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Investigation of the lubrication properties and tribological mechanisms of oxygenated compounds

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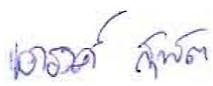
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0523 E. Sukjit, P. Poapongsakorn, K. D. Dearn, M. Lapuerta and J. Sánchez-Valdepeñas

1   **Investigation of lubrication properties and mechanisms of oxygenated compounds**

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11

12   **Abstract**

13   Lubrication properties and mechanisms of various oxygenated compounds were

14   investigated. High-frequency reciprocating rig (HFRR) was applied to measure the lubricity. The

15   effect of humidity, functional group, carbon-chain length, and unsaturation on the lubricity of the

16   oxygenated compound were studied. After the lubricity test, microscopic observation of disc

17   specimens was made in a scanning electron microscope (SEM). The functional moieties were

18   found to be the factor that significantly influenced the lubricity and the sensitivity to humidity of

19   the oxygenated compounds. Abrasive wear was the dominating mechanism for all of the

20   oxygenated compounds. As the vapor pressure increased, wear became more severe due to the

21   contribution of corrosion. While, chain length and unsaturation seemed to have an insignificant

22   effect on lubricity of the fatty acid methyl ester.

23   Keywords: Lubricity, Oxygenated compounds, Wear scar, Humidity.

1 **1. Introduction**

2   Several new technologies have been developed to increase the potential of fuel

3 combustion and decrease engine-out emissions in compression ignition engines. For example,

4 the common-rail systems achieve the high injection pressure to enhance the fuel atomization

5 leading to better air mixing, faster fuel evaporation and more combustion efficiency. The water

6 injection to intake manifold can reduce the supercharged air temperature resulting a reduction in

7 NOx emissions without a large increase in PM emissions [1]. The production of high quality

8 refined fuel and synthetic fuel is another example successful to improve the engine performance

9 and exhaust gas emissions. However all technologies as mentioned challenge with the failure of

10 fuel injection equipment. Severely-loaded injector and pump of common-rail systems need fuels

11 with high lubricating capacity to avoid any tribological damaged surface problem on fuel

12 injection components. The existence of water in the air can significantly affect the lubricating

13 properties of fuel and its effect is dependent on the fuel type and the applied load. A correlation

14 of increased wear scar with increased moisture content in the air was reported when aviation fuel

15 and diesel fuel were tested [2, 3]. The desulphurization process to limit sulfur content in diesel

16 fuel eliminates not only quantities of sulfur in diesel fuel but also those of lubricity-imparting

17 compounds such as polyaromatics and oxygen containing compounds leading to numerous fuel

18 injection equipment failures due to the rapid loss of fuel lubrication performance [4].

19 Oxygenated compounds present in the fuel molecule play a key role on reducing exhaust gas

20 emissions, especially smoke and PM emissions, and their tribological behaviors of oxygenated

21 compounds are different due to polarity of each compound. The absence of polar compounds and

22 reactive species tend to form an oxide layer on the metallic surfaces but this oxide film can be

23 simply eliminated during rubbing process, as a result of producing relatively severe wear. The

1 presence of polar species which are preferentially adsorbed will prevent the formation of an

2 oxide film [2, 5]. For reasons as stated the fuel lubricity is one of the most critical properties of

3 convention fuels or alternative fuels to avoid severe contact condition in fuel injection

4 equipment.

5 Many researches have been reported the use of additive or pure substances as blend

6 components to improve the lubricity of diesel fuel with low content of sulfur. Fatty acid and its

7 methyl ester are widely used as lubricity additive to enhance the lubricating properties of highly

8 refined fuel [6-8]. An increase in carbon-chain length of fatty acid esters tended to increase the

9 effectiveness of the boundary lubricant to reduce friction and wear [9, 10]. However there is no

10 clear trend between carbon-chain length of methyl esters and lubricity enhancing properties

11 when carbon number of 18 to 22 was tested [11]. Comparing the saturated and unsaturated

12 compounds of esters the molecules of saturated compounds can develop stronger lubricating

13 layer due to molecules are easier to align in straight chains and are more closely packed on the

14 surface, resulting in the better lubricity [12]. Conversely, a rough correlation between saturation

15 and lubricity enhancement showed that an increase in unsaturation will improve fuel lubricity,

16 when methyl ester of C_{18} series was investigated [11]. Biodiesels derived from several

17 feedstocks such as palm, rapeseed, soybean, castor and cotton seed have successfully been used

18 as diesel fuel lubricity enhancers and methyl ester of castor containing ricinoleic acid as main

19 composition showed a substantial improvement in lubricity when as little as 1% was added to

20 low sulfur diesel fuel [6]. The effect of functional group present in oxygenated compounds on

21 fuel lubricity was tested and the results showed that the capability to enhance the lubricity was

22 $COOH > CHO > OH > COOCH_3 > C=O > C-O-C$ [13].

1   According to the European and American standards of fuel lubricity, the high frequency

2   reciprocating rig (HFRR) is widely employed as consequence of its ability to provide a wide

3   range of wear mechanisms related with adhesive sliding wear, which is responsible for the fuel

4   injection equipment failures [4]. The test methods require a steel ball sliding on a steel disc

5   submerged in the fuel to form wear on specimens. In general, the wear scar on ball specimen is

6   reported to classify the lubricity of fuels. The wear scars of 460 and 520 μm are the limits of

7   diesel fuel lubricity prescribed by EN 590:2009 [14] and ASTM D 975 [15], respectively.

8   To consider the ambient temperature and the presence of water in the air (humidity)

9   which significantly affects the fuel lubricity during the test [2], the European standard requires

10   that water vapor pressure lies within a specified range for the test, approximately 25%-65%

11   relative humidity at ambient air temperature of 25 ^{o}C. The average wear scar is corrected with

12   the factor as function of vapor pressure as called the humidity correction factor (HCF), leading to

13   final reported value of corrected wear scar (WS1.4). The HCF of 60 μm/kPa is proposed by the

14   standard for unknown chemical composition of the fuel. The recent work revealed that the HCF

15   is dependent on the chemical composition of fuel. It reported that an overestimation on corrected

16   wear scar diameters was observed for paraffinic fuels and alcohols when the standard humidity

17   correction factor was applied, while an underestimation was found in case of biodiesel fuels. The

18   HCF of 55 μm/kPa was proposed to normalize the wear scar of hydrocarbon fuels with carbon

19   number ranged from 10 t0 20. The HCF of 70 μm/kPa was recommended for biodiesel fuel. The

20   HCF of 40 μm/kPa was suggested for alcohol fuel as practical value [16].

21   In this work, the commercial diesel fuels, C_{10} oxygenated compounds and fatty acid

22   methyl ester of C_9-C_{18} were selected to evaluate the effect of the ambient air humidity on the

23   wear scar so that specific humidity correction factors depending on the fuel composition used to

1 normalize the wear scar diameter were proposed. In addition, worn surfaces of tested specimens

2 were observed in a scanning electron microscope (SEM) and lubricity mechanisms of the

3 oxygenated compounds were discussed.

4

5 **2. Materials and methodology**

6 **2.1 Oxygenated compounds**

7 The main characteristics of tested fuels and pure substances comprised of commercial

8 diesel fuels and oxygenated compounds for the lubricity test are given in Table 1 [17-21]. The

9 ultra-low sulphur diesel (ULSD) and biodiesel derived from rapeseed oil (RME) were provided

10 by Shell Global Solutions UK. The ULSD was supplied with additives to keep the lubrication

11 properties below the limitation required by EN 590. The C_{10} oxygenated compounds with

12 different functional groups, selected methyl esters with carbon-chain length between C_9-C_{18} and

13 C_{18} methyl esters with variable unsaturation were purchased from Sigma-Aldrich.

14

15 **2.2 Specimens**

16 The standard test specimens are composed of two pieces, i.e. ball specimen and disc

17 specimen. Both ball and disc specimens are made of ANSI E-52100 steel. The chemical

18 composition of the ANSI E-52100 steel is shown in Table 2 [22]. However, the disc specimen

19 was prepared from annealed rod, while the ball specimen was hardened by quenching prior to

20 tempering [23]. Hardness and roughness of ball and disc specimens provided by the

21 manufacturer are summarized in Table 3. As the disc specimens will be used for an analysis of

22 wear mechanism after the test, the as-received disc specimen was etched and then investigated in

23 a scanning electron microscope (SEM). The microstructure of the as-received disc specimen was

1   shown in Figure 1. As a result of the annealing process, the disc specimen reveals spheroidized

2   carbides dispersed in ferrite.

3

4   **2.3 Lubricity test**

5   The lubricity of tested fuels and pure substances were carried out in the high frequency

6   reciprocating rig (HFRR). The parameters including the fuel temperature, fuel sample volume,

7   reciprocating frequency and stroke, test time and load weight were set according to the test

8   methods specified in EN ISO 12156-1:2006 [24] and ASTM D 6079 standards [25]. The

9   temperature controlled cabinet and salt-water solutions were employed to obtain the different

10 conditions of air humidities during the test. The salts and the range of vapor pressures obtained

11 after the equilibrium of salts are described in Table 2. To evaluate the lubricity in term the mean

12 wear scar diameter (MWSD) the microscope with 100x magnification lens was used to measure

13 the length of wear scar on the tested ball in the axis parallel and perpendicular to the sliding

14 direction. After the lubricity test, tested disc specimens were cleaned with acetone and then

15 investigated in a scanning electron microscope (SEM).

16

17 **2.4 Humidity correction factor (HFC)**

18   Regarding the EN ISO 12156-1 to consider the laboratory air condition during the

19 lubricity test, the mean wear scar diameter was calculated to the corrected wear scar diameter or

20 wear scar normalized to a vapor pressure of 1.4 kPa (WS1.4) as described in Equation (1):

21

22   $WS1.4 = MWSD + HCF(1.4 - p_v)$ (1)

23

1   where p_v is the mean vapor pressure during the test and HCF is the humidity correction factor.

2   The HCF can be determined by the differentiating equation 1 with respect to the vapor pressure

3   shown the detail in equation 2 and the standard recommends the HCF value of 60 μm/kPa for

4   diesel fuel. From Table 5, the HCF of diesel fuel with low content of sulfur determined from the

5   experimental data in this study is 57.70 μm/kPa, which is comparable to the standard HFC value.

6

7     $$HCF = \frac{dMWSD}{dp_v} \qquad\qquad (2)$$

8

9   **3. Results and discussion**

10   **3.1 Effect of functional group**

11   Mean wear scar diameters (MWSDs) measured from specimens tested in various

12   oxygenated compounds at different vapor pressures and the normalized wear scar diameters (WS

13   1.4) for each oxygenated compound are shown in Figure 2 and 3, respectively. To obtain the

14   lubricity (WS 1.4) the HCF values of each compound calculated from linear fitting of results in

15   Figure 2 have been used. Lubricity of the oxygenated compounds decreased with increasing of

16   MWSD. As the oxygenated compounds contain different functional groups, the effect of

17   functional group enhancing lubricity can be listed as the following sequence: carboxyl >

18   aldehyde > hydroxyl > ester > ether > ketone. The results corresponded with the previous studies

19   [26], except the results of carbonyl group which composed of ether and ketone.

20   The sizes of the wear scars optically observed on the disc specimens tested in various

21   oxygenated compounds shown in Figure 4 display a similar trend comparing to the MWSD

22   results (Figure 2). Generally, the lubricity of a fluid depends on its viscosity, i.e. fluid with high

23   viscosity produces good boundary lubrication [27, 28]. Thus, in the cases of decanoic acid,

1   decanal, and 1-decanol having relatively high viscosity (Table 1), small and smooth wear scars

2   were observed (Figure 4 (a)-(f)). However, 1-decanol, possessing the highest viscosity, yielded

3   comparatively larger wear scar, than decanoic acid and decanal. Therefore, viscosity was

4   unlikely the only factor influencing lubricity.

5   It was reported previously that lubricity of organic compounds mainly depends on their

6   adsorption ability to a substrate [13]. Since the organic compounds usually attach to a substrate

7   via the functional moiety, the amount of organic compound molecules being able to adsorb on a

8   substrate as well as the bonding strength between the organic compound and the substrate are

9   directly influenced the characteristic of the functional group. Cook and Hackerman found that

10   the organic compound with carboxyl group (COOH) could yield higher amount of molecules

11   adsorbed on steel than those with hydroxyl group did [29]. Moreover, due to the fact that

12   carboxyl group are more polar than other functional groups presenting in this study, it can form a

13   stronger intermolecular bonding with a metal substrate [13]. Thus, decanoic acid composed of

14   carboxyl group resulted in the smallest and smoothest wear scars, i.e. the highest lubricity

15   (Figure 4 (a) and (b)).

16   In terms of polarity, carbonyl (C=O) and hydroxyl (OH) groups are ranked next to

17   carboxyl group. Therefore, decanal with carbonyl group and 1-decanol with hydroxyl group

18   produced larger wear scars (Figure 4 (c)-(f)), i.e. lower lubricity, than decanoic acid. Even

19   though 2-decanone was also composed of carbonyl group, its lubricity was the lowest (Figure 3).

20   Moreover, deep grooves were clearly observed on the disc specimens tested in 2-decanone

21   (Figure 4 (k) and (l)). Comparing with linear structure of decanal, the relatively branching chain

22   molecule of the 2-decanone prevents the chains to pack closely together and results in the weaker

23   lubricating layer. The same effect can be used to explain the lubrication of methyl nonanoate and

1   dipentyl ether having the branching structures. However, the adsorption of the chain molecule of

2   the compounds also depends on their molecular weight, i.e. increase in molecular weight leads to

3   increasing of adsorption ability on a substrate [30]. Therefore, methyl nonanoate and dipentyl

4   ether, having higher molecular weight comparing with 2-decanone, produced smaller and

5   smoother wear scars (Figure 4 (g)-(j)), i.e. the higher lubricity.

6

7   **3.2 Effect of humidity**

8   The effect of humidity on the lubricity of the oxygenated compounds was investigated by

9   varying the vapor pressure in the test chamber. The results of MWSD at different vapor pressures

10   are shown in Figure 2. It is obvious that increase in vapor pressure led to increasing of MWSD. It

11   is likely that water from surrounding air could be absorbed into the oxygenated compound during

12   the test. As the viscosity of water is relatively low, the presence of water will reduce the overall

13   viscosity of the oxygenated compound. Thus, at higher vapor pressure, the water content in the

14   oxygenated compound became higher and resulted in decreasing of viscosity and lubricity of the

15   compound. Moreover, the existence of oxygen in water could lead to corrosion on metal

16   substrate which might contribute to destroy the lubricating film on the rubbing surface and

17   induce bigger wear scar [16].

18   From Figure 2, the relationship between the MWSD and the vapor pressure is

19   approximately linear and Equation (2) can be applied to calculated the slope of the linear-fitted

20   curve, i.e. the humidity correction factor (HCF). The linear equations which best fitted the

21   experimental results with the HCFs for different oxygenated compounds are summarized in

22   Table 5. It can be seen that 2-decanone was very sensitive to the change in humidity as it has the

23   highest HCF of 99.80 μm/kPa, while decanal was least sensitive to humidity with HFC of 13.46

1   μm/kPa. The sensitivity to humidity usually depends on the ability of the compound to absorb

2   water from surrounding air, i.e. hygroscopy. Thus, it is likely that the functional group had

3   significantly effect on hygroscopy of the oxygenated compound.

4   The close observation of worn surfaces was made in the SEM at high magnification

5   (Figure 5). Worn surface tested in decanal at low vapor pressure revealed quite smooth surface

6   with insignificant grooves (Figure 5 (a)). On the other hand, the evidence of abrasive wear, i.e.

7   grooves, as well as material loss around carbide particles were clearly observed on the worn

8   surface from the test in decanal at high vapor pressure (Figure 5 (b)). Normally, ferrite is softer

9   and more active than carbide. Under corrosive environment, ferrite is likely to be corroded,

10 especially in the critical area, in this case, around carbide particles. Therefore, in the case of

11 decanal, as the vapor pressure increases abrasive wear with corrosion was likely the dominating

12 mechanism.

13   For specimens tested in methyl nonanoate and 2-decanone, since these compounds were

14 quite sensitive to humidity, material loss could be observed even at low vapor pressure (Figure 5

15 (c) and (e)). In the case of methyl nonanoate, slightly deeper grooves were observed as the vapor

16 pressure increased (Figure 5 (d)). However, for 2-decanone which is most sensitive to humidity,

17 the worn surface tested at high vapor pressure revealed the severe abrasive wear with detachment

18 of carbide particles from the surface (Figure 5 (f)).

19

20 **3.3 Effect of chain length and unsaturation**

21   The effect of chain length on lubricity was studied by varying the number of carbon

22 atoms in fatty acid methyl ester (FAME) in the range of 12 to 18 carbon atoms as listed in Table

23 1. The MWSDs for the specimens tested in various types of FAME at different vapor pressures

1   are represented in Figure 6. The linear fitted equations and the HCFs for different FAMEs are

2   also summarized in Table 6. It can be seen that HFCs did not change significantly as the number

3   of carbon atoms in the fatty acid chain changed. Unlike the effect of functional group, the

4   number of carbon atoms was not the factor influencing the sensitivity to humidity of the

5   oxygenated compound. The corrected wear scars of the specimens tested in the FAMEs with

6   different chain lengths are shown in Figure 7. Since the increase of the chain length led to

7   increasing of lubricating film thickness [31], the boundary lubrication of the FAME tended to

8   increase slightly with increasing of carbon atoms in the fatty acid chain. The results also agreed

9   with the previous works [13], which suggested that the chain length had a minimum effect of

10   lubricity.

11   Three types of FAMEs with different degrees of unsaturation were used in this study. The

12   FAMEs contain different numbers of double bond; methyl stearate (C18:0) contains no double

13   bond, methyl oleate (C18:1) contains one double bond, and methyl linoleate (C18:2) contains

14   two double bonds. The MWSDs of the three FAMEs are illustrated in Figure 8. As the most

15   unsaturated fatty acid, C18:2 was very sensitive to humidity, i.e. its HCF is the highest. The HFC

16   decreased with decrease in saturation of the fatty acid chain; the HFC of C18:2, C18:1, and

17   C18:0 are 108.02, 68.86, and 47.75 μm/kPa, respectively. Moreover, it can be seen in Table 5

18   that the HCF of rapeseed methyl ester (RME) is 85.80 μm/kPa. Since the RME is mainly

19   composed of C18:1 and C18:2 [32, 33], the contribution of each component affects the HFC

20   value of the RME.

21   The corrected wear scars of C18:0, C18:1, and C18:2 are shown in Figure 7. The lubricity

22   of the FAME slightly decreased with increasing of unsaturation of fatty acid. However, it was

23   found in the previous works that increase in unsaturation slightly improve the lubricity of fatty

1 acid [34]. Therefore, it should be suggested that the effect of unsaturation on lubricity is trivial

2 for the fatty acid.

3

4 **4. Conclusion**

5 In this study, effect of humidity on lubrication mechanisms of various oxygenated

6 compounds was investigated. The findings can be summarized as follows:

7 • The functional group significantly affects the lubricity of the oxygenated compounds.

8 The effect of functional group enhancing lubricity can be listed as the following

9 sequence: carboxyl > aldehyde > hydroxyl > ester > ether > ketone.

10 • The oxygenated compound with carboxyl group having the highest polarity could

11 strongly adsorb on the metal surface and led to the highest lubricity. While, 2-decanone

12 (ketone) has the lowest lubricity due to its relatively branching structure as well as low

13 molecular weight which prevented the chain molecules from packing closely together.

14 • Lubricity of the oxygenated compounds decreased with increasing of vapor pressure. The

15 sensitivity the oxygenated compounds to humidity was influenced by the functional

16 group. In this study, ketone is most sensitive to the change in humidity, while aldehyde is

17 least sensitive to the change in humidity.

18 • Both chain length and unsaturation of the fatty acid methyl ester have insignificant effect

19 on the lubricity. However, the unsaturation could influence the sensitivity to humidity,

20 i.e. unsaturated fatty acid was more sensitive to humidity that the saturated fatty acid.

21

22 **Acknowledgements**

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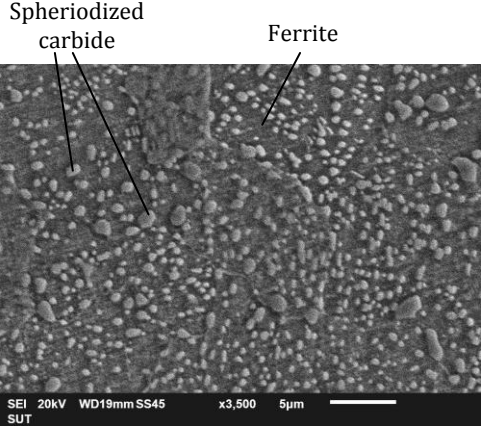
1   Captions

2   Figure 1 Microstructure of the as-received disc specimen.

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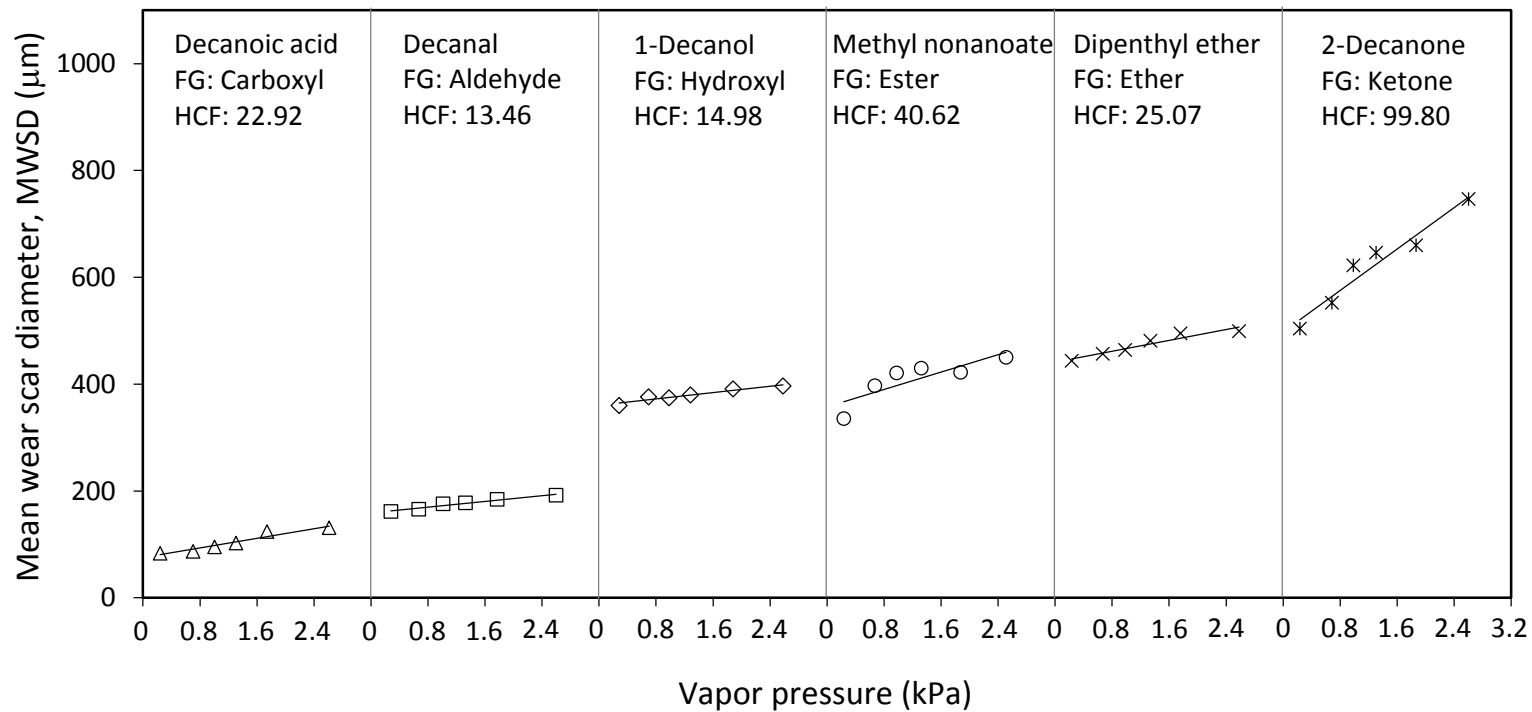
Figure 1 Microstructure of the as-received disc specimen.

Figure 2 MWSD of oxygenated compounds.
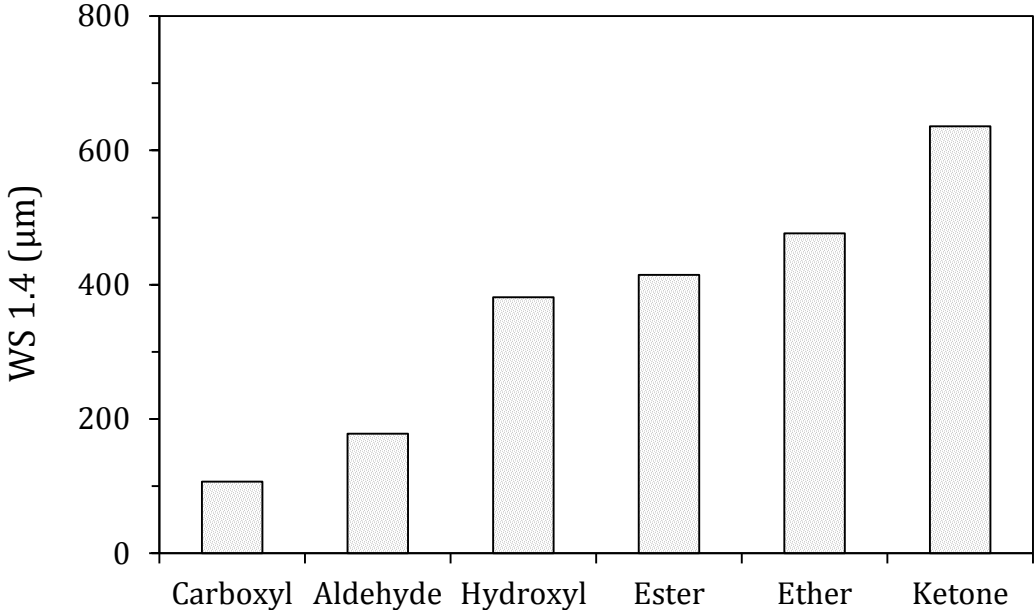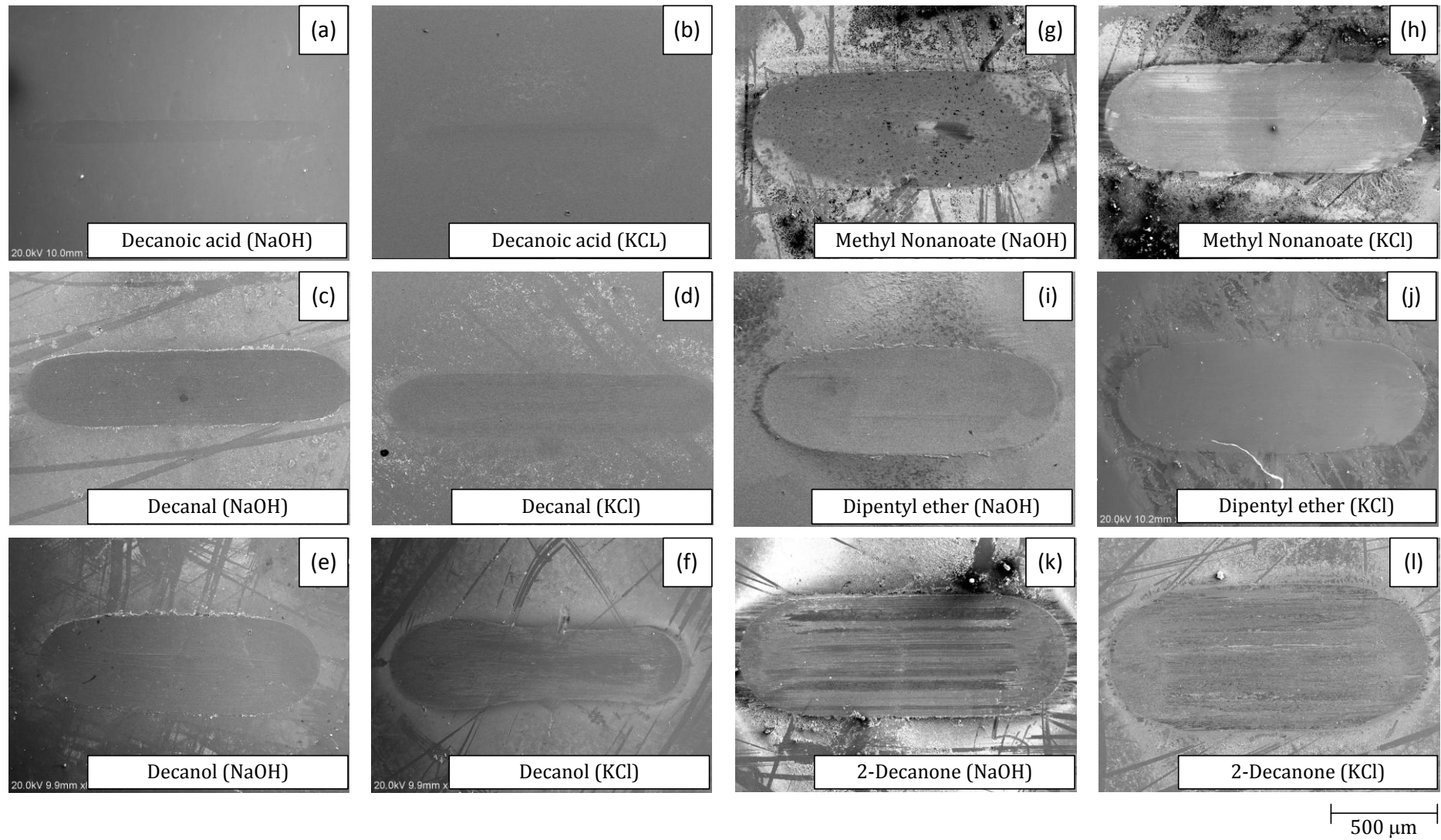
Figure 3 Normalized wear scar of oxygenated compounds.

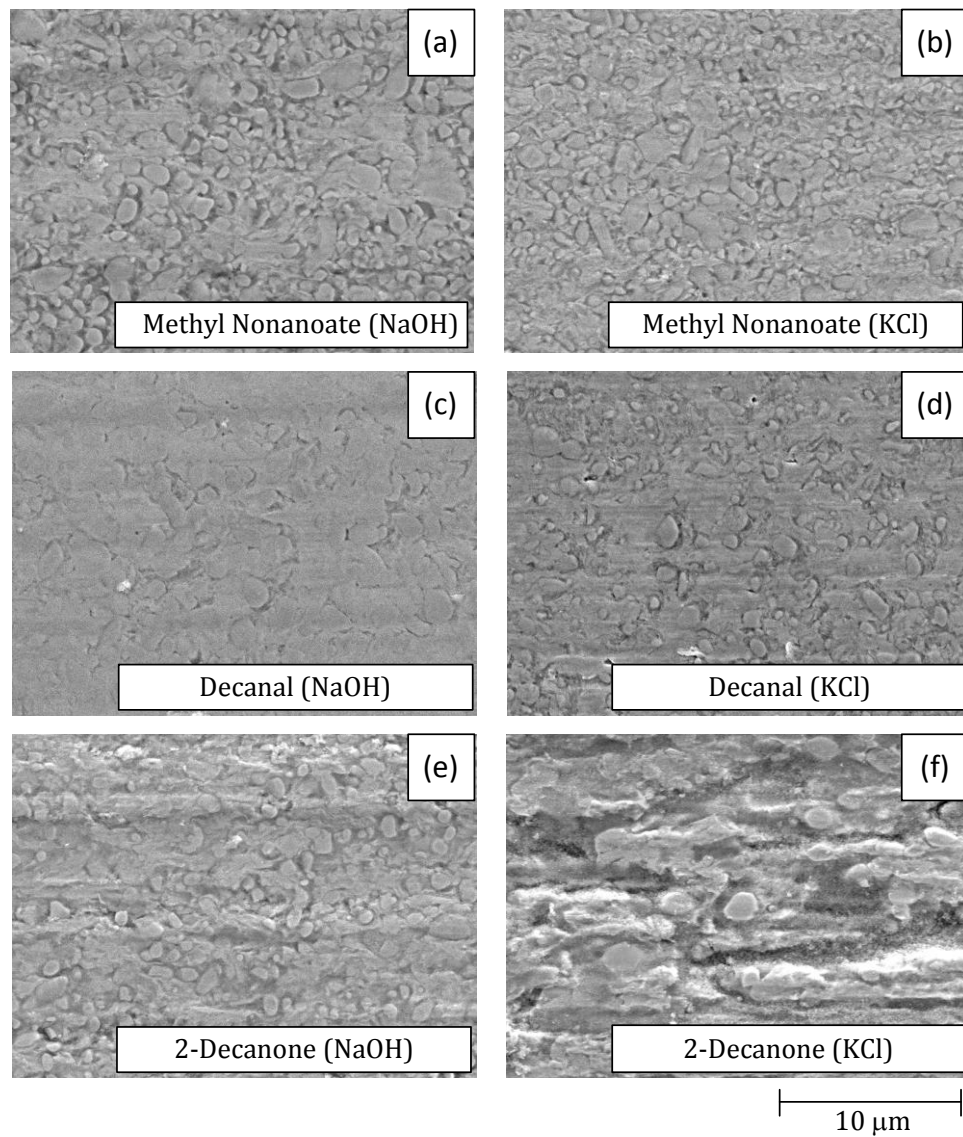Figure 4 Wear scars on disc specimen tested in different oxygenated compounds.

Figure 5 Wear scars on disc specimen tested in different oxygenated compounds at high magnification.
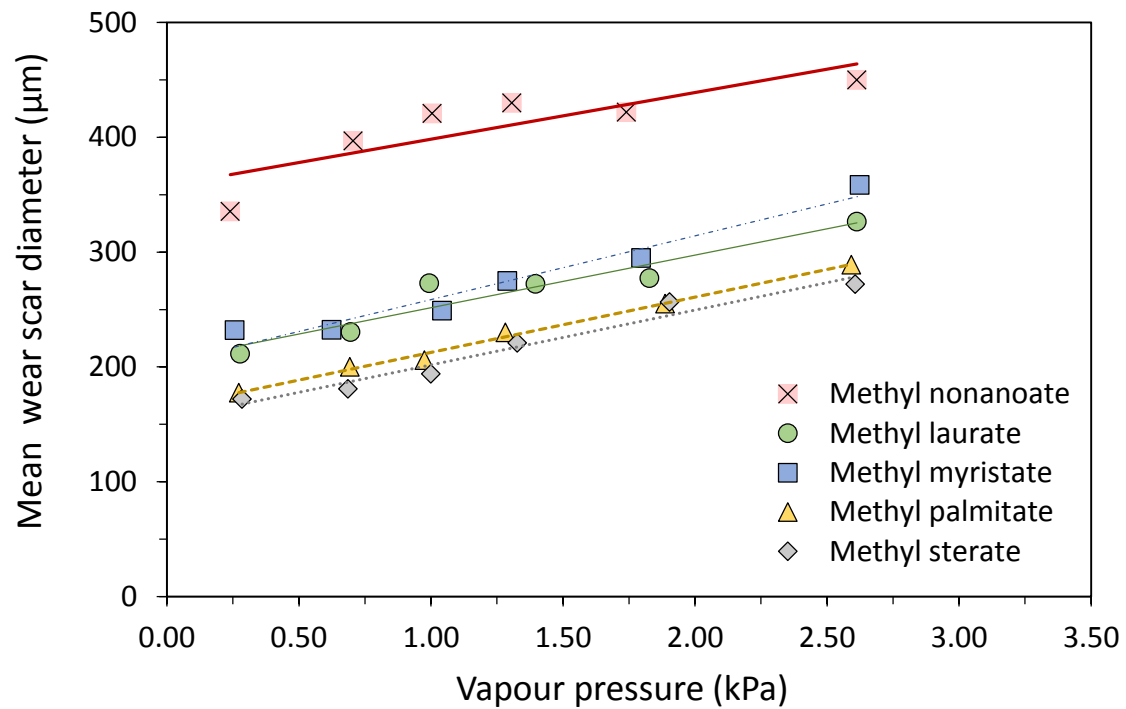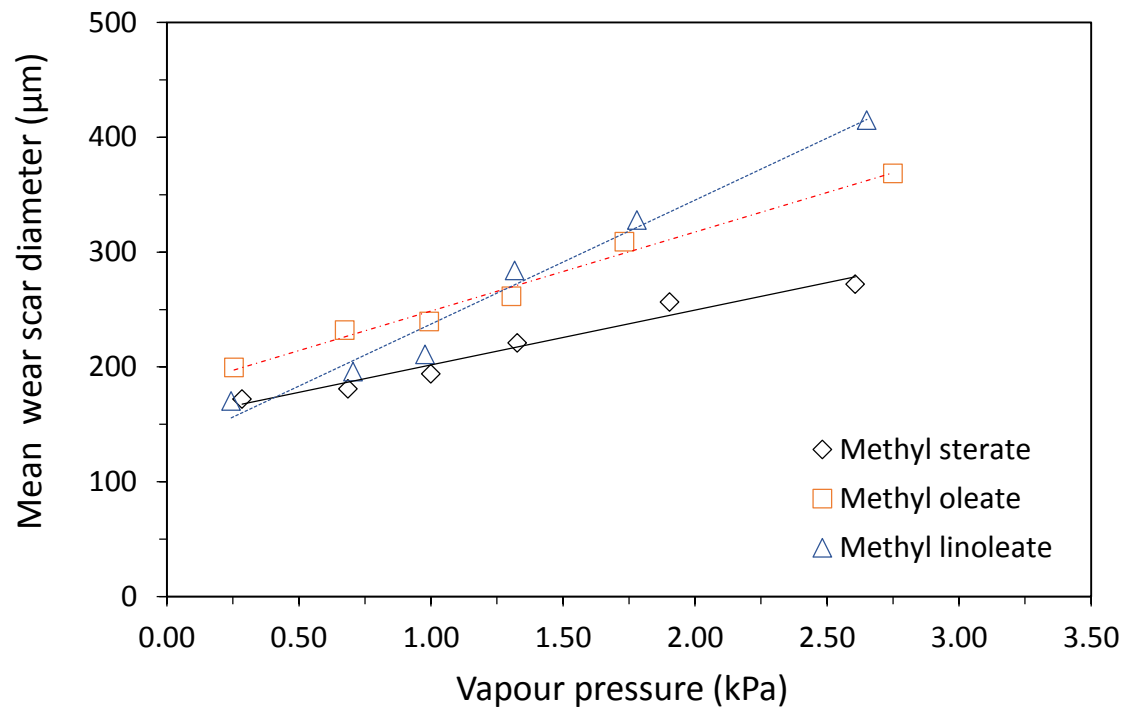
Figure 6 MWSD of FAMEs.

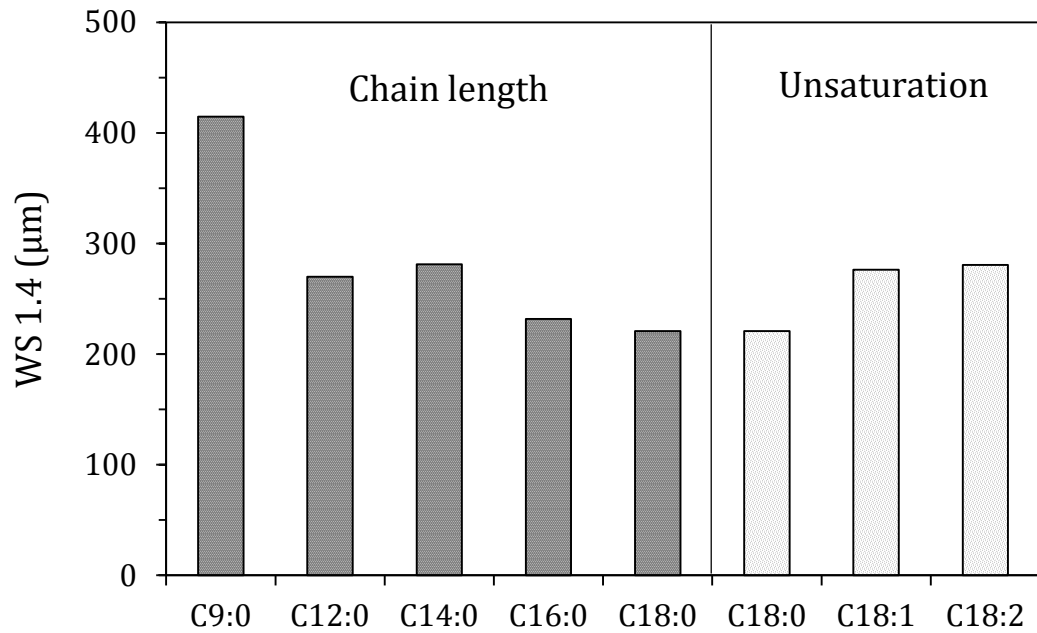Figure 7 Effect of unsaturation of C18 FAMEs on MWSD.

Figure 8 Normalized wear scar of FAMEs.

Table 1. Main properties of tested fuels, oxygenated compounds and fatty acid methyl esters.

Fuel	Description	Molecular formula	Molecular weight (g/mol)	Viscosity at 40 °C (cSt)	Density at 15 °C (kg/m^3)a	Purity (% v/v)
Commercial fuels						
ULSD	Ultra-low sulphur diesel	$C_{14}H_{26.1}$	211.7	2.70[a]	827.1[a]	
RME	Rapeseed methyl ester	$C_{19}H_{35.3}O_2$	294.4	4.53[a]	883.7[a]	
Oxygenated compounds						
Decanoic acid	Carboxyl (COOH)	$CH_3(CH_2)_8COOH$	172.26	5.63[b]	893[c]	>98
Decanal	Aldehyde (CHO)	$CH_3(CH_2)_8CHO$	156.27	1.72[d]	830[c]	>98
1-Decanol	Hydroxyl (OH)	$CH_3(CH_2)_9OH$	158.28	8.04[b]	829[c]	>98
Methyl nonanoate	Esters (COOCH$_3$)	$CH_3(CH_2)_7COOCH_3$	172.26	1.44[b]	875[c]	>97
Dipentyl ether	Ether (C-O-C)	$[CH_3(CH_2)_4]_2O$	158.28	1.08[b]	785[c]	>98
2-Decanone	Ketone (C=O)	$CH_3(CH_2)_7COCH_3$	156.27	1.47[b]	825[c]	>98
Fatty acid methyl esters						
Methyl laurate	C12:0	$C_{13}H_{26}O_2$	214.34	2.43[b]	873.28[e]	>98
Methyl myristate	C14:0	$C_{15}H_{30}O_2$	242.40	3.30[b]	868.18[e]	>98
Methyl palmitate	C16:0	$C_{17}H_{34}O_2$	270.45	4.38[b]	864.19[e]	>97
Methyl stearate	C18:0	$C_{19}H_{38}O_2$	298.50	5.92[b]	867.55[e]	>96
Methyl oleate	C18:1	$C_{19}H_{36}O_2$	296.49	4.78[b]	877.46[e]	>99
Methyl linoleate	C18:2	$C_{19}H_{34}O_2$	294.47	4.25[b]	893.18[e]	>99

[a] [21]

[b] [19]

[c] [17]

[d] [18]

[e] [20]

Table 2. Chemical composition of ANSI E-52100 [22].

Component Elements	C	Cr	Mn	P	Si	S	Fe
Content (%)	0.98 - 1.10	1.30 - 1.60	0.25 - 0.45	≤ 0.025	0.15 - 0.30	≤ 0.025	balance

Table 3. Hardness and roughness of specimens [23].

Specimen	Hardness	Roughness
Ball	HRC 58-66	<0.05 □m Ra
Disc	190-210HV30	<0.02 □m Ra

Table 4. Salts used for humidity control and ranges of humidity at laboratory temperature.

Salt	Temperature (ºC)	Relative humidity (%)	Vapor pressure (kPa)
Sodium hydroxyde (NaOH)	24-27	7 –10	0.23 – 0.31
Potasium acetate (KCH$_3$CH$_2$)	24-27	20 – 23	0.62 – 0.71
Magnesium chloride (MgCl$_2$)	24-27	29 – 33	0.98 – 1.04
Potassium carbonate (K$_2$CO$_3$)	24-27	40 – 43	1.28 – 1.40
Sodium bromide (NaBr)	24-27	54 – 58	1.73 – 1.90
Potassium chloride (KCl)	24-27	80 – 84	2.51 – 2.75

Table 5. Proposed humidity correction factors for commercial fuels and oxygenated compounds.

Fuel	Description	MWSD (µm) linear fit	HCF (µm/kPa)
ULSD	Ultra-low sulphur diesel	57.70 + 263.55	57.70
RME	Rapeseed methyl ester	85.80x + 145.27	85.80
Decaoic acid	Carboxyl (COOH)	22.92x + 74.674	22.92
Decanal	Aldehyde (CHO)	13.46x + 159.23	13.46
1-Decanol	Hydroxyl (OH)	14.98x + 360.27	14.98
Methyl nonanoate	Esters (COOCH$_3$)	40.62x + 357.72	40.62
Dipentyl ether	Ether (C-O-C)	25.07x + 441.18	25.07
2-Decanone	Ketone (C=O)	99.80x + 496.14	99.80

Table 6. Proposed humidity correction factors for individual fatty acid methyl esters.

Fuel	Description	MWSD (µm) linear fit	HCF (µm/kPa)
Methyl laurate	C12:0	45.83x + 205.65	45.83
Methyl myristate	C14:0	55.61x + 202.94	59.24
Methyl palmitate	C16:0	48.00x + 164.55	40.16
Methyl stearate	C18:0	47.75x + 153.95	47.75
Methyl oleate	C18:1	68.86x + 179.85	68.86
Methyl linoleate	C18:2	108.02x + 129.27	108.02