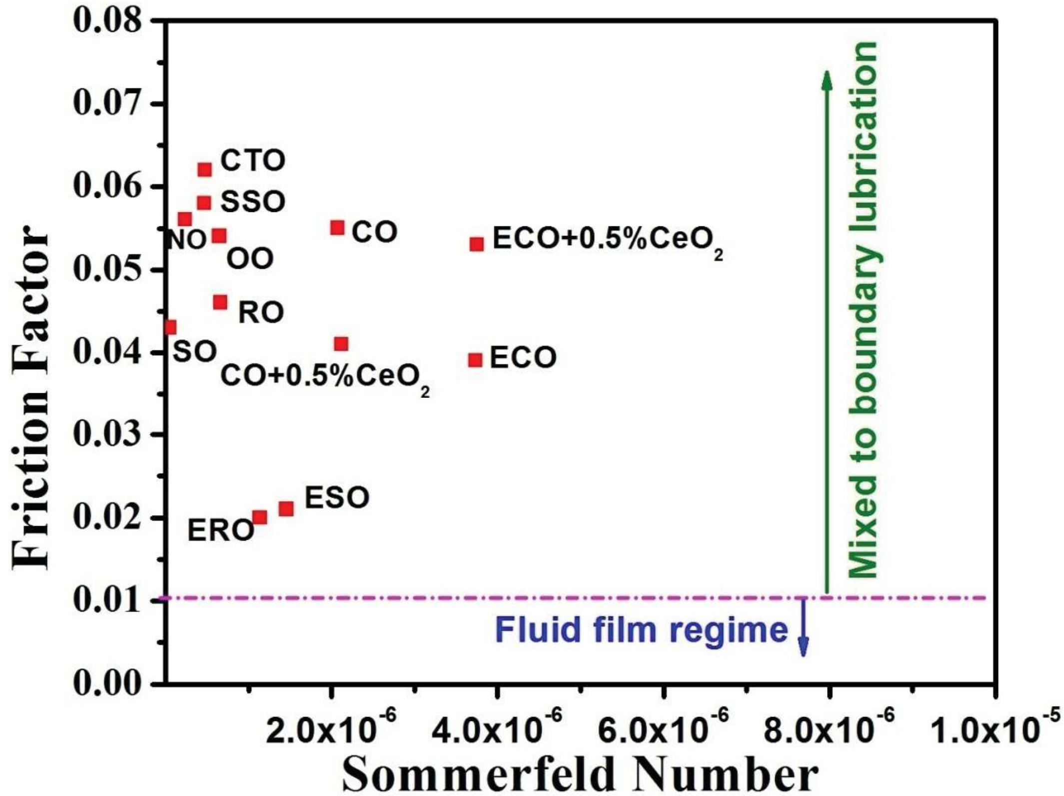
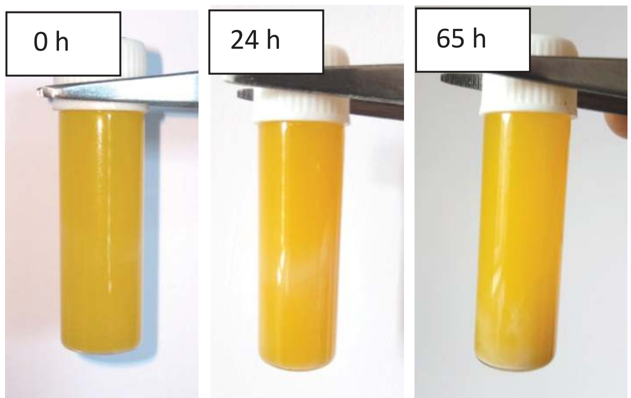


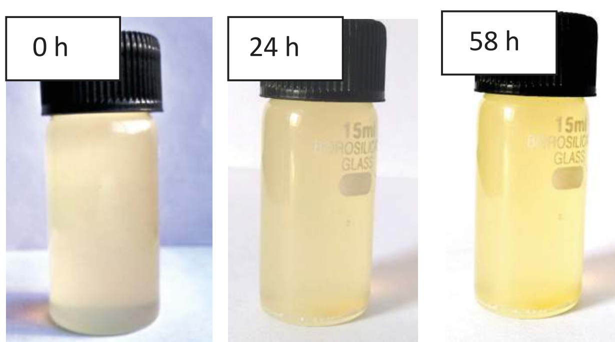
Figure B.1: Stribeck plot for all base oils and CeO_2 based epoxidized and unmodified castor. oil

Appendix-C

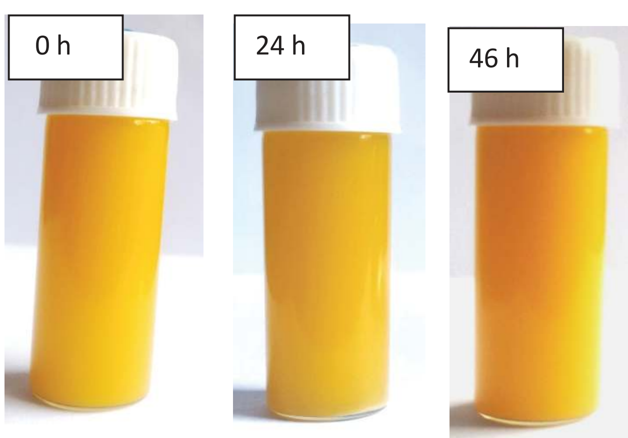
Suspension images of PTFE nanoparticles in different tested biolubricants with 0.25%w/v concentration



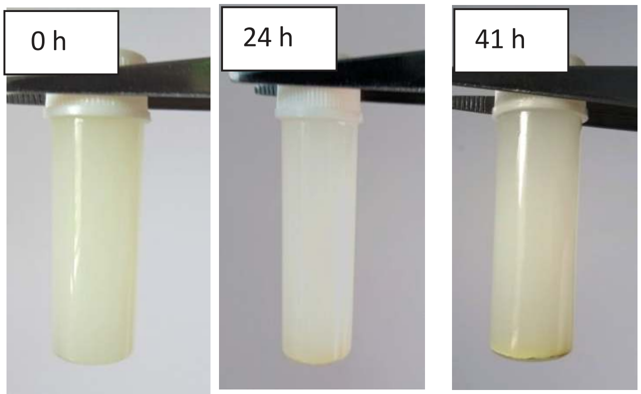
Rapeseed oil + PTFE



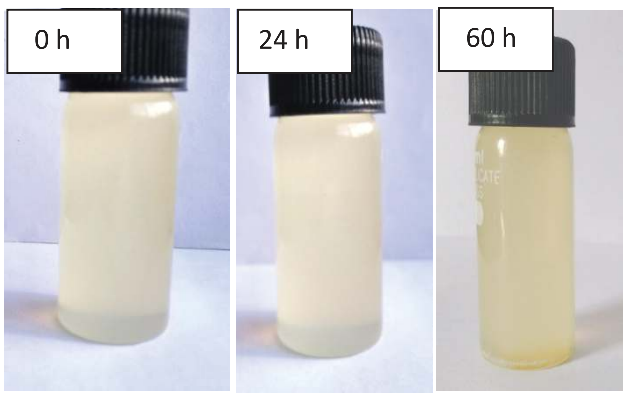
Cottonseed oil + PTFE



Sunflower oil + PTFE



Sesame oil + PTFE



Castor oil + PTFE