BACHELOR

Analysis of Fuel Properties of Commercial and Novel Fuels

van Zutphen, Jasper J.A.

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Analysis of Fuel Properties of Commercial and Novel Fuels

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Jasper van Zutphen

Project supervisors:
M.C.M. Cuijpers
N.C.J. Maes
Author:
J.J.A. van Zutphen 1322176

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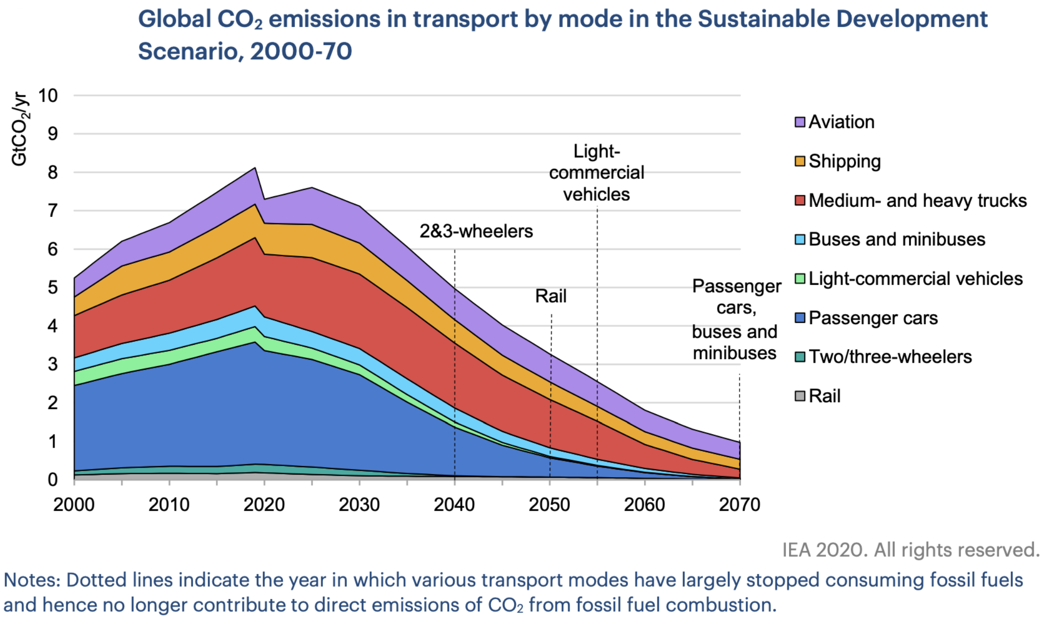
List of Symbols

Symbol	**Property**	**Unit**	**Abbreviation**
μ	Dynamic viscosity	Centi Poise	cP
F	Force	Newton	N
A	Area	Meter squared	m^2
υ	Kinematic viscosity	Meter squared per second	m^2 s^{-1}
ρ	Mass density	Kilogram per cubic meter	kg m^{-3}
r	Radius	Meter	m
W	Total Friction	kilo Joules	kJ
ω	Rotational speed	Radians per second	rad s^{-1}
τ	Torque	Newton meter	Nm
t	Time	Second	s
θ	Angle	Radian	rad
T	Temperature	Celcius	^{o}C
V	Volume	Milliliter	mL
d	Wear diameter	Millimeter	mm

1 Introduction

In recent years the effects of climate change are becoming more prevalent, extreme droughts, floods, the extinction of flora and fauna and the overall lower air quality in cities [1]. This is also the reason that in the UN climate convention strict goals are being set to decrease CO_2 emissions, see 1.1. A large contributor is the transportation sector which is rapidly growing [2], the growth of this sector combined with the desired reduction of emissions means that a substantial energy transition is needed. There are currently a few promising options for this such as, electrochemical batteries, hydrogen fuel cells or carbon neutral fuels. However most parts of the transportation infrastructure are designed for combustion engines and a transitioning period is needed if it needs to be phased out completely, carbon neutral fuels could potentially be used to solve this.



Global CO_2 emissions in transport by mode in the Sustainable Development Scenario, 2000-70

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Notes: Dotted lines indicate the year in which various transport modes have largely stopped consuming fossil fuels and hence no longer contribute to direct emissions of CO_2 from fossil fuel combustion.

Figure 1.1: Imposed reduction of CO2 emissions 2000-2070 [2]

Carbon neutral fuels are fuels that have a net zero CO_2 emissions. This can be achieved by for instance making use of bio-based fuels which are fuels made from organic matter. Organic matter uses the photosynthesis process to capture CO_2 out of the air when it is growing so it offsets the CO_2 emitted when it is ignited. More recently synthetic carbon neutral fuels are also being researched. Instead of being plant based they are synthetically made with captured CO_2 and hydrogen to make long carbohydrate chains much like fossil fuels, this capturing of CO_2 makes it carbon neutral. Furthermore the combustion of these synthetic fuels is cleaner and creates less harmful fumes [3], which is better for the air quality. This is only the case when the hydrogen is produced from a carbon neutral source if not the synthetic fuel will not be fully carbon neutral.

The transportation sector is still not totally convinced yet on the use of bio-based and synthetic fuels since some of these fuels are still in the early stage of development, little information is available which gives rise to doubts about its viability. More research is needed to make these fuels truly a viable alternative. The behaviour of the fuel, fuel properties and the economic viability are in need of more research. Currently, carbon neutral fuels are often used in combination with fossil fuels in order to decrease overall emissions while still allowing for compatibility with traditional engines.
In diesel combustion engines the fuel does not only provide power but also provides essential lubrication to the fuel circuit, including the fuel pump and fuel injectors, which would wear out quickly without the lubricating properties of the fuel [4].

This report aims to provide a comprehensive examination of the lubricating properties, wear prevention capabilities, and viscosity of alternative fuels in comparison to diesel. Furthermore, it seeks to establish a correlation between these properties in order to gain a deeper understanding of their interdependence.

2 Background information

The following chapter covers the necessary theory and information related to fuels, such as a thorough explanation of the various types of fuels, essential terminology, and relevant material properties.

2.1 Terminology

The research and experiments handled in this project are part of rheology. Rheology is a study that covers the deformations and the flow of matter for solids and liquids. This report will mainly focus on tribology. Tribology is a substudy of rheology which focusses on the interaction between two surfaces in relative motion, this includes friction and lubrication. Friction is a force that opposes the relative motion and it occurs when two surfaces move at a relative velocity of each other while remaining in contact. This friction causes wear to the surfaces and is the cause for losses in the system and damage to machines. Lubricants can be used to reduce these occurrences. Lubricants are explained in further detail in chapter 2.2.3.[5].

2.2 Material properties

This section gives a deeper explanation of all the important material properties that are discussed in the report to give a clear image of what is meant by them.

2.2.1 Density

An important property of fuel is the density. It is measured in mass per unit volume. A high density fuel is often related with a higher volumetric energy density. Densities of biofuels are generally higher than densities of diesel, however the mass energy density of biofuels are much lower therefore the larger density only partially compensates.[6]

2.2.2 Viscosity

Viscosity is a measure for the resistance to deformation in a fluid. As a general rule, higher viscosity is indicative of a thicker consistency of a liquid. There is a distinction between two types of viscosity: kinematic and dynamic viscosity. Where the dynamic viscosity also incorporates the density of the fuel whereas the kinematic viscosity does not. Dynamic(μ) and kinematic(υ) viscosity is described in formula 2.1 & 2.2 respectively.

$$\mu = \frac{Shear\ stress}{Rate\ of\ shear\ strain} = \frac{F}{A} \cdot \frac{y}{u} \tag{2.1}$$

$$\upsilon = \frac{\mu}{\rho} \tag{2.2}$$

Where F[N] is the force acting on the fluid, A[m^2] is the surface area that is being affected, $\frac{y}{u}$[s] is a measure of the speed of deformation and $\rho[\frac{kg}{m^3}]$ being the fluid density.
In real world applications the dynamic viscosity is the most important, therefore this report will focus on dynamic viscosity.

Fluids can be classified in two groups, newtonian fluids and non-newtonian fluids. Newtonian fluids have a constant viscosity which is independent of the shear rate whereas non-newtonian fluids have a viscosity that changes depending on the shear rate [7].

The flow and spray characteristics in an engine are all affected by the viscosity. A higher viscosity will lead to more pumping losses and negatively impact the flow and spray characteristics. These losses will convert to an increase in fuel consumption. With regard to only these factors, a lower viscosity will result in better fuel economy, this however does not take into consideration the lubricity and how viscosity is related to it.

2.2.3 Lubricity

Lubrication is the process of reducing friction and wear between two surfaces in contact. It is an essential aspect of machine operation, as it helps to reduce the amount of heat and wear generated during a mechanical process. Having a well lubricated engine greatly helps to improve the overall efficiency and helps to prevent overheating and damage to components.

Lubricity is a measure for how well a lubricating agent helps with the lubrication of the machine. Lubricity cannot be measured directly like speed or density in gram per liter, it can only be quantified by performing experiments and setting some arbitrary rules for a quantification. There are several ways to define the lubricity of a medium.

A currently used standard for testing lubricity in diesel and liquids alike is based on moving a pin over a plate at high frequencies that is submerged in the liquid that is to be tested at a controlled temperature, a so called high frequency reciprocating rig (HFRR)[8]. Diesel fuels currently need to comply to standards in a certain range set by ISO (International Organization for Standardization)[9], the diameter of the wear that has occurred after a test is measured and compared for different liquids. By doing this, the size of the diameter is a quantification of the lubricity of the liquid. Another method is to measure the coefficient of friction, see chapter 3.1. The coefficient of friction is however dependent on many parameters, it can fluctuate strongly during an experiment.

2.3 Wear scar

During experiments wear occurs at the point of contact, after the test this wear is measured by making use of a digital microscope. The wear scar is defined as the area of material loss or damage resulting from this mechanical wear. A deeper explanation on the wear scar is given in chapter 4.5.

2.4 Tested Fuels

Diesel
Diesel is a type of fossil fuel derived from crude oil, consisting mainly of hydrocarbons and typically used in diesel engines. It is known for its high energy density and relatively high cetane number which allows for efficient combustion in diesel engines. Diesel is used in a wide range of applications including transportation, power generation, marine propulsion, mining , construction and agriculture industries[10].

MGO
Marine gasoil (MGO) is a type of fossil fuel that is composed entirely of distillates, derived from crude oil through the process of fractional distillation. These distillates are condensed from the gaseous phase into liquid fractions and are then blended to form marine gasoil. This type of fuel is similar to diesel fuel, but has a higher density due to its higher concentration of distillates[11].

FAME
Fatty acid methyl esters is a biodiesel. FAMEs are chemically similar to diesel fuel, but have lower carbon content and produce fewer emissions when burned. FAMEs are made from sources like vegetable oils, animal fats, waste cooking oils, and their composition varies based on the source material[12].

OMEs
Oxymethylene ethers (OME) are synthetic fuels which are produced with hydrogen and CO_2. The hydrogen can be produced using renewable energy and the CO_2 can be captured out of the air, which could make this fuel potentially carbon neutral. Since OMEs show potential they are currently intensely investigated. The fuels exhibit promising fuel properties and combustion characteristics with strongly reduced particle and NOx emissions. OME fuel can potentially be carbon neutral since it uses just as much CO_2 in the production process as its emits while burning. OMEs can have different chain lengths an can be chemically described as $CH_3O(CH_2O)_nCH_3$, with n being the chain length, in this report OME and its chain length is described as $\mathrm{OME_n}$ [13].
These OMEs also have potential to be mixed in with well established fuels. In this report $\mathrm{OME_{3\text{-}6}}$ diesel blends are used which are indicated as such: OME25x in this case the blend consists of 25% $\mathrm{OME_{3\text{-}6}}$ and 75% diesel.

HPO

Hydrotreated pyrolysis oil is a biofuel produced through the pyrolysis of biomass, which is the decomposition of organic matter through high heat in the absence of oxygen. The resulting oil is treated with hydrogen gas under high pressure and temperature in the presence of a catalyst to remove impurities and convert it into a more stable form. This oil is rich in hydrocarbons and can be used as a substitute for fossil fuels in power generation, heating, and transportation. It is also considered to be a cleaner and more sustainable alternative. It can be upgraded further to produce renewable diesel or jet fuel[14].

3 Setup

This chapter will go over the tools and formulas that are used in the experiments. It explains in depth how the tribometer works, how the microscope measures the wear scar and how the viscosity is measured.

3.1 Tribometer

For the measurements of the lubricity of fuels an Anton Paar rheometer MCR 302 will be used, shown in figure 3.1. This rheometer is equipped with a ball on three metal plates measurement cell a clear image of the measurement cell is shown in appendix C figure 10.1. It has some improvements compared to the older HFRR, it has a larger operating range and because it makes use of a rotational shaft the readings are far more accurate.[15] There are certain variables the rheometer can adjust, some of which are: temperature, normal force of measuring ball and rotational speed. The provided torque can be accurately measured and it can calculate the coefficient of friction of the system.
After each experiment the ball and the plates have to be replaced to make sure all test conditions are the same for new experiments.

Figure 3.1: Anton Paar Rheometer

3.1.1 Calculating the coefficient of friction

As explained before, the lubricity of different fuels will be evaluated. This will be done by making use of the tribology measurement system. The rheometer makes use of a ball on tree steel plates configuration, the ball is pushed onto the three plates with a specified normal force and is rotated with a certain speed, the provided torque is measured and from this the friction coefficient can be calculated, see fig.3.2.

The coefficient of friction is a measure of the resistance to motion between two surfaces in direct contact, often times with a thin film of lubricant between the two surfaces. It is defined as the ratio of the force of friction between the two surfaces to the normal force pressing the two surfaces together. The coefficient of friction can vary depending on the materials of the two surfaces and the properties of the lubricating agent when used. It is generally represented by the symbol μ and is given as a value between 0 and 1, with higher values indicating a greater resistance to motion[16].

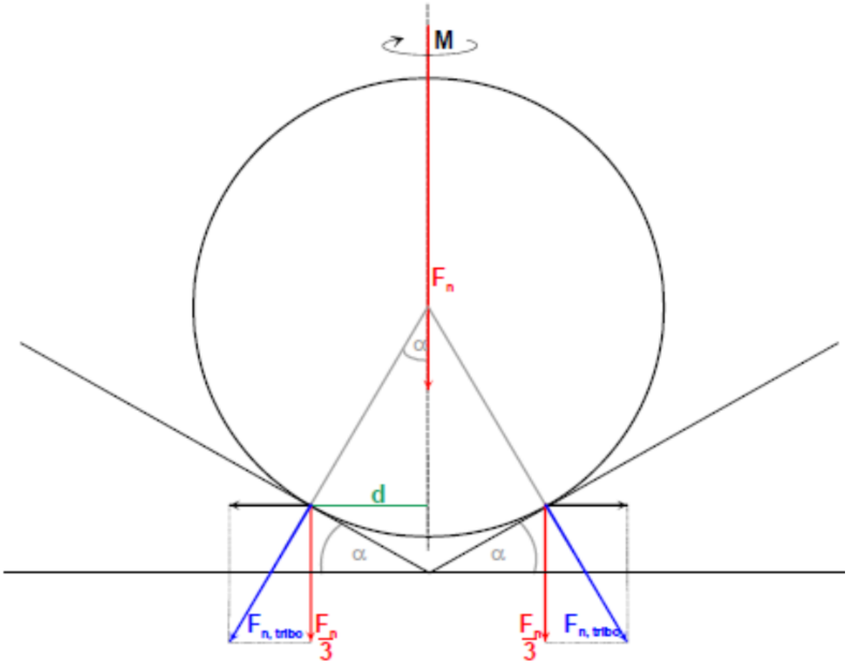

Figure 3.2: Schematic view of ball on three plate setup. [17]

To get the coefficient of friction, the friction force F_f, and the normal force $F_{N,tribo}$ is needed.

$$F_f = \frac{M}{3 \cdot r \cdot sin(\alpha)} \tag{3.1}$$

With M representing the measured torque the motor supplies, α representing the angle of the plates, and r being the radius of the measuring ball, see fig. 3.2
$F_{N,tribo}$ is the normal force that is applied by the one of the three steel plates, because the ball does not align perpendicularly, equation 3.2 needs to be applied.

$$F_{N,tribo} = \frac{F_N}{3 \cdot cos(\alpha)} \tag{3.2}$$

F_N is the normal force actually applied over the length of the shaft.

The dynamic coefficient of friction μ is calculated using equation 3.3

$$\mu = \frac{F_f}{F_{N,tribo}} \tag{3.3}$$

3.1.2 Viscosity measuring

The measuring of the viscosity is also done using the same tribometer, but with the use of a different measurement cell. This measurement cell is called a "double-gap cylinder"[18][19].
A double-gap system is a type of device used to measure the viscosity of low-viscosity liquids. It consists of a cup with a second cylinder inside, and a probe that fits between the outer and inner walls of the cup. The probe has a large surface area that comes into contact with the liquid being measured, which allows it to detect even small amounts of torque generated by the liquid. This makes double-gap systems particularly useful for measuring the viscosity of low-viscosity liquids.

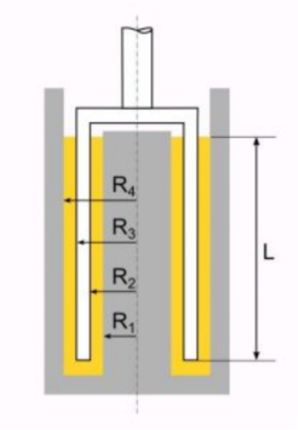

Figure 3.3: Double gap viscosity measuring system.

3.2 Microscope

As explained in chapter 2.3 it is important to know the wear scar of a specific test, it is a measure for the lubricity of the liquid. The wear scars that occurs on the plates can be very small and are difficult to measure with the naked eye, that is why a microscope is used. An "amscope" camera is inserted into a microscope, where the lens is normally located. Pictures are taken of all the different plates on which wear has occurred, the exact same resolutions are used for all the plates so the images are equal for all fuel tests. The diameter of the wear scar can be measured using the microscopes software of the microscope.

4 Experiments

4.1 Literature review

This report continues on the bachelor final project of Hessel Kweens at the TU/e[17], in this report many tests have been done on multiple fuel types. The tests that were conducted were so called rpm sweeps. This is a test where the normal force, and temperature are of constant value, but the rpm are logarithmically increased from 0 to 3000 RPM after this the rpm are decreased back to 0 RPM again. The value of the friction factor is calculated at a set interval and the results are shown in figure 4.1.

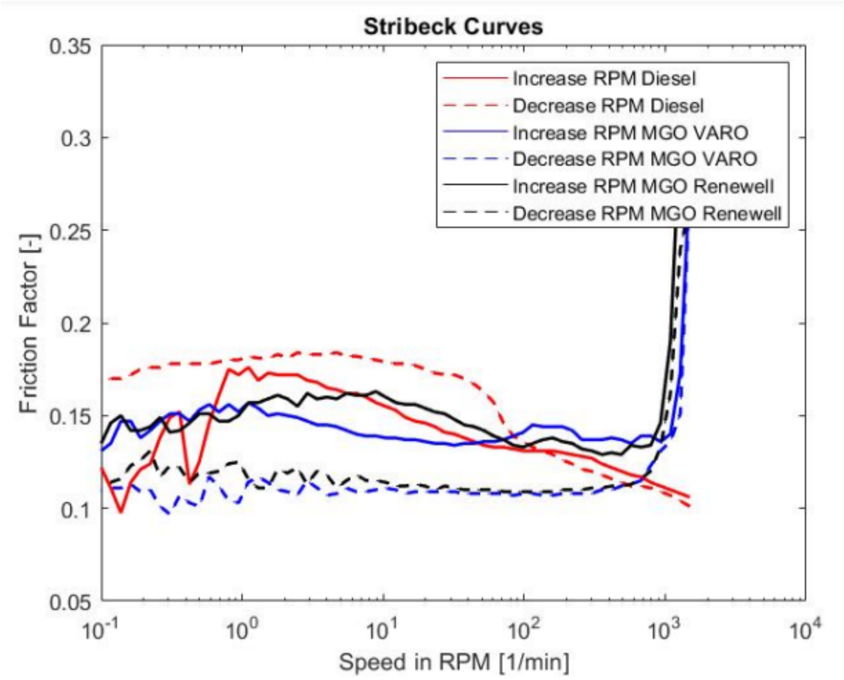

Figure 4.1: Stribeck curves of fossil fuels experiments Kweens.[17]

The report states that when performing such a test the first part of the test should have lower values for the friction factor than the second part of the test due to the wear that has occurred during the first part. It states that the occurrence of wear will cause more friction. Based on this increase in friction at the end compared to the beginning, assumptions are made about how well a fuel lubricates and thus prevents wear.

4.2 Improvements on previous work

In the last chapter Kweens[17] mentioned that an improvement to his research could be to have experiments at a constant rpm and temperature for a longer period, following the recommendation it would possible to see the influence of time on the experiments. Because if the coefficient of friction also fluctuates over time it is not possible to make a clear correlation between the COF and rpm of a specific fuel.

In order to test this, a test with a constant rpm of 1500 and at a temperature of 25°C was conducted for only diesel and $OME_{3\text{-}6}$. The tests have been conducted multiple times to make sure they are reproducible. See fig.4.2

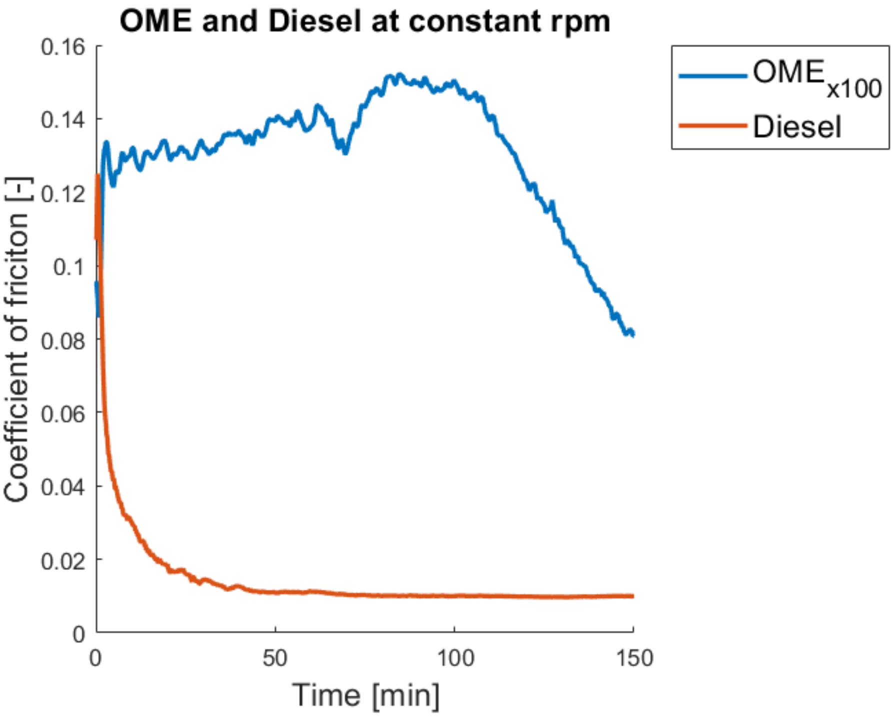

Figure 4.2: Diesel and OME at constant RPM

The data presented in Figure 4.2 illustrates the COF of diesel and OME over a period of time. The initial COF for diesel is observed to be high, however, it rapidly decreases and reaches a steady state at a considerably lower value after approximately 50 minutes. The COF of OME even begins below diesel but rapidly jumps to a higher value after which it steadily increases for 100 minutes, after which a sudden transition to a linear decrease in COF is observed.

The tests from the previous study[17] were reconstructed using the same methedology, but with the same sample fuels as in 4.2, this experiment took only 6 minutes compared to the 150 minutes of the constant rpm test. Results of this test are shown in figure 4.3.

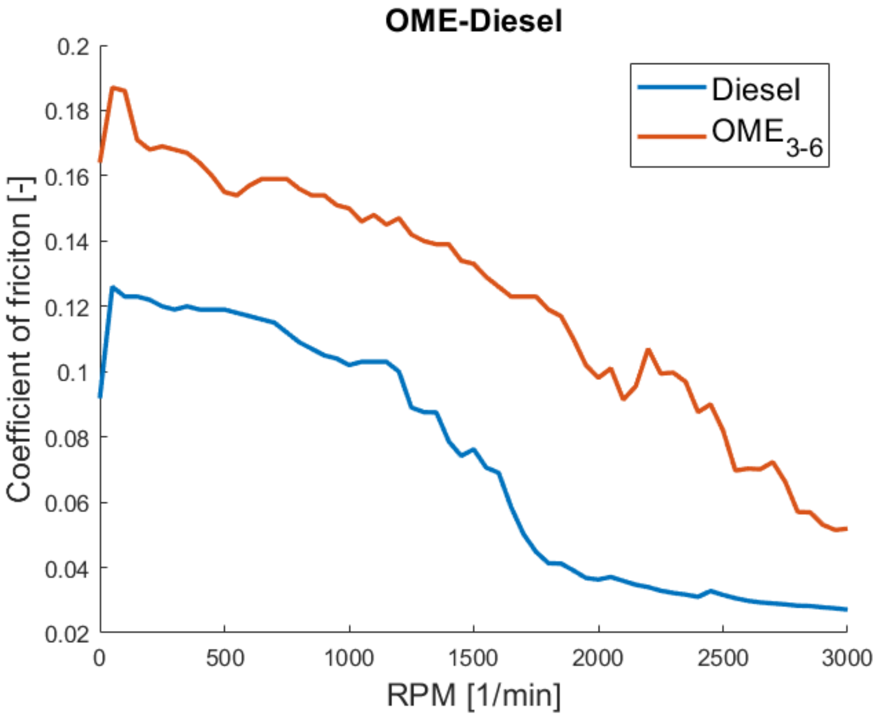

Figure 4.3: Diesel and OME at increasing RPM

The COF between diesel and OME fuels are found to be relatively similar when analyzed through an RPM sweep test. The results of this test reveal that the COF of diesel ranges between 40-60% of that of OME. However, when analyzing the constant RPM test as depicted in figure 4.2, a substantial difference in COF is observed. The results of this test indicate that the COF of diesel ranges between 8-13% of that of OME. This significant disparity in results suggests that the RPM sweep test has to short of a timescale to provide sufficient data to make accurate assumptions regarding the lubrication properties of these fuel types.

4.3 Measure for lubricity

In chapter 2.2.3 it is explained that currently diesel fuels have to comply to standards set by the EN590 which are based on a wear scar that is measured after doing a 90 minute test on a high frequency reciprocating rig[9]. The experiments that are conducted in this report cannot directly be compared to this standard because the friction is applied and measured in a different manner, this is described in more detail in chapter 3.1.
During this research a different measuring method is used, see 3.1. This is a relatively new method and therefore lacks standardized testing protocols. As such, it will be necessary to carefully select appropriate parameters for the experiments. Further research and development of standardized testing protocols i are needed to facilitate comparison of results across different studies using this measurement setup [20].

As demonstrated in the figures of Appendix B, the COF is not a constant value and exhibits a significant degree of variability across different fuels. The COF curves for some fuels exhibit a wide variation, with some fuels failing to reach equilibrium within the 150-minute timeframe, while others achieving equilibrium in less than 50 minutes. Therefore, it can be concluded that using a single value for the COF after at a fixed time does not provide a comprehensive understanding of the lubrication properties of a fuel and thus is an incomplete method of quantification.

The best way to take all these factors into account is to measure the exact amount of energy that the motor has to provide to overcome this friction, this method incorporates everything that affects the friction during the entire tests.

This quantitative measure for lubricity can be obtained by measuring the total energy lost due to friction over a specified time period. This approach allows for direct comparison of the lubricating properties of different fuels, providing a valuable metric for assessing their potential viability, such a measure can be calculated using equation 4.3.

$$W = \Delta\theta \cdot \tau \tag{4.1}$$

With W[J] being the total work that is done, $\Delta\theta$ [rad] being the total angular displacement, and τ[Nm] being the torque applied. Since the applied torque is not a constant value, it has to be evaluated at every single point and integrated over time.

$$dW = \omega\tau dt \tag{4.2}$$

dW is the work done over a infinitesimally small timeframe. ω is the rotational speed $[\frac{rad}{s}]$, and t is the time[s].

$$W = \int_{t_0}^{t_n} \omega\tau dt \tag{4.3}$$

After integration equation 4.3, becomes the equation for frictional work done during a specified time period from t_0 to t_n.
With this formula a constant RPM can be used but also data with a changing rpm. It will give the exact amount of energy the motor has provided in Joules.
When the motor is starting up and still increasing its rotational energy, not all energy is converted to frictional energy. When the motor has reached a constant rotational speed all the energy the motor provides to the system is dissipated through friction.

These equations will be implemented in a matlab script to get a numerical result of each test with different parameters. Because only discrete datapoints can be collected from the tribometer the continuous equation 4.3 needs to be modified so it can be approximated using these discrete numbers.

$$W = \sum_{i=0}^{i=n} \omega_i\tau_i\Delta t \tag{4.4}$$

With i being the index of the datapoints, n being the total amount of datapoints, and Δt being the time interval between datapoints. The value W refers the total friction in the rest of the report.
To test the reproducibility of this measure for lubricity multiple tests were conducted of which standard deviations were calculated, standard deviation and reproducibility are positively correlated, with low standard deviation indicating high reproducibility in measurements. The standard deviations of the lubricity are shown in appendix A.

It is important to note that no method of quantifying lubricity is perfect. The lubrication properties of a fuel are influenced by a variety of factors and not all of these can be captured in a single numerical value. This lubricity quantification is merely a representation of the lubrication properties of a fuel and is only an approximation of its actual performance. It should be noted that even though a numerical value can provide an indication of how well a fuel lubricates, it does not provide a complete picture of the fuel's performance over time. For example, a high lubricity value at certain conditions does not necessarily indicate that the fuel will maintain that level of lubrication under different circumstances. This number can give indications on the lubricity, yet it is still crucial to consider the performance of the fuel for each specific application when evaluating its lubrication properties, and not rely on a single number to draw definitive conclusions.

4.4 Viscosity

As mentioned in 2.2.2 viscosity measures the resistance to deformation of a liquid. The viscosity of a fluid is temperature dependent and their relation can be described as in4.5[21].

$$log(\mu) \propto \frac{1}{T} \tag{4.5}$$

As the temperature increases the viscosity exponentially decreases, the consistency of the fluid becomes less thick. To get a value for the viscosity for different fuels at different temperatures the measurement cell described in chapter 3.1.2 is used.

4.5 Wear

The wear scar diameter after each test is measured, it is important that the plates are renewed after every test and the test duration is the same for every test, so that all tests are comparable.
Figure 4.4 is an example of an image of what a wear scar looks like under the digital microscope.

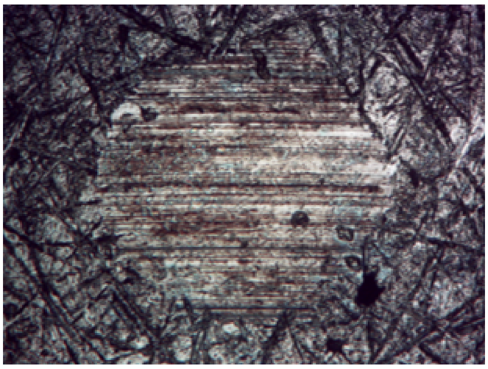

Figure 4.4: Microscopic image of the wear scar captured after testing

At the edges of the image, scuffs can be seen, these impurities are already present in the plates. The horizontal lines that together form a circle is the point of contact where the ball meets the steel plate, these lines align in the direction of the sliding motion. The diameter of this circle is referred to as the wear scar. This wear scar is digitally measured using the camera software. It does not matter which of the three wear scars is measured since due to the high accuracy of the tribometer the forces are evenly distributed, measurements confirm this.

4.6 Testing procedure

The tests that have been conducted need to have clear parameter set, also some tests need to be conducted multiple times to see the reproducibility for the test of each fuel.

Parameters used for the lubricity measurements:

- Rotational speed: 1500RPM
- Temperature: 25°C
- Normal force: 10N
- Fuel volume: 3mL
- Duration: 150 minutes

A rotational speed of 1500 RPM is used since in diesel engines it falls in a normal operating range. The temperature of 25°C is used since the fuels are pumped through the system at around this ambient temperature before combustion. More tests at different temperatures would have been conducted if it were not for the limitations in time and material expenses. A normal force of 10 Newton was arbitrarily chosen, the tribometer has a operating range of 0.01N to 30N so a value around the middle of this range was chosen. The fuel volume is not as important, it has to be enough so the balls and plates are fully submerged. Finally, a test duration of 150 minutes was selected for the experiment. It is worth noting that test procedures similar to this one often have time durations that range from 90 minutes to several tens of hours. After careful consideration of both time management and the desired level of accuracy for the test, it was determined that a duration of 150 minutes represents an appropriate compromise. This duration allows for sufficient time to observe the changes in the lubrication properties of the fuel while still being able to complete the test in a reasonable amount of time.

Parameters used for the viscosity measurements:

- Rotational speed: increased logarithmically 0.1-3000RPM
- Fuel volume: 3.8mL

- OME-Diesel blends temperatures: 25, 40, 55, 70, 85, 100°C
- Other fuels temperature: 25°C

Viscosity testing was done using a measurement template provided by Anton Paar in the operating software of the tribometer. Only the temperature could be changed. Diesel was tested over a temperature range since the lubricity of diesel was also tested at different temperatures, OME-Diesel blends were also tested over this temperature range because it was needed for other research. The rest of the fuels were only tested at 25°C since their lubricity was also only tested at this temperature.

5 Results

This chapter describes the results of the experiments that have been conducted. The results can be categorized into the sections COF, viscosity, and wear scar. Finally the results of each section will be compared with each other into a combined result.

5.1 Viscosity

Tests were conducted according to the test procedures as described in chapter 4.6. The tribometer measures the dynamic viscosity of the liquid. The viscosity of OME-Diesel blends where each measured at six different temperatures. Results are presented in figure 5.1. The other fuels where only tested at 25°C due to limitations of time and material expenses. The viscosity of the other fuels tested at 25°C are shown in appendix A table 8.1

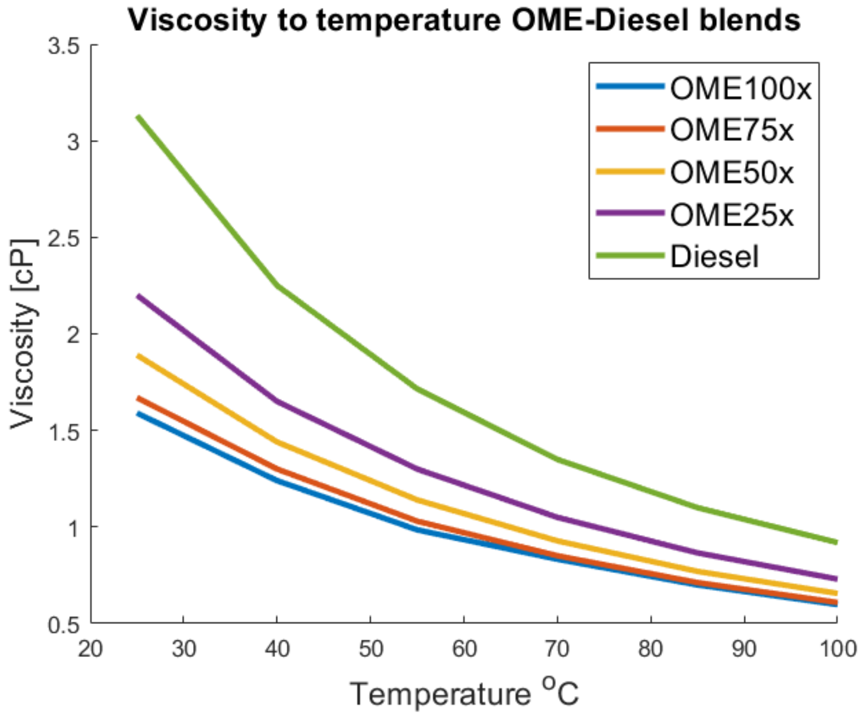

Figure 5.1: Viscosity plotted against temperature of OME, Diesel and blends

The fuels that were tested over a temperature range show a clear correlation between viscosity, blend concentration and temperature directly following equation 4.5.

5.2 Coefficient of friction

The figures show the coefficient of friction of all the fuels over a timespan of 150 minutes. Some tests were conducted multiple times. In order to avoid visual congestion, only one of the performed tests for each fuel is depicted in the figures. Additionally, the graphical representations have been divided into two separate images to improve readability and understandability of the data.

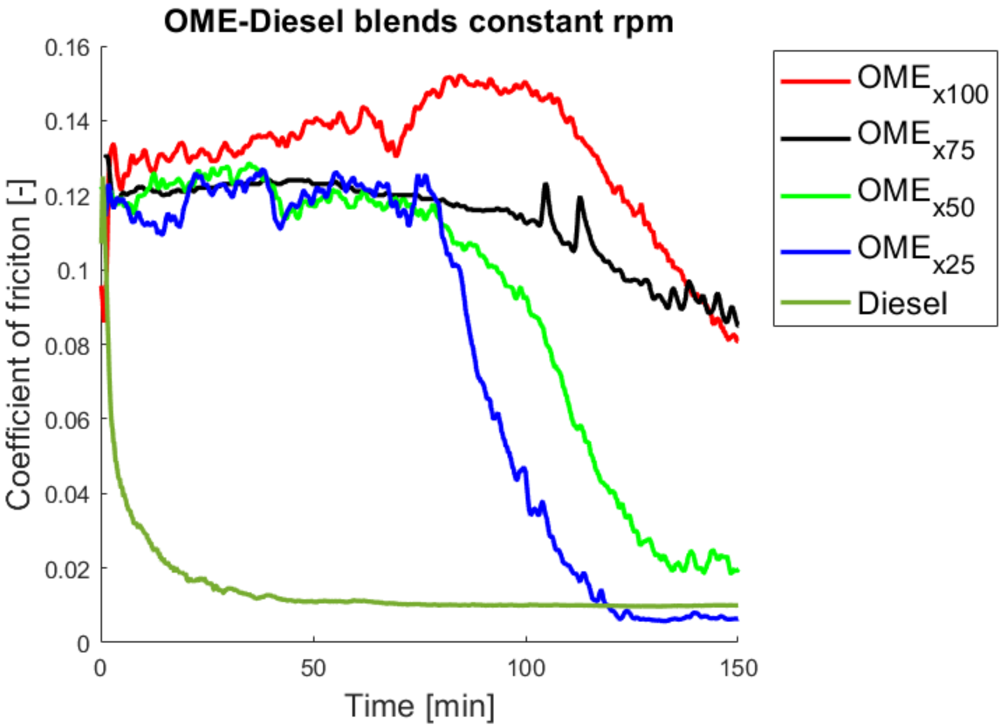

Figure 5.2: OME-Diesel blends COF over time period

Diesel

The results obtained from testing pure diesel fuel demonstrate high consistency. A series of experiments conducted using this fuel source have yielded results that are highly similar to one another. The initial COF values observed are relatively high, however, the COF rapidly declines and reaches a steady, low value. Additionally, the total energy dissipated during these tests is significantly lower when compared to other fuel types.

OME$_{3\text{-}6}$-Diesel blends

The blends start at much higher values than diesel and remains high until they reach a point where the steady COF starts to decrease. This sudden decrease seems be related to the concentration of diesel, the sudden decrease starts out earlier and is more prevalent in fuels with higher concentrations of diesel.

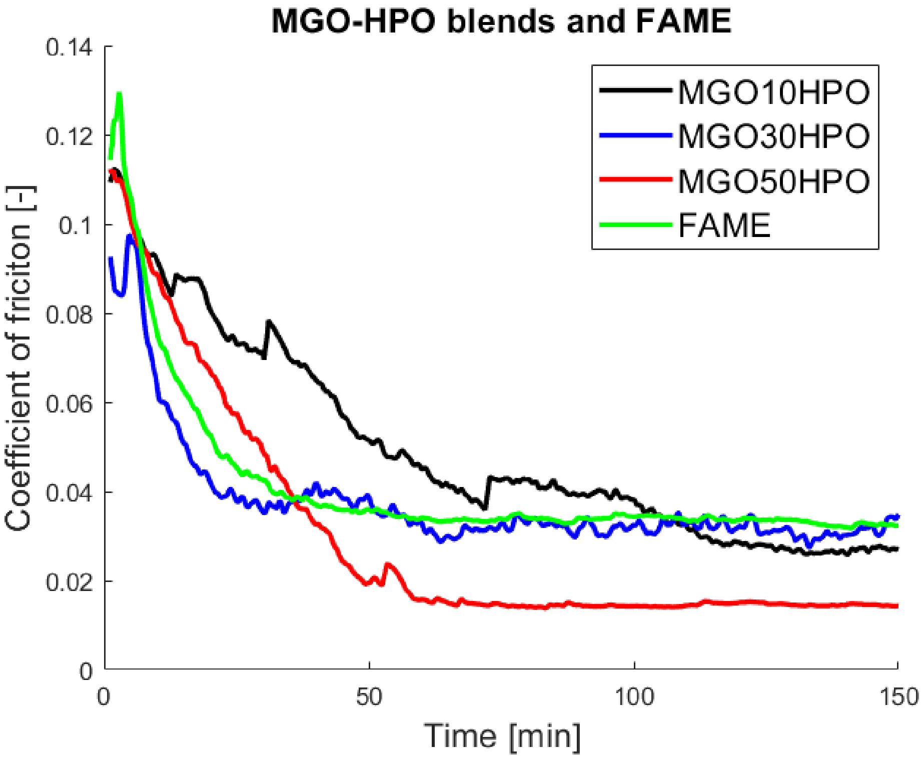

Figure 5.3: MGO-HPO blends, and FAME COF over time period

In figure 5.3 MGO-HPO blends and fame are depicted since they exert similar properties.

MGO-HPO blends
MGO-HPO blends also start out at a higher COF, but these values start to decrease from the beginning. The results of multiple experiments are consistent. In contrast to diesel, for which the COF approached the equilibrium quadratically, MGO-HPO seems to approach the equilibrium more linearly. In these measurements can be seen that a higher HPO concentration will lead to a lower COF value at the equilibrium, these tests were however only conducted once.

FAME
FAME shows many of the same properties, starting at a high COF, decreasing quickly and reaching an equilibrium after 50 minutes.

5.3 Downward slope COF

What is interesting to see is that is all experiments the COF starts out at a much higher value than it reaches after the 150 minutes. This behavior is further studied in this section. The downward movement of the COF suggests that over time something variable is changing which makes the system experience less friction. All variables in the machine have been set to a constant value, even the temperature is kept constant, so the heat generated by friction is not heating the fuel. The decrease of COF is very significant ranging from 25% to even 90%.
The only factor that is changing during the experiment is the size of the wear scar and the addition of steel particles that came of the steel plates or ball into the fuel.

The increase of the wear scar means that there will be a greater contact area between the ball and the steel plates. According to the formulas 3.3 the contact area of the friction should not play a role in the value of the COF as explained in chapter 3.1.

To test if the wear that has occurred has an impact on the COF, a test was done without replacing the ball and plates, the fuel however was refreshed.

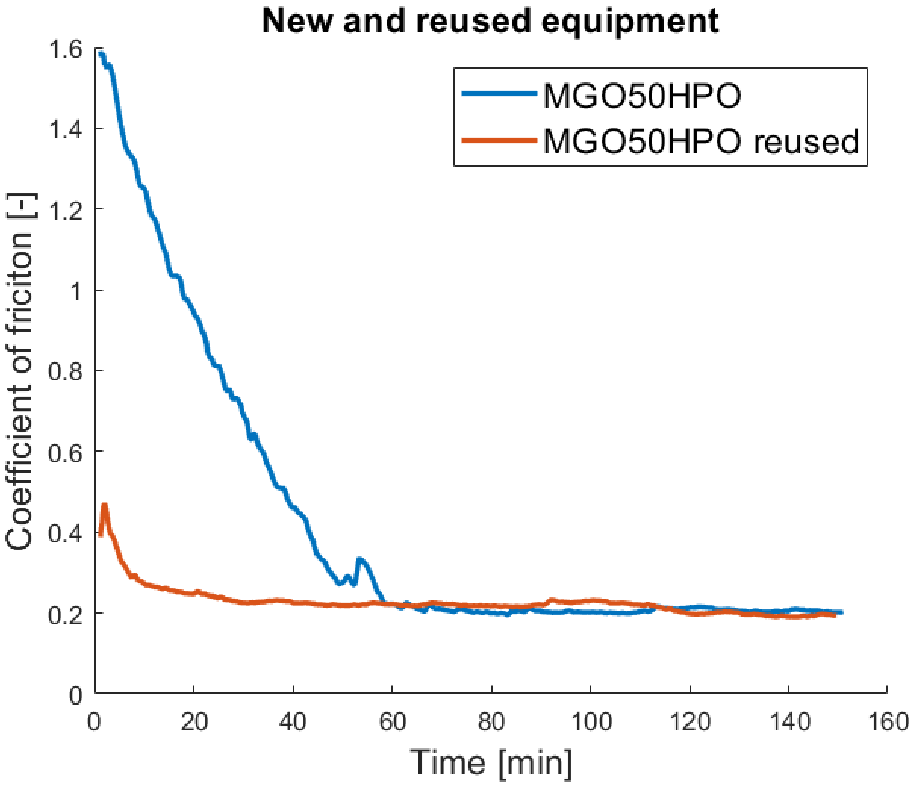

Figure 5.4: Effect of a larger contact area between ball and plates

The second experiment shows that the weared-off plates do have an impact on the COF, it quickly reaches the same value that the first test could only reach after a long time.

This suggests that a larger contact area results in a lower COF, this is because the local pressure is lower at the contact point. Because this local pressure is lower, the lubricant can more easily entrain between the two surfaces which makes it lubricate better.

There is a strong relationship between local pressure and film thickness in lubricated systems. As the local pressure between the surfaces increases, the lubricant film thickness will tend to decrease. This is because the higher pressure causes the lubricant to be squeezed out from between the surfaces, reducing the thickness of the film.
Conversely, as the local pressure decreases, the film thickness will tend to increase. This is because there is less force acting on the lubricant, allowing it to build up between the surfaces and form a thicker film which will decrease the COF [22]. This means that when the COF is high, lots of wear occurs and the wear scar diameter increases rapidly. When the local pressure gets low enough the lubricant is able to get a bigger film thickness, which makes the wear scar diameter increase less quickly until eventually the film thickness gets large enough that only minimal wear occurs.

5.4 Combined results

In this section, a comprehensive analysis of the accumulated results from all of the tests will be conducted to determine the correlations between viscosity, friction, and wear scar.

In figure 5.5 the relation between the viscosity of a fuel and the total friction are plotted, the total friction is quantified as explained in chapter 4.3.

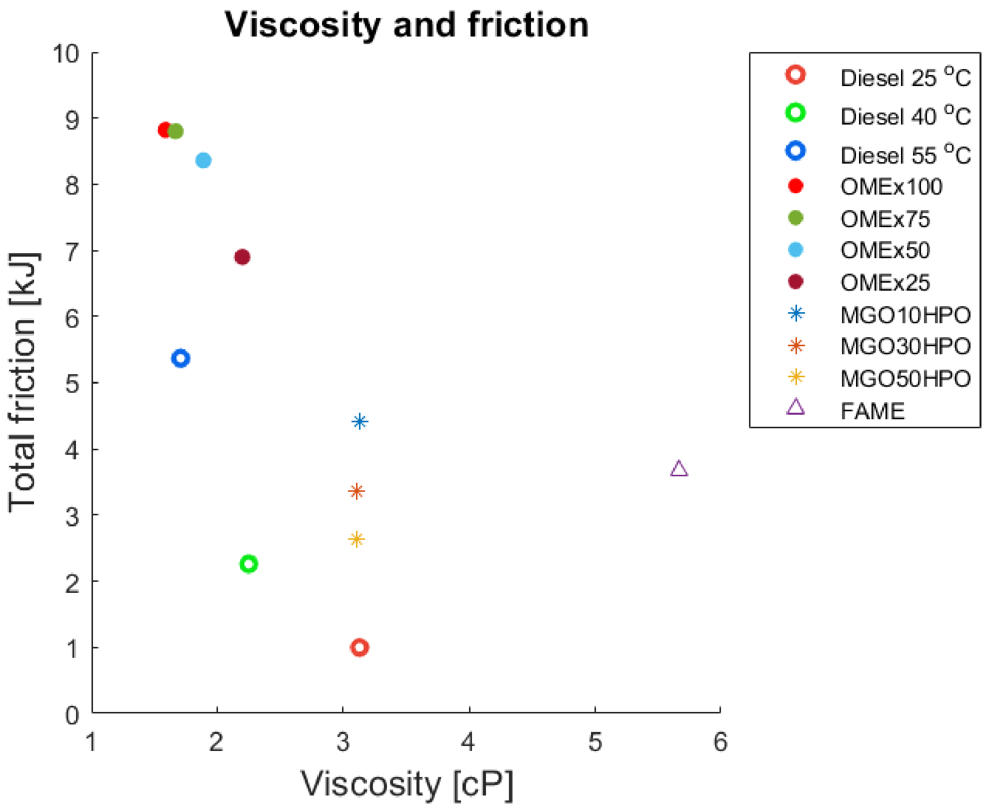

Figure 5.5: Results of the total frictional energy dissipated plotted to the viscosity of the fuel.

In figure 5.5 the datapoints are put into a scatterplot and grouped into four categories: Diesel at different temperatures, OME-Diesel blends at different concentrations, MGO-HPO blends at different concentrations, and FAME. Tests that were conducted multiple times were averaged out, standard deviations of these results can be found in appendix A.

When looking at all the datapoints together, there does not seem to be a strong correlation between the viscosity and the lubricating properties. However if the fuel groups are analyzed separately correlations can be seen.

Diesel

The diesel was analyzed at 3 different temperatures. As presented in figure 5.1 the viscosity decreases as the temperature increases. There is a clear correlation between the viscosity and lubricity in this regard, diesel at 25°C shows the best lubricating properties of all fuels, which drastically worsens when increasing the temperature. This test isolates the viscosity, well since the temperature is the only differing factor which is known to have a direct effect on the viscosity as explained in chapter 2.2.2 [21]. The other categories do not isolate the viscosity as well as this category does.

OME-Diesel blends

This category consists of OME-Diesel blends at different concentrations. Note that "Diesel 25°C" can also be included in this category since it is the same as OMEx0. OME has a low viscosity and significantly worse lubricating properties compared to the other fuels, this is also represented in the figure. The datapoints show that the blends are in between the two extreme points of 100% and 0% concentration of OME. The fuels follow a negative nonlinear correlation between the viscosity and lubricity. These two fuels have different lubricating properties, blends with a higher concentration of diesel will have properties more close to diesel and vice versa. It is interesting to note that with even though the concentrations are increased linearly, the viscosities and lubricities do not conform to a linear correlation.

MGO-HPO blends

MGO has a slightly higher viscosity than that of HPO, which causes these three fuels to have a viscosity that falls in a very narrow range, the viscosity is very similar to the viscosity of diesel. The lubricity however does vary by significantly, the fuels with higher concentrations of HPO show better lubricating properties.

FAME

FAME is the only datapoint in this category, the viscosity is almost double that of diesel. FAME does not not show remarkably good or bad lubricating properties.
Figure 5.6 shows the wear scar diameter plotted to the total friction.

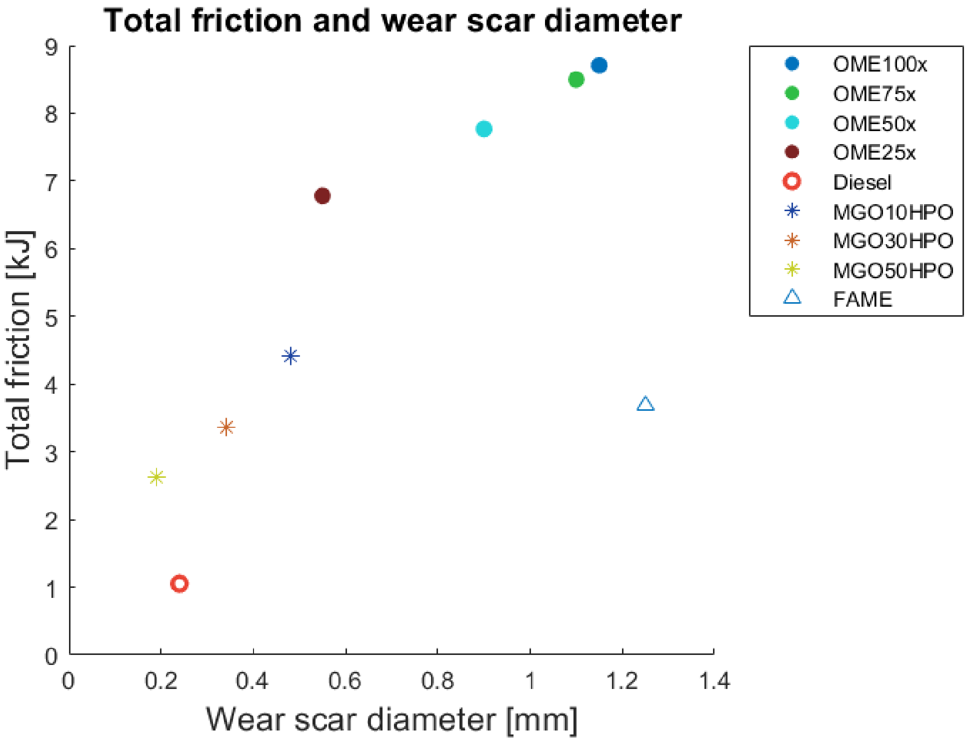

Figure 5.6: Total friction plotted to the wear scar diameter

There is a strong correlation between total friction and the wear scar diameter. The more friction has occurred the larger the wear scar diameter is. All fuels but FAME follow this correlation. It should be noted that the dataset for wear scar diameters is smaller than that of the total friction.
Similar studies show that an increase in COF will lead to an increase in wear scar [23].

6 Conclusions

With the results shown in the previous chapter conclusions about each fuel can be made, furthermore a relation between viscosity, lubricity and wear protection is made.

The viscosity of a liquid and lubricity show a correlation, a higher viscosity generally makes for a better lubricant, FAME however shows that if the viscosity gets too high, more friction will be present. Lubricants at higher temperatures, and thus lower viscosities also provide worse lubrication. The MGO-HPO blends show that the lubricity is not solely dependant on viscosity, some fuels exert better lubricity at similar viscosities.

It is clear that the wear is related to the total friction that has occurred during the test, the more total friction has occurred during the test the larger the wear scar diameter, FAME however does not seem to follow this relation.

Measurements obtained during the test, indicate that there is an increase in the contact area due to wear. This increase in contact area results in a decrease in the local pressure. A lower local pressure facilitates a better entrainment of lubricant between the contact surfaces. Which will lead to an increase in the film thickness, and subsequently decreases the coefficient of friction. The wear scar diameter will increase until the coefficient of friction lowers to such a value that minimal additional wear occurs.

Diesel exhibits excellent lubricating properties. In contrast, the lubricity of OME is significantly inferior, even with a blend containing as little as 25% OME and 75% diesel, resulting in a sevenfold increase in friction when compared to pure diesel.

HPO gives promising results, mixed with MGO. Blends with a higher concentration of HPO provide more lubrication than blends with a lower concentration HPO. Yet 50% HPO-50%MGO blends still have a total friction 2.6 times higher than that of diesel.

FAME is a fuel that exhibits a significantly higher viscosity than the other fuels that were tested. This significantly higher viscosity may contribute to the observed fourfold increase in total friction during the tests, when compared to diesel fuel.
Overall in scope of lubricity OME does not seem that of a substitute to diesel even when considered at smaller concentration blends. HPO however does seem like a good substitute but the tests where only conducted once so the reproducibility is not that high.

7 Reflection

I think overall there are some pretty strong conclusions, which are constructed well. Yet there are some inconsistencies, mainly in the amount of times some experiments were done. The wear scar diameter measurements where mostly only done once, this is because the idea to measure the wear came up later in the project and at that time the weared-off plates where already discarded so no more testing could be done on them.

The total friction tests were conducted over a timeperiod of 2.5 hours, most diesel engines rarely operate for this long at a constant rpm, the total friction is only an approximation but I think it provides a better understanding than just measuring the wear scar diameter in a conventional HFRR setup.

The total friction is in my opinion a fairly good quantification, however the total duration of the test is of great importance for this quantification. For some fuels the COF quickly falls to a low value making the total energy consumed much lower than that of fuels which take much longer to fall to a lower value.

In some OME tests the equilibrium value was not yet reached after 2.5hours. It could have been interesting to see what these values were, but then the measurement for the wear scar diameter would not be comparable anymore.

The MGO-HPO blends were only conducted once so it is difficult to make a strong conclusion on that.

The COF curves of diesel at different temperatures show interesting behaviour, unfortunately there was not enough time to go do more meaningful research about this phenomenon.

Further research could provide a little more data on the wear scars, perhaps testing on more fuels at varying temperatures. Other than that I do not think this experimental setup can provide much more information on this topic, testing using real engines would in my opinion be the best way to properly investigate how each fuel interacts with the engine.

8 Appendix A

Table 8.1: Summary of key measurements and parameters

Fuel	**T [°C]**	**Viscosity [cP]**	**Total friction tests[kJ]**	**Total friction average ±SD [kJ]**	**Wear-Scar [mm]**
Diesel	25C	3.13	1.12;0.961	1.055 ±0.0675	0.55
Diesel	40C	2.25	2.26	2.26	
Diesel	55C	1.75	5.37	5.37	
OME3-5	25C	1.57	16.5	16.5	
OME100x	25C	1.59	8.51;8.71;9.85	8.82 ±0.590	1.15
OME75x	25C	1.67	8.50;9.10	8.80 ±0.30	2.7;0.8
OME50x	25C	1.89	7.77;8.95	8.36 ±0.59	0.9;0.9
OME25x	25C	2.20	6.78;7.01	6.9 ±0.115	0.55;0.4
MGO10HPO	25C	3.13	4.42	4.42	0.56
MGO30HPO	25C	3.11	3.37	3.37	0.34
MGO50HPO	25C	3.10	2.64	2.64	0.19
FAME	25C	5.67	3.68	3.68	1.25

Table 8.1 includes all the data collected during this research. Total friction is the total energy consumed by the tribometer as explained in chapter 4.3. The third row shows the average total friction and standard deviation for experiment setups that were tested more than once.

9 Appendix B

This appendix includes the COF-time graphs of all experiments that were included in the report, they are grouped by fuel type. If multiple tests where conducted with the exact same parameters(fuel and temperature) the last digit in the legend shows the index number of the experiment.

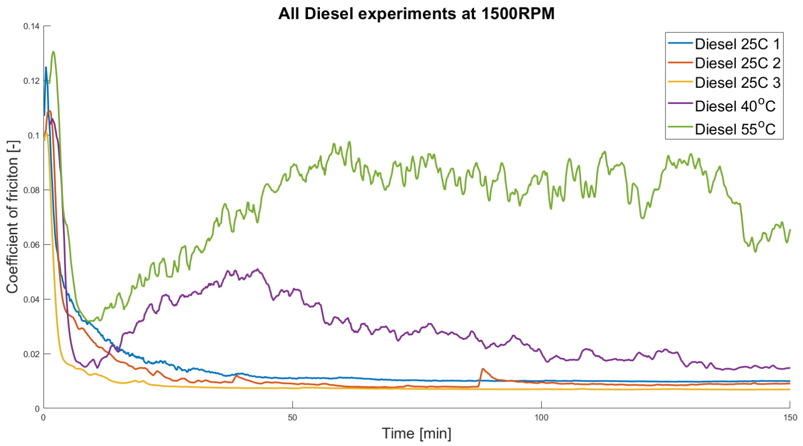

Figure 9.1: All experiments at a constant 1500 rpm for diesel

In figure 9.1 all diesel experiments at 1500 RPM can be seen.

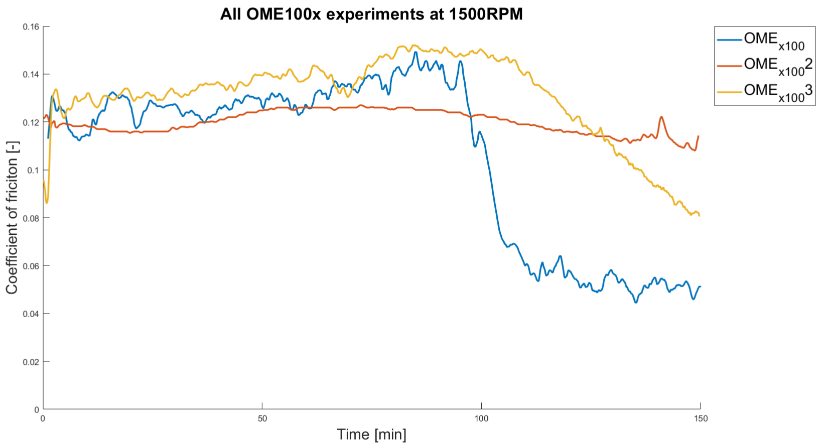

Figure 9.2: All experiments at a constant 1500 rpm for OME100x

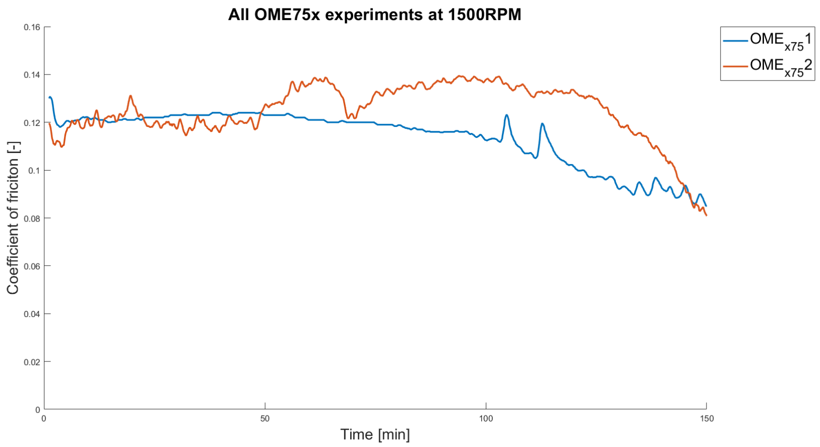

Figure 9.3: All experiments at a constant 1500 rpm for OME75x

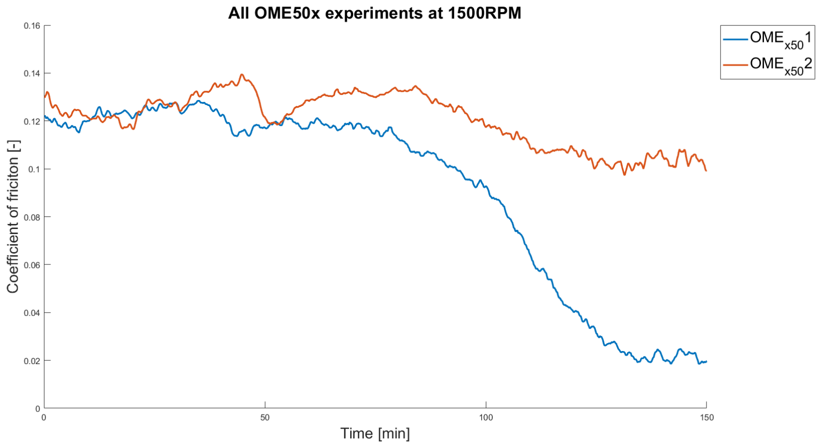

Figure 9.4: All experiments at a constant 1500 rpm for OME50x

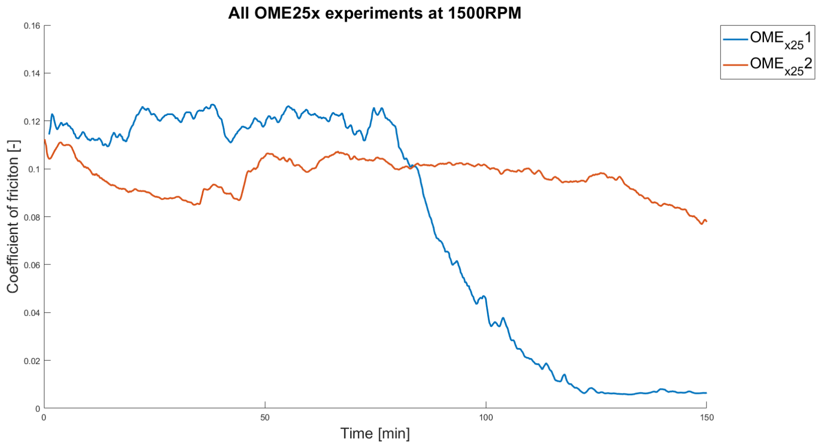

Figure 9.5: All experiments at a constant 1500 rpm for OME25x

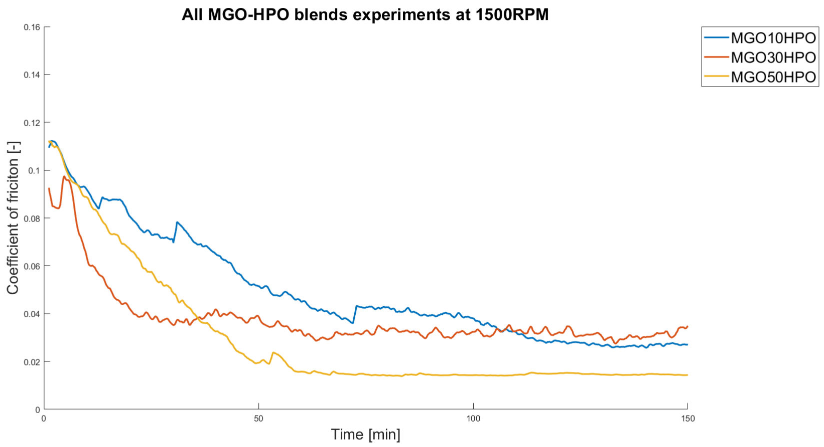

Figure 9.6: All experiments at a constant 1500 rpm for MGO-HPO blends

10 Appendix C

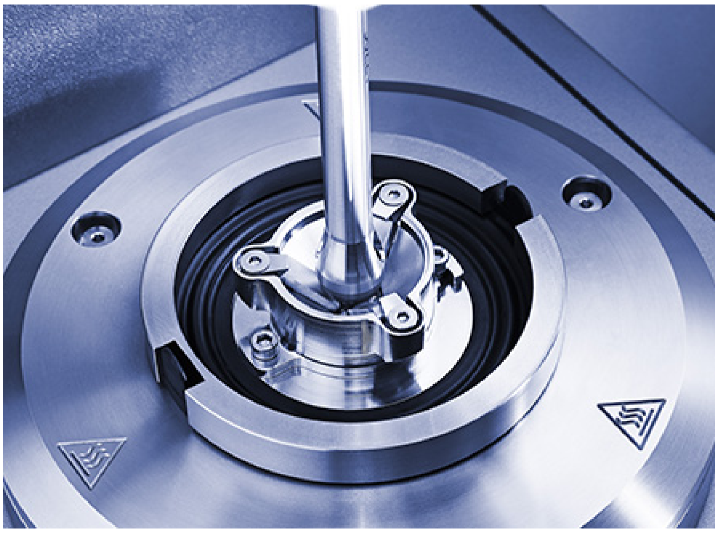

Figure 10.1: Ball on three plates measurement cell

Measurement cell that was used for the measurement of the COF.

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