# The effect of ageing on elastohydrodynamic friction in heavy duty diesel engine oils

**Marcus Björling[1], Kim Berglund[1], Andrew Spencer[2] and Roland Larsson[1]**

## Abstract

To further improve the efficiency of machine components found in automotive engine systems it is important to understand the friction generation in these components. Modeling and simulation of these components are a crucial part of the development process. Accurate simulation of the friction generated in these machine components is, amongst other things, dependent on a realistic lubricant rheology and lubricant properties, where especially the latter may change during ageing of the lubricant. Many modern heavy duty diesel engines are in operation for several hundred hours before the engine oil is changed. In this work, two engine oils, one 10W-30 and one 5W-20 have been aged in full heavy duty diesel engine bench tests for 400 and 470 hours respectively. This roughly corresponds to the amount of ageing these oils are subjected to between oil drains in field conditions. The aged oils were subjected to a number of oil analyses showing, among others, a maximum increase in oil viscosity of 12.9 % for the 5W-20 oil and 5.5 % for the 10W-30 oil, which is most likely primarily an effect of evaporation and oxidation. The aged oils were tested in a ball on disk test rig under elastohydrodynamic conditions where friction was measured and the performance was compared to fresh samples of the same oils. The results show that there is almost no difference in elastohydrodynamic friction when comparing the aged oils with the fresh oils. These results indicates that it is not necessary to include oil ageing in numerical EHD friction models as long as the oil is changed before the ageing has reached a critical level.

## Introduction

The automotive industry is facing increasing restrictions in terms of emissions and is therefore spending considerable resources on research and development in several areas to reduce emissions. One area of research is lubricant technology. Lubricants play a vital part in reducing friction and provide cooling in a variety of machine components in a vehicle. It has been assessed that 33 % of the fuel energy in a car is used to overcome friction, and that 30-35 % of these friction losses originates from the engine system[8]. In heavy road vehicles and buses, 34 % of the fuel energy is used to overcome friction, and approximately 18 % of these losses originates from the engine system[9].

One way to further reduce emissions in a vehicle is to improve the efficiency of the engine system by optimizing machine components and lubricants. Modeling and simulation of these components are a crucial part of the development process. Accurate simulation of the friction generated in these machine components is, amongst other things, dependent on a realistic lubricant rheology and lubricant properties, where especially the latter may change during ageing of the lubricant. Many modern heavy duty diesel engines are in operation several hundred hours before the engine oil is changed. The friction that is generated in elastohydrodynamically lubricated contacts found in for instance gears, rolling element bearings and cam followers is strongly dependent on the rheological properties of the lubricant. It is therefore of great interest to investigate the effect of ageing on engine oil rheological properties and tribological performance.

Previous studies have investigated oil degradation in a one cylinder petrol engine and seen large changes in viscosity and tribological performance from oil extracted from the top ring zone as well as the oil sump of the engine system[10;11]. However, as far as the authors know, there have not been any studies performed under realistic operating conditions in heavy duty diesel engines on oil ageing and the effect on EHD friction.

In this work, two engine oils, one 10W-30 and one 5W-20, have been aged in full heavy duty diesel engine bench tests for 400 and 470 hours respectively. This roughly corresponds to the amount of ageing these oils are subjected to between oil drains in field conditions. The aged oils were tested in a ball on disk test rig under elastohydrodynamic (EHD) conditions where friction was measured and the performance was compared to fresh samples of the same oils. The antioxidant levels in the used oils were evaluated

[1]Division of Machine Elements, Department of Engineering Science and Mathematics, Luleå University of Technology, Luleå, Sweden
[2]Dynamics, Acoustics and Tribology, Engine Dynamics, Scania, Scania Technical Centre, 15187 Södertälje, Sweden

**Corresponding author:**
M. Björling, Division of Machine Elements, Department of Engineering Science and Mathematics, Luleå University of Technology, Luleå, SE-97187 Sweden
Email: marcus.bjorling@ltu.se

with RULER® (Remaining Useful Life Evaluation Routine) and the viscosities were measured of the fresh oil and during several steps of the ageing process. Several other measurements such as volatility, total base number (TBN), total acid number (TAN), fuel dilution and soot levels were also measured to better explain the nature of the ageing.

## Overall Methodology

The following sections cover the test specimens and lubricants. It also contains information about how the different lubricant properties were measured. Finally, there is a description of how the experimental equipment for the friction tests and engine bench tests were set up, and how the experiments were performed.

### Test specimens and lubricant

The test specimens for the ball on disk machine were produced in DIN 100Cr6 (AISI 52100) bearing steel and measured to a surface roughness, RMS of 25 nm for the balls and 35 nm for the disks, which gives a combined roughness of approximately 43 nm. The surface roughness measurements were conducted in a Wyko NT1100 optical profilometer system from Veeco. The measurements were performed using 10x magnification and 1x field of view. The balls are grade 20 with a 13/16 inch (20.63 mm) outer diameter and a hardness of about 60 HRC. The disks have a 4 inch (101.6 mm) outer diameter, a circumferential grind (before polish) and are through hardened to about 60 HRC.

The lubricants used in the tests were two engine oils with two different viscosity levels, one 5W-20, and one 10W-30.

### Ball on disk tribotester

The experiments were carried out with a Wedeven Associates Machine (WAM) 11, ball on disk test device. The lubricant is supplied at the center of the disk in an oil dispenser that distributes the lubricant across the disk surface. The lubricant is circulated in a closed loop from the oil bath, through a peristaltic pump to the oil dispenser at the center of the disk. The peristaltic pump is delivering approximately 180 ml/min. Three thermocouples are used in the test setup, one located in the oil bath, one in the outlet of the oil supply, and one trailing in the oil film close to the inlet region of the ball on disk contact. A more thorough description of the test rig and its features is presented in previous work[4].

### Ball on disk test procedure

The ball on disk test device was used to generate friction data from a series of tests under different operating conditions. In each test cycle, the entrainment speed was varied between 0.45 and 4.45 m/s while the slide to roll ratio (SRR) was varied from -0.0002 to -0.49. SRR is defined as the ball surface speed minus the disk surface speed, divided by the entrainment speed. All tests in this investigation were hence conducted with the disk having a higher surface speed than the ball. Both ball and disk specimens were cleaned with heptane and ethyl alcohol before starting the experiments for each of the test cases. All tests were performed with a load of 300 N which corresponds to a maximum Herzian pressure of 1.94 GPa. The tests were performed at three

**Table 1.** Investigated conditions

| Lubricant | 5W-20 and 10W-30 |
|---|---|
| Temperature | 40, 80 and 100 ° C |
| Contact load | 300 N |
| Maximum hertzian pressure | 1.94 GPa |
| Entrainment speed, $U_e$ | 0.45 to 4.5 m/s |
| Slide to Roll Ratio, SRR | 0.0002 to 0.49 |

different temperatures; 40, 80 and 100°C. Before starting the experiments for each test case, the test device was warmed up to the desired operating temperature for approximately 60 minutes with lubricant circulation over both ball and disk to ensure thermal stability. When a stable temperature was reached, a 300 N load was applied and the machine was calibrated for pure rolling by adjusting spindle angle and positioning of the ball to ensure a condition of no spinning. These settings were then held constant for 20 minutes to ensure a mild run-in. Subsequently, the test cycle was started, wherein the load was kept at a constant value, and entrainment speed and slide to roll ratio were varied from the lowest to the highest value. The test cycle contains several loops where SRR is held constant for each loop and the entrainment speed is ramped from 4.5 to 0.45 m/s. In the first loop the SRR is held at 0.0002 and is then continuously increased with each loop until it reaches 0.49. The temperature of the oil bulk and fluid adhered to the disk surface was typically deviating less than ± 1.5°C from the target temperature of 40, 80 and 100 °C during testing. The results are shown as so called friction maps discribed in previous work[3;4]. A summary of the test conditions is found in Table 1.

### Engine tests

The engine oils were run in a Scania V8 engine in an engine bench test through their standard endurance test cycle. The endurance test is a combination of idle, full load at different speeds and exhaust braking operating points, at both normal and elevated oil temperatures, and has been developed to promote accelerated ageing of the engine. The engine is put through the most severe conditions that might be seen with an end user. During testing the engine oil was changed every 400-500 hours which has been empirically found to lead to similar ageing of the oil that would be experienced in a customer vehicle between oil drains.

### Lubricant analysis

The RULER® is a linear voltammetric technique designed to evaluate the relative amount of antioxidants of an aged lubricant sample compared to a fresh lubricant sample. The investigated lubricant is mixed with a solvent and an electrolyte. The measurement probe of the RULER® instrument is placed in the sample solution and voltage is increased linearly across the measurement probe. The oxidation current is measured as voltage increases during the test. Current peak heights can be used to indicate the concentration of an antioxidant and the voltage potential range is related to the type of antioxidant. The measurements were performed according to ASTM D6971.

The kinematic viscosity of the oil was measured using a glass capillary kinematic viscometer according to the
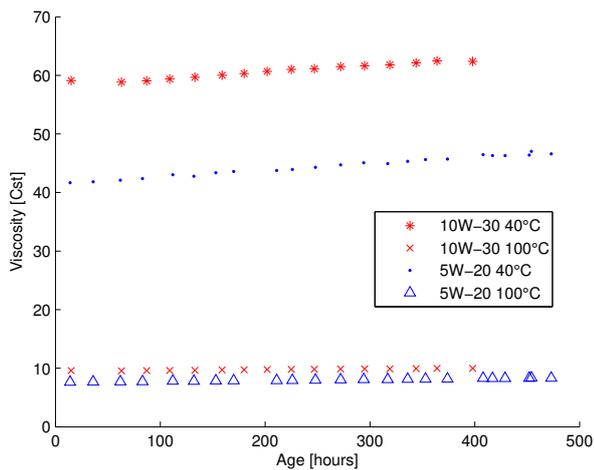
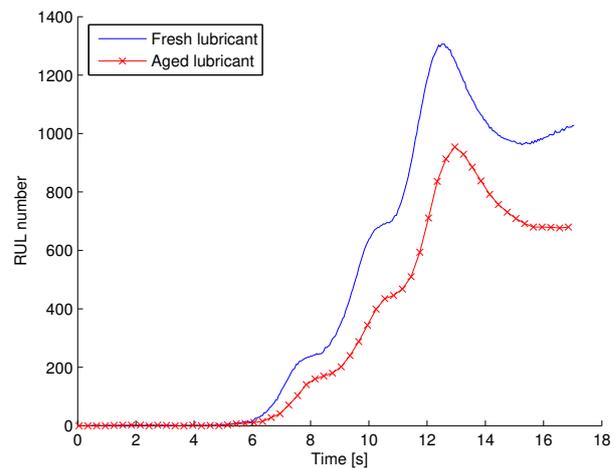**Figure 1.** Kinematic viscosity of the 5W-20 and 10W-30 oils with ageing time



**Figure 2.** Antioxidant levels in 5W-20 in fresh lubricant and lubricant aged for 470 hours. The RUL value after ageing was measured to 67 %.
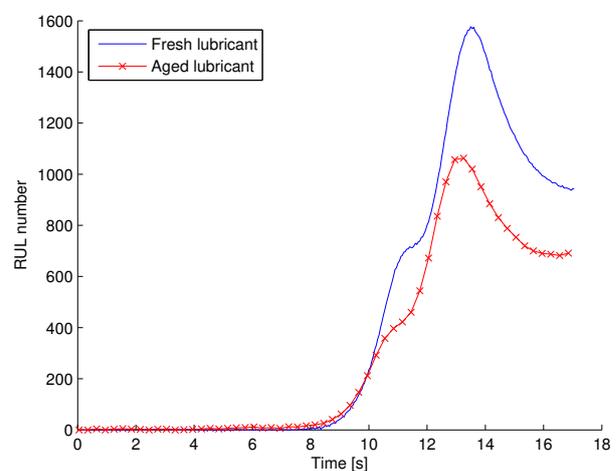


**Figure 3.** Antioxidant levels in 10W-30 in fresh lubricant and lubricant aged for 400 hours. The RUL value after ageing was measured to 73 %.

standards ASTM D446 (operating instructions of the viscometer) and ASTM D445 (test method for measuring viscosity). In a glass capillary viscometer fluid passes through a fixed-diameter orifice under the influence of gravity. The rate of shear is less than 10 s$^{-1}$. The time taken for a specified volume of lubricant to flow through the capillary is measured at a controlled and known temperature. The kinematic viscosity is then a product of the measured time for the lubricant to flow through the capillary and a calibration constant of the viscometer. The test is run twice and the mean of the two values is taken as the final result. The dynamic viscosity is then calculated by multiplying the kinematic viscosity by the density.

The evaporative loss of the oils was evaluated by Noack volatility test, ASTM D5800. The total base number was evaluated according to ASTM D2896 and the total acid number by ASTM D664. The fuel dilution was evaluated according to ASTM D3524-04. The soot leveles were measured according to ASTM D7844.

## Results

In this section, the results from the lubricant analysis are presented together with the results from the experimental friction measurements.

The results from the viscosity measurements are shown in Fig. 1. Both oils show an increase in viscosity with ageing time. For the 5W-20 oil the viscosity increased by 12.9 % at 40°C and by 9.4 % at 100°C at the end of the ageing process. For the 10W-30 oil the viscosity increase was 5.5 % at 40°C and 4.1 % at 100°C when the ageing was finished.

The results from the RULER® measurements are presented in Figs. 2 and 3 for the 5W-20 and 10W-30 oils respectively. The RULER® measurements of a fresh lubricant sample compared to an aged lubricant sample are shown in each of the figures. The peaks of each curve represent different antioxidant species and it can therefore be observed that the 5W-20 lubricant contains three types of antioxidants, while the 10W-30 contains two types. The peak height indicates antioxidant concentration. Thus, the degradation of antioxidant species can be seen

as lowered peak height of the aged lubricant compared to the fresh sample. The RUL value, i.e. the relative amount of antioxidants, was calculated by dividing the RULER® curve areas of the fresh and aged lubricant sample. RUL values after ageing were 67% and 73% for the 5W-20 and the 10W-30 respectively. Thus, both lubricants show sufficient oxidation protection even after ageing.

TAN decreased by 42 % for the 5W-20 oil and 22 % for the 10W-30 oil while TBN decreased by 27 % for the 5W-20 oil and 13 % for the 10W-30 oil. The soot levels increased to 0.07 weight % for the 5W-20 oil and 0.01 weight % for the 10W-30 oil. The fuel dilution remained below 0.4 weight % for both oils. The Noack volatility test showed an evaporative loss of 11.8 weight % for the 5W-20 oil and 9.3 weight % for the 10W-30 oil.

The results include friction coefficients for the measurements performed with the fresh 5W-20 and 10W-30 oils, and comparisons in percentage of the differences between the fresh oils and the aged oils. The results from the friction measurements of the 5W-20 and 10W-30 oils are presented
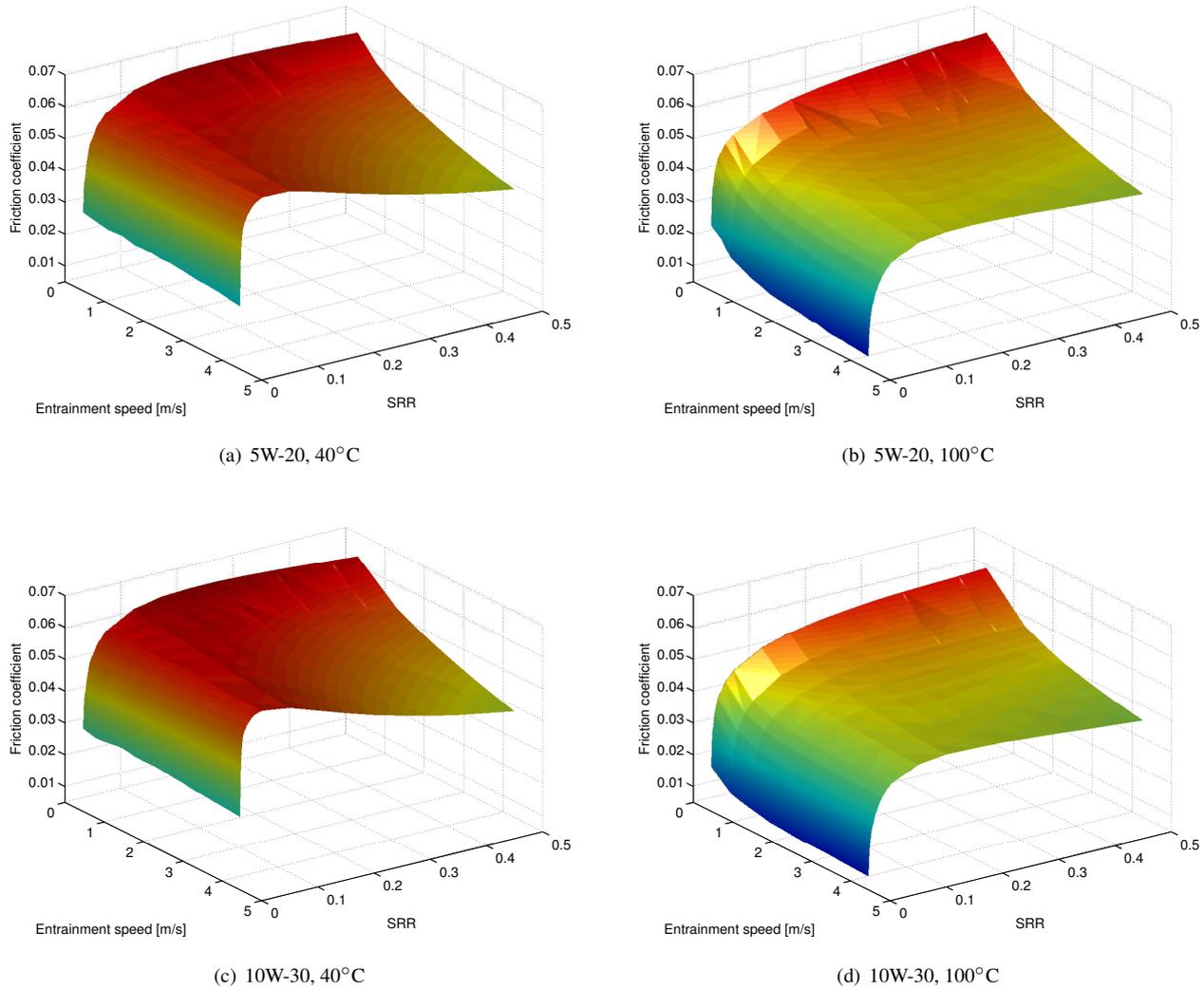
(a) 5W-20, 40°C



(b) 5W-20, 100°C



(c) 10W-30, 40°C



(d) 10W-30, 100°C

**Figure 4.** 3D friction maps - Fresh oils, 5W20 and 10W30 @ 40 and 100°C

in Fig. 4 where Figs. 4(a) and 4(b) are from the friction measurements performed with the 5W-20 oil and Figs. 4(c) and 4(d) are from the friction measurements performed with the 10W-30 oil. In each figure the friction coefficient is plotted versus entrainment speed and SRR.

The authors believe that the majority of the friction measurements were performed in full film lubrication since the combined roughness of the specimens are quite low, around 43 nm, as described in the overall methodology section. There may be some degree of asperity contact in the test performed at 100°C at the lowest entrainment speeds where the film thickness is at its lowest values. This may explain why the higher viscosity 10W-30 oil shows slightly lower friction coefficients than the lower viscosity 5W-20 oil in this region, see Figs 4(b) and 4(d). The minimum film thickness was calculated with the formula proposed by Chittenden *et.al.* [13] to a value of 25 nm at the lowest entrainment speed for the 5W-20 oil at 100°C, and to around 30 nm for the 10W-30 oil at 100°C. Both of these oils have a calculated minimum film thickness that exceeds the combined roughness before reaching an entrainment speed of 1 m/s. The same oils have a minimum film thicknesses of 65 nm and 85 nm respectively at an entrainment speed of

0.45 m/s at 40°C, thus clearing the combined roughness even at the lowest tested speed. Based on this formula the aged oils have even higher film thicknesses at the same conditions due to their higher bulk viscosities compared to the fresh oils.

All friction maps cover several different friction regimes; from the linear increase in friction at low SRRs, to the non-linear region where the behaviour is non-Newtonian, where shear thinning and ultimately the limiting shear stress is dominating the friction coefficient. At even higher SRRs the friction starts to decrease due to a combination of shear thinning and thermal softening of the lubricant. Finally, at the lowest entrainment speeds there may be some asperity contacts between the surfaces and the friction coefficient is therefore a combination of hydrodynamic effects and asperity interaction. For a more thorough description of the friction regimes, see previous work [3,4].

Figure 5 shows the difference between the fresh oils and the aged oils in percentage. A positive number indicates that the fresh oil has a higher friction coefficient compared to the aged oil and vice versa for a negative number. Figs. 5(a) and 5(b) show the results for the fresh and aged 5W-20 oil and Figs. 5(c) and 5(d) show the results for the fresh and aged 10W-30 oil.
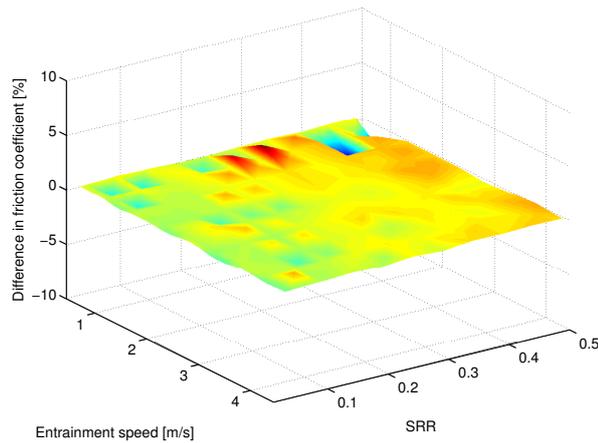
(a) 5W-20 - Difference between fresh and aged oil, 40°C
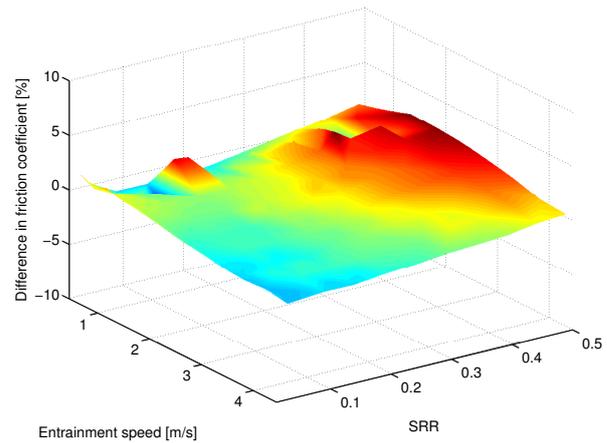


(b) 5W-20 - Difference between fresh and aged oil, 100°C
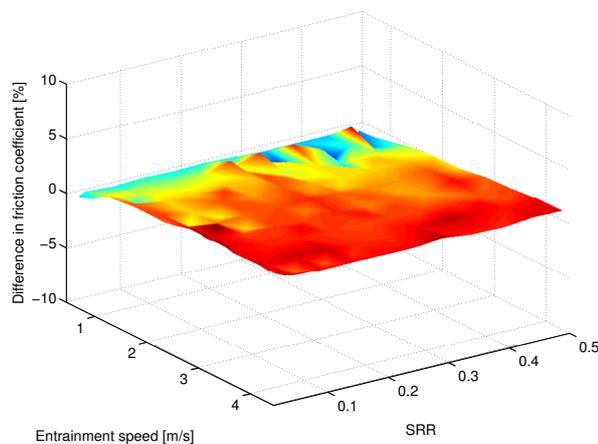


(c) 10W-30 - Difference between fresh and aged oil, 40°C
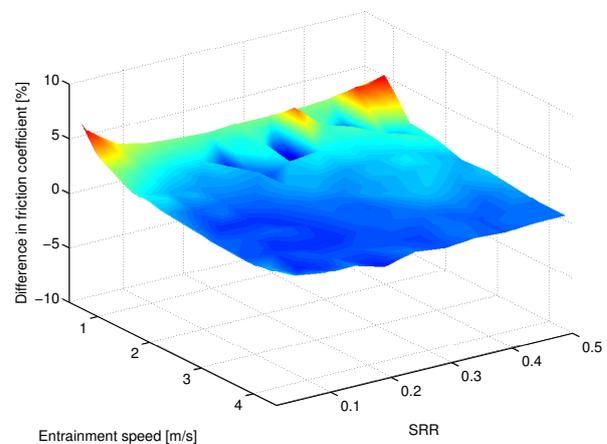


(d) 10W-30 - Difference between fresh and aged oil, 100°C

**Figure 5.** 3D friction maps - Difference between fresh and aged oils, 5W-20 and 10W-30 @ 40 and 100°C. A positive number indicates that the fresh oil has a higher friction coefficient compared to the aged oil and vice versa for a negative number.

The results for the tests performed at 80°C are not shown here to save space, but the results were showing the same trends as the tests performed at 40 and 100°C. However, there are no signs of visible wear after the tests on either ball or disk.

## Discussion

It is often stated that when an oil degrades in an operating engine the viscosity initially decreases due to a combination of fuel dilution and in case of fully formulated oils, mechanical degradation[6;7]. Such behaviour is seen for the 10W-30 oil at both temperatures in Fig. 1, but not for the 5W-20 oil. It is possible that the 5W-20 oil still shows this kind of behaviour and that this would have been seen should shorter intervals between viscosity measurements have been used. The dominating trend for both oils is instead a viscosity increase where the viscosity is increased by a larger extent for the 5W-20 oil in comparison to the 10W-30 oil. The increase in viscosity is most likely primarily caused by two different mechanisms. The first one being chemical reactions in the oil where the oxidized molecules

are polymerized and thus increase the average molecular weight of the oil[1;5;12]. This process is accelerated by the high combustion temperatures and the effect of combustion gases passing through the piston rings as blow by and reacting with the oil in the crankcase. The second one is the evaporative loss where especially the smaller and lighter molecules are reduced thus increasing the viscosity of the lubricant. Fuel dilution and soot levels were both at such a low level that it is considered not to influence the results. The larger viscosity increase of the 5W-20 oil is most likely to a great extent explained by the fact that it was aged for 70 hours longer than the 10W-30 oil and has a higher evaporation loss in the Noack volatility test.

As indicated in Figs. 2 and 3 there are still plenty of antioxidant reserves left in the oils at the end of the motor bench tests. It is likely that the viscosity increase of the lubricants would have been much greater if the antioxidants would have been depleted.

As seen in Fig. 5 the EHD friction performance is almost unaltered comparing the fresh oils to the used oils, especially when a test temperature of 40°C were used. The changes are slightly higher at a temperature of 100°C, but these variations

14. Shirzadegan, M., Björling, M., Almqvist A., Larsson R.,: Low degree of freedom approach for predicting friction in elastohydrodynamically lubricated contacts Tribology International **94**, 560–570 (1985). DOI 10.1016/j.triboint. 2015.10.010