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TEMPERATURE EFFECT IN MINIMUM OIL FILM THICKNESS MEASUREMENTS IN A SIMPLIFIED SINGLE-RING TEST RIG USED TO SIMULATE THE PISTON-CYLINDER ASSEMBLY

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Abstract: *As part of the study of the complex lubrication phenomena between the piston-ring and the cylinder liner, it is important to characterize the oil film thickness in view of new designs that can be implemented for the piston-ring assembly. In previous studies parametric results of different lubricants, speed, load, temperature and piston-ring surface were presented to complement on the cavitation rheological phenomena (initiation and development) and to interpret the effect of physical-chemical properties of the lubricants in oil film thickness, friction and oil film pressure. Measurements were conducted in a simplified single-ring test rig, where a steady piston-ring section of overall width 5 mm is placed under a flat surface used as a reciprocating liner, taking advantage of significantly less uncertainties when compared to engine experiments. The advantage of this layout is that it can provide abundance of results that in turn, are being simultaneously interpreted in an easier and safer way prior to engine implementation and testing. In this manner, the effect of different operating conditions is assessed to achieve solid experimental results, useful in engine tribological applications in the piston-cylinder assembly, that comply with the emission regulations of today and the near future.*

This presentation is focused on the effect of temperature in minimum oil film thickness measurements (MOFT) for different lubricants. An electrical method is used in this set of experiments to measure the oil film thickness (capacitance). The testing is applied for different speeds and loads so that a complete picture of the lubricants behavior can be taken and, in parallel, friction measurements are presented to assess the MOFT results for specific parts of the stroke. The results show the effect of different lubricant properties in MOFT and give an insight of the conditions of cavitation occurrence at the early parts of the stroke as temperature rises. Further processing of these results provides very useful conclusions and the combination of the lubricants behavior under cavitating conditions, can lead to innovative additives design-formulation and new lubricant properties.

Keywords: *piston-ring, single-ring test rig, oil film, friction, capacitance, cavitation.*

1. INTRODUCTION

As part of the optimisation process of the lubrication in between and under the piston-rings of the piston-cylinder assembly, the development of the oil film thickness is studied to give an insight of the lubrication rheological phenomena. The above process is complemented with reduced friction losses, low oil consumption and minimised wear to meet the present and future tribological engine requirements.

Engine oil formulation should be specifically blended to provide optimum all-around performance according to the engineering specifications [1]. These include the enhancement of load carrying capacity, where the appearance of different forms of cavitation has the opposite effect [1, 2, 3].

According to Rastogi and Gupta [4] the primary purpose of the additives is to reduce the dependence of lubricant viscosity on temperature. Polymer addition enhances viscoelastic properties and the oil properties turn to slightly shear-thinning [1, 4]. It was speculated that shear-thinning results in a larger cavitation zone. Lubricant viscosity is subject to shear stress apart from the apparent temperature effect [1]. The addition of viscoelastic additives raises the load carrying capacity and reduces any wear that might occur [5].

The viscosity of different oils varies at different rates with temperature. The lubricant film thickness and load carrying capacity reduces significantly with temperature [6]. Viscosity has a damping effect on cavity growth and collapse, i.e. the reduced viscosity of shear thinning lubricants should lead to large sized cavities [4]. The significant loss of load capacity verifies the need to control the lubricant properties under these circumstances. Viscosity has a major impact on flow separation points, which in turn has an impact on oil film pressure distribution and cavitation [7].

A single ring test rig specially designed for lubrication experiments is the essential tool to provide abundance of parametric results as well as implementation of novel measuring techniques. The piston-liner interface is simulated by a steady parallelepiped piston-ring section with a curved top surface and a reciprocating flat liner, providing the necessary simplicity to avoid the complex lubrication and rheological phenomena of the engine experiments [3, 8, 9, 10]. Easy access to the ring-liner interface is its basic characteristic. Eventually a better understanding of the lubrication and the lubricant characteristics is achieved through a series of measurements from sensors mounted in this experimental set-up [2, 3, 8, 9].

In view of the above effects, a parametric study of different lubricants is presented, with results focused on minimum oil film thickness and friction, measured with a capacitance sensor and a force sensor respectively [10].

2. EXPERIMENTAL SET-UP

The test rig structure provides easy access to the ring-liner interface. In Figures 1 and 2 the photo and schematic of the simulation test rig is shown. Within the test rig, the speed, load and temperature can be adjusted.

The liner is driven by an electric motor coupled to the main drive train via rubber couplings. Reciprocation is achieved via a crank mechanism. Liner velocity is sinusoidal [1, 8, 9, 10].

For the minimum oil film thickness measurements, a capacitance sensor is used. This electrical method is a very popular technique for measuring oil film thickness [2, 8, 9]. The capacitance is directly proportional to the surface area and inversely proportional to their separation, which is around 30 microns. The sensor is mounted in such a way that the lubricant film can be measured throughout the 50 mm stroke regardless of the reciprocating velocity. The signal acquired from the custom made capacitance sensor is taken to a Capacitec signal conditioning unit, which converts the signal output to voltage and then is recorded via the data acquisition system. Films up to 10 microns thick can be measured with this popular technique [11]. Development of the lubricant film begins as the liner accelerates away from the top dead center. Close to the dead center of the stroke, asperity interaction between the surfaces remains significant but the squeeze film effect also takes place resulting in beneficial load support, as it is supported partly by the lubricant present in the contact. This region corresponds to the mixed lubrication regime and as velocity increases, the surfaces separate, asperity interaction decreases and the regime is full film-hydrodynamic. From near mid-stroke to bottom dead center, the opposite happens. As velocity lowers the regime from hydrodynamic turns to mixed and further on, the surfaces cannot separate and the lubrication returns to mixed lubrication. At this point the developed forms of cavities diminish into bubbles and the effect of the squeeze film takes place at the other end of the stroke [1, 8, 9, 12].

Friction is measured by a force measuring sensor (load cell), PCB 208B sensor, which is very sensitive to small displacements of the ring assembly due to axial friction during the reciprocating motion. Through the signal amplifier, the signal is being recorded from the data acquisition system.

In Figures 1 and 2 a schematic of the experimental set-up is shown accompanied by a photo.

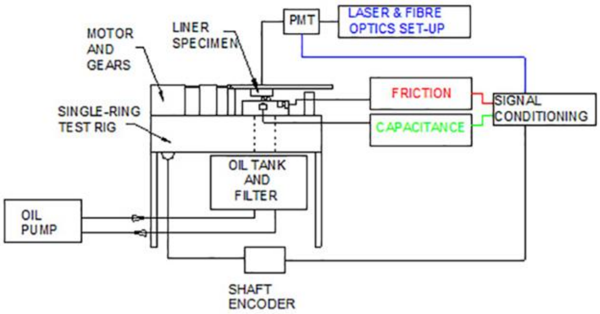
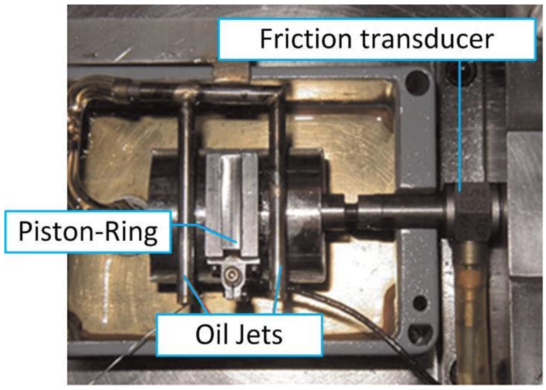


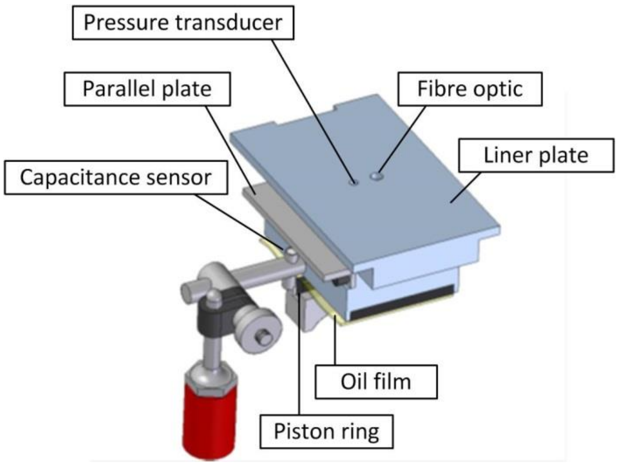
Figure 1. Schematic of the single-ring test rig [1, 3]

Figure 2. Photo of the single-ring test rig [1]

Figure 3(a) shows a close up of the test rig with the sensors when the liner surface is removed and in Figure 3(b) a 3-D schematic of the test rig which is focused on the mounting of the sensors.



(a)



(b)

Figure 3. (a) Top view photo of the sensors layout and (b) 3D schematic of the capacitance measurement with the magnetic holder and the flat surface on top of the capacitor [2]

The load cell of the friction sensor, as shown in Figures 2 and 3, is mounted outside the oil bath [2, 10]. This movement results in tension or compression of the transducer and the tests, as validated by the capacitance minimum film thickness measurements show friction peaks close to the dead centers, where the lubrication is boundary and mixed (boundary and elastohydrodynamic). Increased surface separation decreases asperity contact in boundary lubrication conditions, which is evident as a lowering of the friction spike in the friction signal as it is acquired throughout the stroke [5].

Tested Lubricant Properties

For the parametric study the following set of six lubricants were used, as shown in Table 1.

Table 1. Oils tested for temperature investigations

Blend Code	003B	006E/02	005A/02	002A/02
Grade	0W-30	0W-40	0W-20	10W-40
HTHS (mPa s)	3.30	3.4	2.14	4.05
V_{100} (cSt)	12.16	12.8	6.04	14.97
V_{40} (cSt)	68.93	66.8	31	97.8
VI	182	196	146	160

The temperature effect was studied so that the oil behaviour under high temperature testing could be determined. The expected trend is that oil film decreases as oil temperature raises, i.e. similar behaviour as with the viscosity decrease. So, this study is going to be an investigation of viscosity and physical-chemical properties on minimum oil film thickness (MOFT) measurements [8].

3. RESULTS

3.1 Temperature Parametric Lubricant Testing

According to Walther's equation the kinematic viscosity of oil varies with temperature.

$$\log\log(v+0.7)=A+B\log T \tag{1}$$

where v is the kinematic viscosity and T the temperature in Kelvin. A, B are constants different for each oil tested. Figure 4 shows the effect of temperature on the viscosity of oil 3B, that further explains the difference in oil film thickness measurements with the capacitance technique for the varying temperatures.

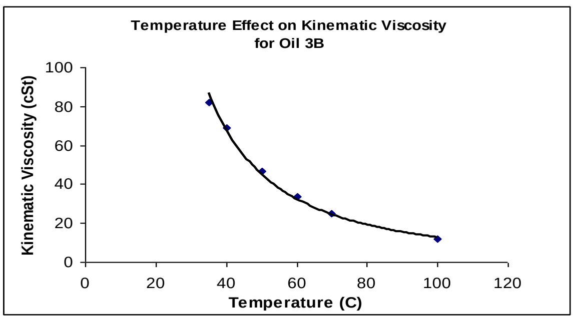
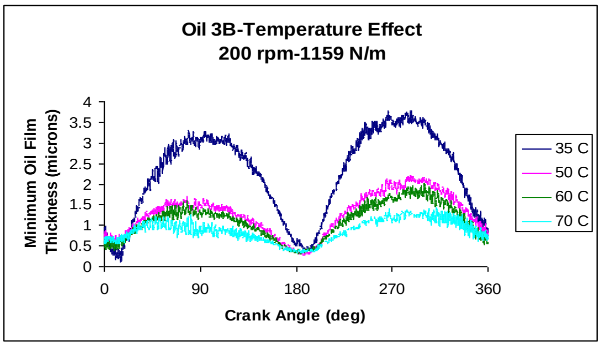


Figure 4. Temperature effect on kinematic viscosity, oil 3B



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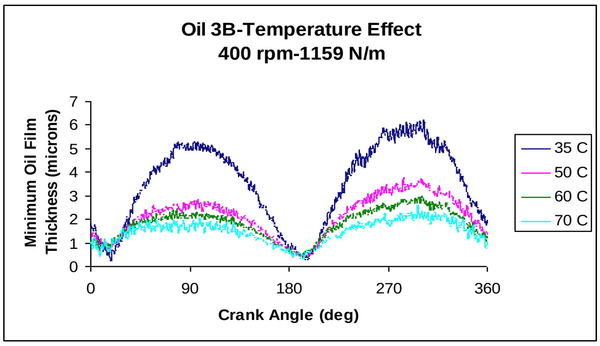

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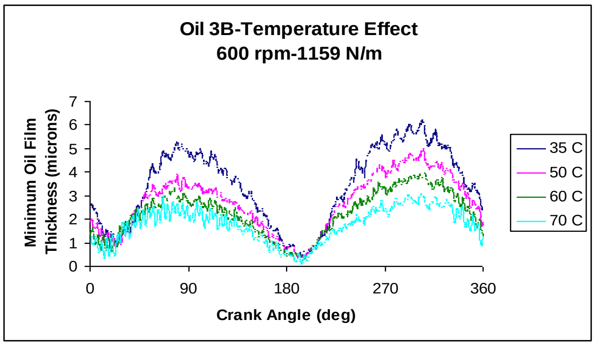
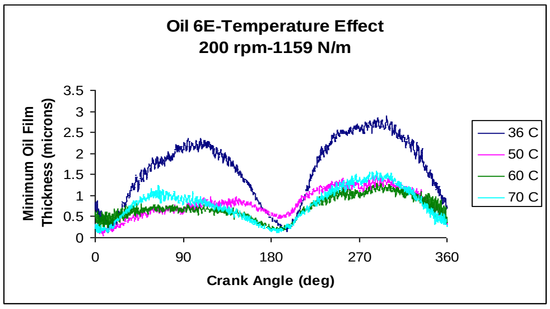


(c)

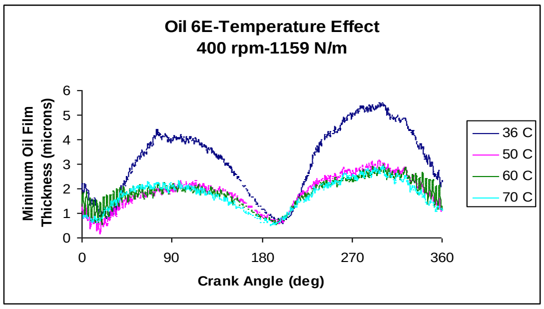
Figure 5. (a) Temperature effect at 200 rpm, 1159 N/m, (a) at 400 rpm, 1159 N/m and (c) at 600 rpm, 1159 N/m, oil 3B

The temperature results for oil 3B show the following trend: at higher temperatures the minimum film thickness decreases. There is a big gap between the ambient oil temperature (35°C) and the higher ones and this is observed in every graph for oil 3B (Figures 5(a) - 5(c)). This "step" in all the speed cases can be interpreted by the viscosity variation with temperature seen in Figure 4. Viscosity changes dramatically from 35°C to 50°C. Afterwards it decreases again in a smoother curve. The oil film thickness decreases 46.58% (at 92.16 deg CA at 200 rpm) whereas the viscosity decreases 43.35% from 35°C to 50°C [8].

The results for oil 6E (Figures 6(a)-(c)) showed that the temperature effect on MOFT above 50°C is not comparable to the trend noticed for the previous oil 3B. Therefore for every speed test case in Figures 6(a) - (c), the minimum oil film thickness curves coincide. The viscosity variation with temperature according to Walther's equation (Figure 7) produced a similar curve for oil 6E as for oil 3B.



(a)



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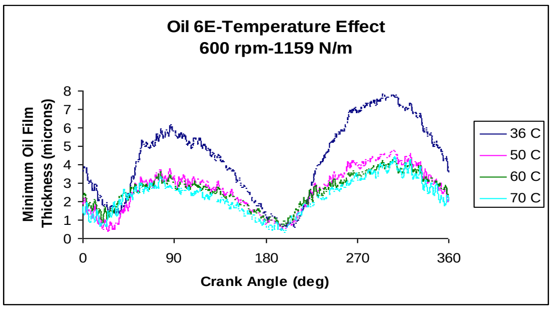


(c)

Figure 6. (a) Temperature effect at 200 rpm, 1159 N/m, (b) at 400 rpm, 1159 N/m and (c) at 600 rpm, 1159 N/m, oil 6E

Viscosity comparison between the two lubricants tested (3B and 6E) with rising temperature, showed that it has an increased value for oil 6E by 1% at 50°C, 2.6% at 60°C and 4.6% at 70°C. This slight increase by itself is not capable to justify the difference in the minimum oil film thickness temperature results between the two oils. It can be inferred by these results that the lubricant formulation-chemical properties can play an important role in changing the MOFT high temperature characteristics of a specific oil. The absolute oil film thickness measurement is greater in oil 3B than in 6E. The higher viscosity index of oil 6E does not justify by itself an increase in the minimum oil film thickness where it was shown that for higher viscosity index (VI), the minimum oil film thickness increases for the same grade of oil (0W-30) [2, 8].

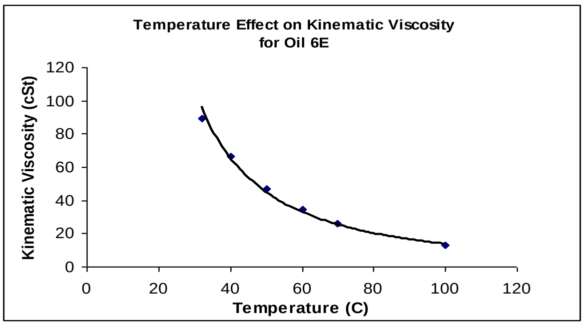
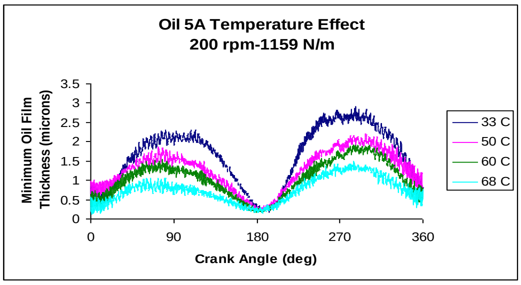
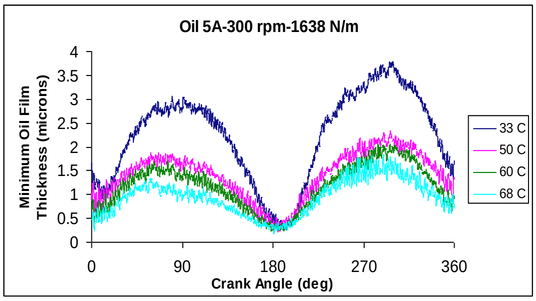


Figure 7. Temperature effect on kinematic viscosity, oil 6E

For oil 5A (Figures 8(a)-(d)) a similar trend to the previous oils (6E and 3B) is noticed. This time though, at very low speeds, MOFT has a low absolute value, maximum 2.7 μm at 200 rpm (Figure 8(a)), 33°C, compared to oils 6E and 3B. Temperature effect on viscosity provides an explanation regarding oil 5A behaviour, in Figure 9, where the viscosity values are almost 50% lower than oil 3B and 53% lower than oil 6E at 35°C. Similar trend is noticed for the high speed test (600 rpm – Figure 8 (d)). Higher viscosity results cannot be distinguished from the low viscosity ones at high temperature. At 600 rpm the reduction from ambient to 50°C is 16% compared to 200 rpm (Figure 8(a)) where the reduction in MOFT magnitude is 23%. Similar results were presented for oil 3B. At high speed (600 rpm – Figure 5(c)) the temperature effect does not have such a strong effect as at low speeds, the percentages this time at 600 rpm are 34% and 53% (reduction) respectively at 200 rpm (Figure 5 (a)). Oil 6E on the other hand shows greater stability in this aspect. MOFT reduces at 600 rpm by 47% (Figure 6(c)) which is comparable to 55% reduction at 200 rpm (Figure 6 (a)).



(a)



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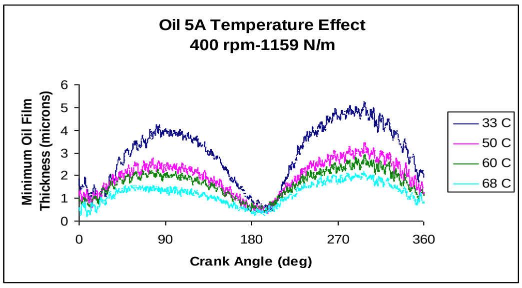

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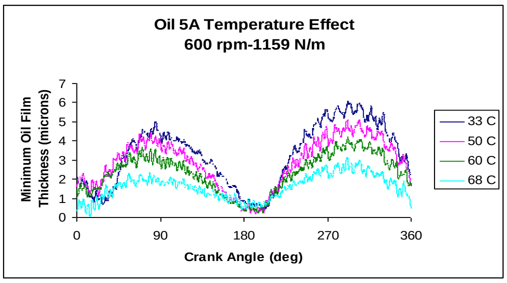


(d)

Figure 8. Load effect – high temperature testing, oil 5A: (a) at 200 rpm, 1159 N/m, (b) at 300 rpm, 1638 N/m, (c) at 400 rpm, 1159 N/m and (d) at 600 rpm, 1159 N/m

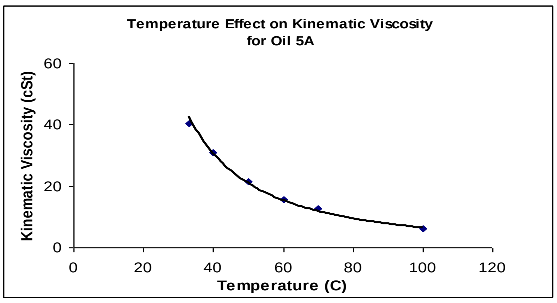
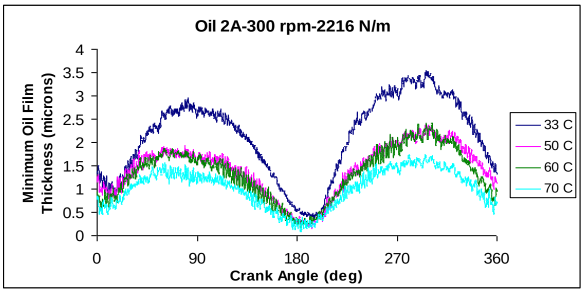
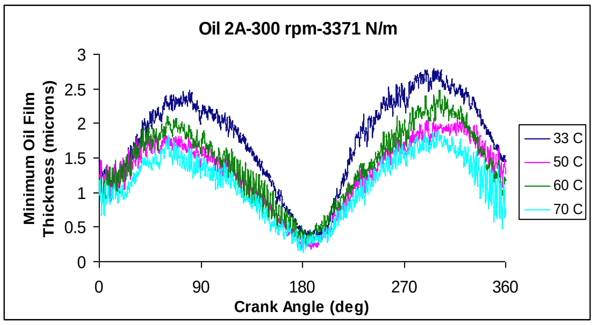


Figure 9. Temperature effect on kinematic viscosity, oil 5A



(a)



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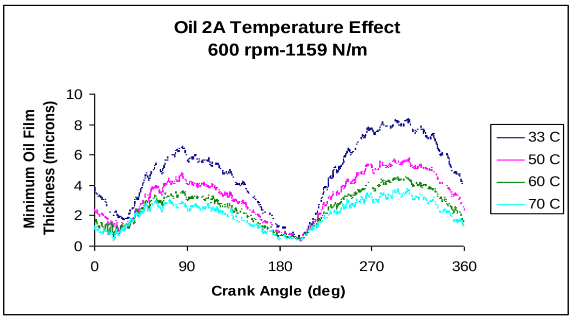


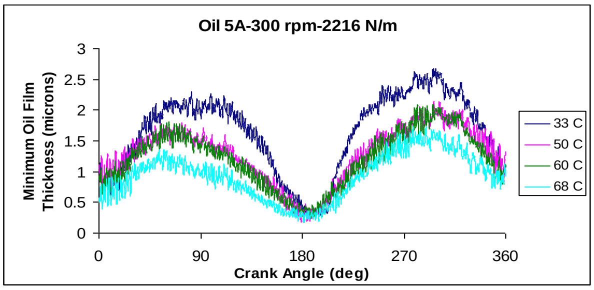
(c)

Figure 10. Load effect – high temperature testing, oil 2A: (a) at 200 rpm, 2216 N/m, (b) at 300 rpm, 3371 N/m and (c) at 600 rpm, 1159 N/m

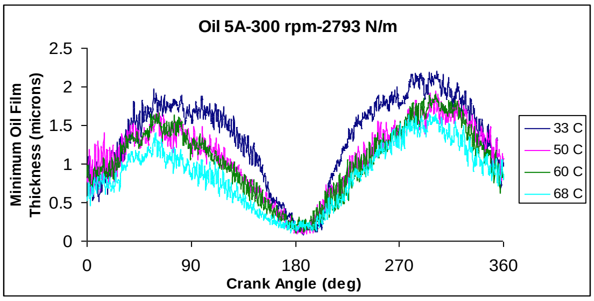
Additionally, oil 5A does not have a similar behavior to 2A (compare Figure 8 (d) to Figure 10 (c)). Oil 2A follows the trends noticed for oils 3B and 6E that have considerably higher VI, V_{100}, V_{40} and HTHS values than oil 5A (see oil properties in Table 1). Figure 9 shows temperature effect on viscosity for oil 5A.

3.2 Load Effect in oil film Thickness at High Temperature

Oil 5A was tested for the effect of load on oil film thickness at high temperature. The results show the trend at 300 rpm (Figures 11 (a)-(c)) and 500 rpm (Figures 12 (a)-(c)). In all cases, there is a remarkably strong effect of load on the minimum oil film thickness, regardless the temperature. Eventually, as load gets higher (Figures 11 (b)-(c) and 12 (b)-c)) the temperature effect on minimum oil film thickness becomes less than in the low load test cases (they represent the temperature effect at 1159 N/m) [8]. The trend noticed is that the film thickness has a certain value (considerably low) which decreases by a slight margin for the highest temperature test case (68°C – Figures 11(a)–(c) and Figures 12(a)- (c)).



(a)



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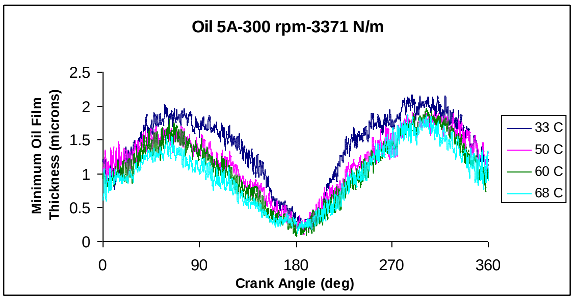
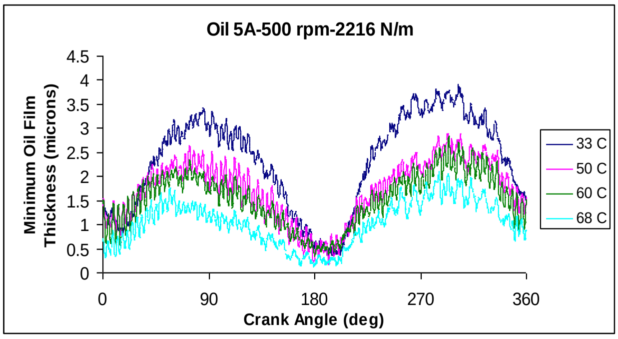


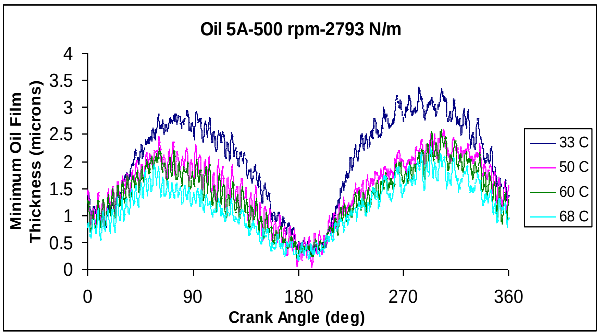
(c)

Figure 11. Load effect – high temperature testing, oil 5A: (a) at 300 rpm, 2216 N/m, (b) at 300 rpm 2793 N/m and (c) at 300 rpm 3371 N/m

According to Figures 11 (a)-(c) and 12 (a)-(c), MOFT is smaller close to BDC than at TDC which, in turn, has an effect on the squeeze film. The squeeze film itself, is not affected in terms of crank angle appearance in the high temperature cases. There is a slight shift towards the dead centers compared to the ambient temperature results (33°-35°C) and the load tests, in general, also showed that at high loads there is a marginal shift of the MOFT curves towards the dead centers [8].



(a)



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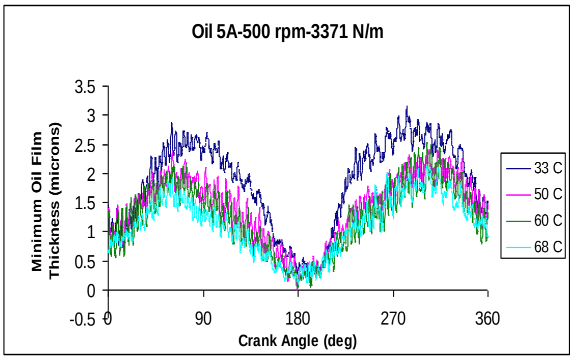
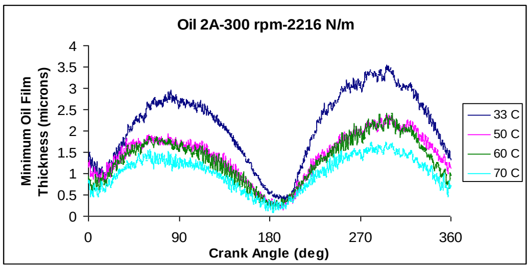


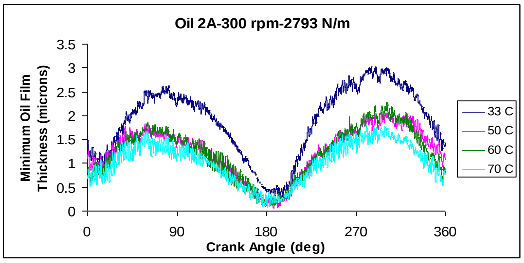
(c)

Figure 12. Load effect – high temperature testing, oil 5A: (a) at 500 rpm, 2216 N/m, (b) at 500 rpm, 2793 N/m and (c) at 500 rpm, 3371 N/m

The figures below show (Figures 13 (a)-(c)) how load is affecting the minimum oil film thickness, for oil 2A, with temperature variation. Oil 2A which has greater V_{40} and V_{100} (and VI) than oil 5A gave similar results, i.e. the temperature effect on MOFT is not evident at high loads.



(a)



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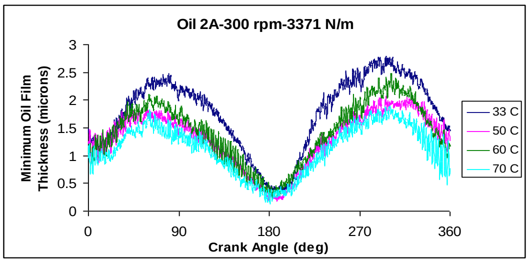


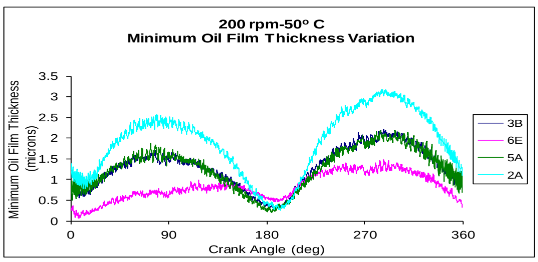
(c)

Figure 13. Load effect – high temperature testing, oil 2A: (a) at 300 rpm, 2216 N/m, (b) at 300 rpm, 2793 N/m and (c) at 300 rpm, 3371 N/m

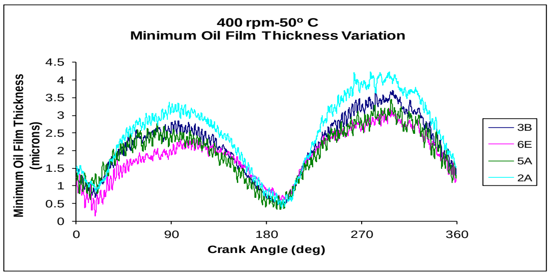
3.3 Effect of High Temperature on MOFT for the Tested Oils at Different Speeds

The absolute value of the minimum oil film thickness can be directly compared to each one of the different oils used. The effect of high temperature is taken into account for these comparisons and graphs are presented for all the oils tested at high temperatures, at 50° C (Figs. 14(a)-(c)), at 60° C (Figs. 15(a)-(c)) and 68°-70°C (Figs. 16(a)-(c)).

(a) 50°C



(a)



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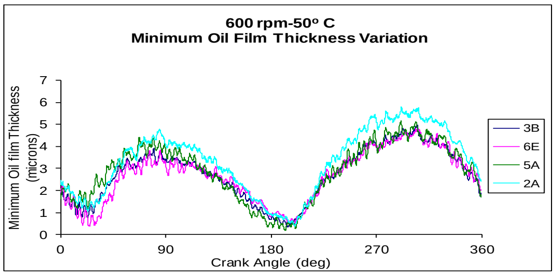
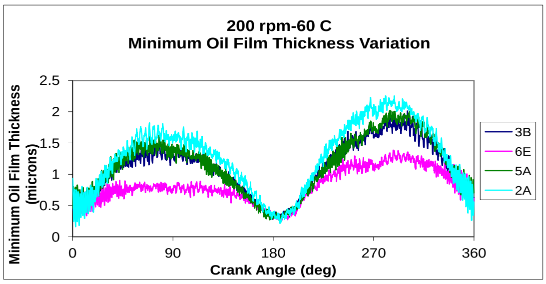


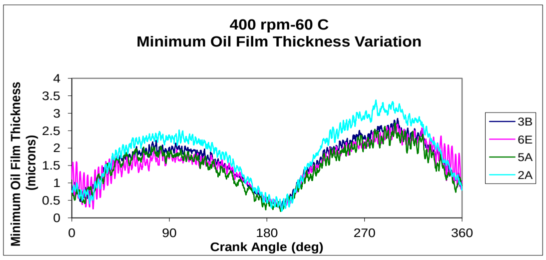
(c)

Figure 14. MOFT variation: (a) at 200 rpm, (b) at 400 rpm and (c) at 600 rpm – 50°C for all tested oils

(b) 60°C



(a)



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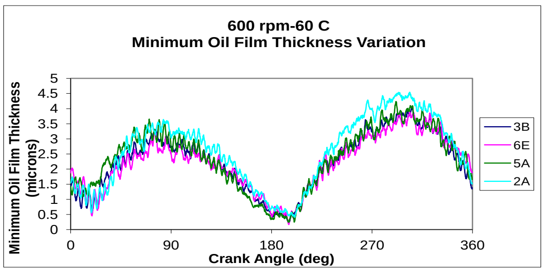
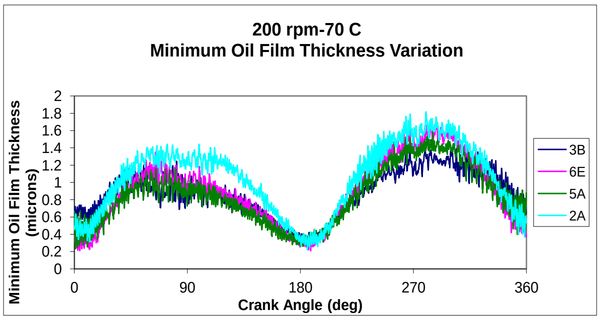


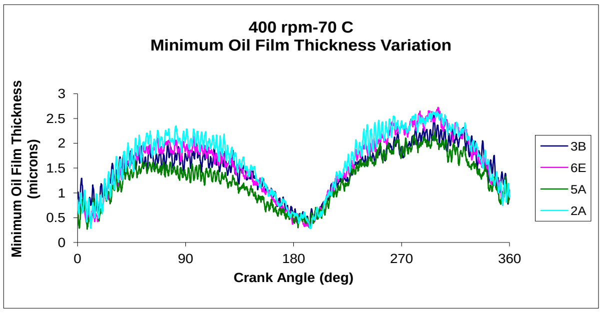
(c)

Figure 15. MOFT variation: (a) at 200 rpm, (b) at 400 rpm and (c) at 600 rpm – 60°C for all tested oils

(c) 68°-70°C



(a)



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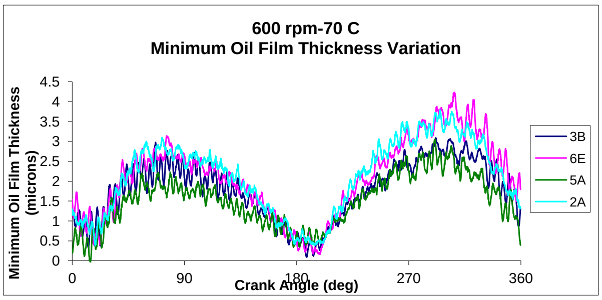

(c)

Figure 16. MOFT variation: (a) at 200 rpm, (b) at 400 rpm and (c) at 600 rpm – 68°-70°C for all tested oils

The majority of the testing showed that for the above series of experimental data (Figures 14 (a)-(c), Figures 15 (a)-(c) and Figures 16 (a)-(c)), oil 2A had the thickest film as the temperature varies in comparison to oils 6E, 5A and 2A. According to viscosity variation with temperature curves, oil 2A has the highest viscosity of all the tested lubricants at all temperatures. Oil 2A produces a thicker MOFT, which is more pronounced at 50°C (Figures 14 (a)-(c)) whereas at 60°C (Figures 15 (a)-(c)) and 68°-70°C (Figures 16 (a)-(c)) the MOFT curves of the tested oils become more even; oil 2A still producing marginally thicker films. Table 2 shows the viscosity variation for each oil tested at 50°, 60° and 70° C:

Table 2. Viscosity properties for the temperature-load effect experiments and VI properties

Blend Code		002A /02	005A /02	006E /02	003B
Viscosity (cSt)	50 °C	64.34	21.49	47.13	46.61
	60 °C	45.76	15.72	34.55	33.65
	70 °C	33.46	12.60	26.29	25.09
VI		160	146	196	182

3.4 Friction Experiments

The following test is considered to give evidence to the high friction peaks noticed when the oil viscosity changes. Oil 2A has been tested at maximum load (3371 N/m):

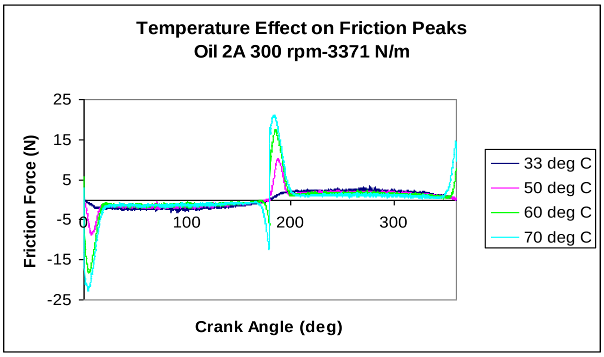

Figure 17. High temperature friction results for oil 2A

According to Figure 17, high friction results are taken at flow reversal points for the high temperature testing. The boundary and mixed lubrication region at high loads and high temperatures is more extensive. Friction force increases at high temperature when the interface between the liner surface and the piston ring is under these conditions (boundary and mixed). The formulation of the lubricant is an important factor because at higher temperatures the additives of the lubricant react in a different way with the surfaces in contact, thus increasing or reducing the effect of the resulting asperity contact. Additionally, friction force at the dead centres is reversing rapidly (steeper curve) compared to the ambient temperature results (33 °C).

4. CONCLUSIONS

This parametric study showed that there is a directly comparable amount of decrease in the minimum oil film thickness with increasing temperature. Results showed:

- MOFT is strongly viscosity dependent. Temperature affects capacitance offset [2].
- Lubricant chemistry plays an important role in MOFT measurements. At high rpm, however, it is not evident as at low rpm.
- The squeeze film seems to be partially affected for the different lubricants. There are differences between TDC and BDC, that are evident at high temperatures and high loads (shift towards dead centers) for each lubricant. The dynamic characteristics of the test rig and its geometry affect the lubrication but since this asymmetry in MOFT is more pronounced (Figs 11 and 12), it can be inferred that the squeeze film is altered, not in crank angle degrees (location) but in absolute thickness measurements.
- High temperature testing is combined with higher friction and extensive boundary and mixed lubrication areas compared to ambient temperature results. A rapid friction increase is also noticed for the boundary lubrication area.
- For higher VI, MOFT increases for the same grade of oil [2].
- Load and speed effect on cavitation initiation and number of (string) cavities [1] might accordingly apply to temperature effect results.

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