

Oleic Methyl Ester Investigations in an Indirect Injection Diesel Engine; Stage One: Combustion Investigations

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ABSTRACT

The authors investigated the injection and combustion characteristics of a methyl oleate (Methyl 9(Z)-octadecenoate C19H36O2; Mw 296.495), in blends with diesel No. 2 of 20-50% (wt./wt.) in order to evaluate the possibility of using it as an additive to full bodied biodiesel for performance improvement. The FAME test fuel has been injected in an experimental single cylinder separate combustion chamber engine with 77mm bore, with a compression ratio of 23.5:1 at a pressure of 147 bars, that proved capable of atomizing the higher viscosity fuel. The diesel fuel was blended with Methyl Oleate up to 50%, (O50) and the mixtures have shown favorable ignition characteristics, with the ignition delay of about 1.03 ms for petroleum diesel (D100) and slightly decreased for O50 at 2000rpm with about 1% or 0.01 ms. The heat release rate for O50 displayed a similar development compared with the reference diesel fuel, the premixed combustion phase being combined with the diffusion combustion and reaching a maximum of 17.5 J/deg for diesel versus 15.5 J/deg for O50. Maximum combustion pressure was approximately 73 bars for diesel compared with 75 bars for the O50 fuel, while the diesel instantaneous volume-averaged gas temperature reached 2120 K vs. 2150 K for the O50. The total heat flux calculated by Annand model produced values of 2.05MW/m² for diesel fuel compared with 2.07 MW/m² for O50. The convection flux for both petroleum diesel and 50% oleic FAME in diesel blend had values of 1.5 MW/m², and a maximum radiation flux of about 0.66 MW/m² for diesel versus 0.70 MW/m² for oleic FAME. Based on the heat fluxes, the heat loss in convection and radiation for both fuels throughout the cycle showed similar values, negligible during the combustion around TDC and increased losses during the power stroke especially from the

convection phenomenon. The engine's mechanical efficiency with oleic FAME showed lower values than that in diesel combustion of 78% vs 86% at 4.78 bmep (100% load) while the engine overall efficiency obtained with any blend including diesel was constant at 32%. The study showed that the new biodiesel produced from methyl oleate proposed by the authors has favorable combustion properties and very similar to those of diesel No 2 showing good prospects as performance improver.

INTRODUCTION

The technologies that enabled vegetable oil transesterification and compression ignition engines have a history that dates back over 100 years. Driven by global economic, environmental, and political conditions, the biodiesel transesterification, in the U.S., has recently been evolving at a higher pace. Alone, the transportation sector accounts for about 68 percent of the total liquid energy demand [1], and is expected to rise to 73 percent in 2030. Energy Independence and Security Act of 2007 (EISA) is requiring the average fuel economy of new light-duty vehicles (both cars and trucks) to reach 35 miles per gallon by 2020. As well as a 38 percent increase in average fuel economy for in-use stock light-duty vehicles in 2030 compared to 2006 values [1].

Though the U.S. is still far behind Europe, that was using 5% biodiesel mixed with regular diesel since the early 90's, recent legislations help to ensure that the U.S. is becoming a frontrunner in such innovative and growing industries as renewable biofuels. The value of this particular industry is that it satisfies US national goals of creating jobs, energy security, and reducing societal impact on the environment.

With the requirements emplaced through the Renewable Fuels Standard, 1.150 billion gallons [2] of biofuels are to be used domestically from 2009 to the end of 2010. This requirement will gradually increase until 2012 and over the following decade there is a requirement to use another 1 billion gallons and the Environmental Protection Agency is given the authority to increase that minimum requirement [2]. Adding to this need for biofuels, there is also the expectation that consumption of energy will increase by 20 percent between 2006 and 2030. This increase in energy consumption is due to a predicted relative decrease in energy intensity and increase in population. Total biofuel consumption is predicted to reach 29.7 billion gallons (2.8 quadrillion Btu) by 2030, which represents almost 11.3 percent of total motor vehicle fuel, [1]. As amended by the EISA2007, Section 211(o) of Clean Air Act sets a requirement of 36 billion gallons of total renewable fuels by 2022 of which 21 billion gallons are to be advanced biofuels [3].

The benefits of biodiesel cover topics of recent increased importance such as energy security, renewability, sustainability, environmentally friendly, increased safety, enhanced lubrication effects, and a reduction of SO_x, particulate matter and exhaust emissions in general, as well as the ability to produce a homogeneous mixture with petroleum diesel. However, before it can reach a larger mass application some technical issues associated with the new fuel must be solved as shown in the following chapters.

LITERATURE REVIEW

The technological problems associated with biodiesel, are the oxidative stability, poor low-temperature properties, and a slight increase in NO_x emissions, especially from biodiesel derived from vegetable feedstock, even though the NO_x issue may be solved with the introduction of innovative exhaust emission control technologies. This behavior is connected to the reliance of fuel properties on the fatty acid composition [4]. As a result of the relatively large number carbon molecules of biodiesel versus diesel, the biofuels are susceptible at low temperatures to separate and crystallize, resulting in a higher cloud point. This occurrence of solid crystals in the fuel increases the viscosity and the passage of the fuel through the fuel filter. It has been revealed also that the Cetane number, decreases with a decreasing chain length, and an increasing unsaturation in the fatty acid chain [5]. However saturated esters, which have high and therefore desirable, cetane numbers, are characterized by poor cold-flow properties. Unsaturated, in particular polyunsaturated, fatty esters have lower melting points, which are desirable for improved low-temperature properties but also have lower cetane numbers and reduced oxidative stability, which is detrimental for a fuel [4].

There are several approaches that have attained common practice to alleviate these issues. One of the most common

approaches is the use of additives, such as antioxidants, cetane enhancers, or cold-flow improvers, [4]. Another solution is the production of biodiesel from an alcohol other than methanol [6], forming ethyl and isopropyl esters which display improved low temperature properties without reducing cetane number or oxidative stability. The problems associated with this method are the significantly increased cost of production as well as modifications required of the transesterification process [7]. A fourth approach, and the one of most interest to this study, is the use of bio-oils with reformulated fatty acid compositions that provided the biofuel with improved properties. Respectively, oleic FAME is being under investigation as the leading component of such doped biodiesel. This technology, would address both the technical issues related with biodiesel use without adversely affecting other properties, as with the use of alcohols other than methanol. A recent preliminary discussion, on the topic of altering the esterified fatty acid composition of biodiesel was opened. Additional options to oleic FAME, include esters of palmitoleic acid, saturated short-chain esters, hydroxyl containing esters, and esters other than methyl [4].

Reid, Prausnitz and Poling (1987) show how chemical structure can be used to compute properties for pure components. They also discuss mixing rules to estimate properties for mixtures. Many such properties are directly measured by chemical analysis, or are calculated by knowing the ester composition in the fuel. In particular, the kinematic viscosity, cetane number, and cloud point of the fuel are dependent on the ester composition. In the formulation of biodiesel, the chemistry of the components is well defined. Since the fuel is an ester of fatty acids derived from natural sources, the main fatty acids normally present in considerable quantity are palmitic acid, stearic acid, oleic acid, linoleic acid, linolenic acid and erucic acid. The fatty acid profile of biodiesel is identical to that of the parent oil or fat while the composition changes by feedstock, but the components do not. The most common fatty esters contained in biodiesel are therefore; palmitic (hexadecanoic) acid, stearic (octadecanoic) acid, oleic (9(Z)-octadecenoic) acid, linoleic (9(Z),12(Z)-octadecadienoic) acid, and linolenic (9(Z),12(Z),15(Z)-octadecatrienoic) acid as presented in Table 1. This composition holds true for biodiesel feedstock, such as soybean, sunflower, rapeseed (as canola), palm, and peanut oils.

Previous experiments using a 10% vol. biodiesel blend (palm oil feedstock) on common-rail engine were performed in [8]. The experiments included measurement of the in-cylinder pressure, regulated pollutants emissions and fuel consumption. The palm-oil biodiesel resulted in both higher and lower smoke and NO_x emissions over the engine map. This was attributed to the effects of both the chemistry and the physical properties of the biodiesel. An analysis of experimental data of neat biodiesel to diagnose how various

Table 1. The chemical composition of the main fatty acids and their methyl esters

Fatty acid	Structure	Acronym	Methyl Ester
Palmitic acid / Hexadecanoic acid; C16H32O2, Mw 256.428	R-(CH2)14-CH3	C16:0	Methyl palmitate / Methyl hexadecanoate; C17H34O2, Mw 270.457
Stearic acid / Octadecanoic acid; C18H36O2, Mw 284.481	R-(CH2)16-CH3	C18:0	Methyl stearate / Methyl Octadecanoate, Mw 298.511
Oleic acid / 9(Z)-octadecenoic acid; C18H34O2, Mw 282.465	R-(CH2)7- CH=CH- (CH2)7-CH3	C18:1	Methyl oleate / Methyl 9(Z)-octadecenoate C19H36O2; Mw 296.495
Linoleic acid / 9(Z),12(Z)-octadecadienoic acid; C18H32O2, Mw 280.450	R-(CH2)7- CH=CH- CH2-CH=CH- (CH2)4-CH3	C18:2	Methyl linoleate / Methyl 9(Z), 12(Z)-octadecadienoate; C19H34O2, Mw 294.479
Linolenic acid / 9(Z),12(Z),15(Z)-octadecatrienoic acid; C18H30O2, Mw 278.434	R-(CH2)7- (CH=CH- CH2)3-CH3	C18:3	Methyl linolenate / Methyl 9(Z),12(Z),15(Z)-octadecadienoate; C19H32O2, Mw 292.463

key performance parameters are affected by the use of 100% palm olein biodiesel was done by Brandon et al, (2009) [9]. The study identifies that fuel-air ratio and inlet mixture density tend to increase with biodiesel while volumetric efficiency tends to decrease with biodiesel. Exhaust nitric oxide emissions tend to increase and smoke concentrations tend to decrease with the use of biodiesel.

Manbae et al, (2008), investigated the effects of soybean and coconut-derived biodiesel fuels on combustion characteristics in a direct injection, common rail diesel engine [10]. In conventional diesel combustion mode, particulate matter (PM) and nitrogen oxides (NOx) emissions were similar for all fuels studied except soybean B20. Soybean B20 produced the lowest PM but the highest NOx emissions. Mueller et al, [11], conducted experiments in a single-cylinder version of a heavy-duty diesel engine with extensive optical access to the combustion chamber. He operated an engine using two biodiesel fuels and two hydrocarbon reference fuels, over a wide range of loads. Results suggest that the biodiesel NOx increase is not quantitatively determined by a change in a single fuel property, but rather is the result of a number of coupled mechanisms.

Zhang, (2008), studied combustion and emission characteristics of diesel and biodiesel blends (soybean methyl ester) in a single-cylinder Direct Injection (DI) engine [12]. The results showed that NOx emissions and fuel consumption increased with increasing biodiesel percentage. Reduction of smoke opacity was significant at higher loads with a higher biodiesel ratio. Compared with the baseline diesel fuel, B20 (20% biodiesel) has a slight increase of NOx emission and similar fuel consumption. Smoke emission of B20 is close to that of diesel fuel. Patterson et al, (2006), used methyl esters derived from vegetable oils by transesterification as an alternative fuel in compression ignition engines [13]. In this study, three different vegetable oils (rape, soy and waste oil) were used to produce biodiesel fuels that were then tested in

direct injection engine. Engine performance and emissions for all of the 5% biodiesel blends were indistinguishable from mineral diesel. However, at higher blends, the rape fuel exhibited better emission and performance characteristics than either the soy or waste fuels. Furthermore, whilst emissions trends varied for each blend and fuel, emissions of smoke were significantly reduced at all speed and load conditions, and NOx was reduced by up to 50% at low loads. It was also shown that while engine performance was not significantly deteriorated by biodiesel, there was evidence of increased ignition delay with higher blends, and a possible two-stage ignition process where mineral diesel ignited earlier than the biodiesel.

Kong et al (2008), measured particulate matters, nitrogen oxides, and carbon monoxides emissions using diesel/biodiesel blends [14]. Tests were performed using the regular diesel fuel and biodiesel blends (B10, B20, B100). Test results showed that particulate matters and carbon monoxides decreased significantly as biodiesel content increases, whereas nitrogen oxides increased. Grimaldi et al (2006), worked to evaluate the potentialities of bioderived diesel fuels, the effect of fueling an automotive diesel engine with biodiesel and fossil/biodiesel blend on its emission and combustion characteristics [15]. The fuels tested were, a 50% biodiesel blend in the reference diesel, and a 100% biodiesel, obtained by mixing rape seed methyl ester (RME) and recycled cooking oil (CME). Experimental evidences showed appreciably lower CO and HC specific emissions and a substantial increase in NOx levels. A significant reduction of smoke emissions was also obtained.

Beatrice et al (2009) made an experimental evaluation of the impact of the diesel/biodiesel blends and presented it in terms of engine performances and pollutant emission analysis [16]. In-cylinder combustion evolution and injection law characterization were carried out on a single cylinder engine, on an optical single cylinder engine and on an injection test

rig. Increasing the biodiesel percentage a reduction mainly in terms of smoke emission was observed. The engines performance, as well as the pollutant emissions, was not substantially changed. Eckerle et al (2008), studied the effects of methyl ester biodiesel fuel blends on NO_x emissions experimentally and analytically [17]. A precisely controlled single-cylinder diesel engine experiment was conducted to determine the impact of a 20% blend of soy methyl ester biodiesel (B20) on NO_x emissions. In addition, the impact on the engine control system of the lower specific energy content of biodiesel was determined. Because the magnitude and even direction of NO_x effect changes with engine load, the NO_x effect associated with burning biodiesel blends over a duty cycle depends on the duty cycle average power and fuel cetane number. In his work, the difference in NO_x emissions between a B20 and its base diesel fuel was relatively small.

The fuel properties, the diesel combustion and the exhaust emissions of palm kernel oil methyl ester (PKME) and a blend of 20% PKME with gas oil (PK-B20) were investigated by Myo, (2007) [18]. In this study, the fuel properties were measured by laboratory analyses and the engine experiments were carried out by using a single-cylinder direct injection diesel engine. To make comparison between biodiesels and conventional diesel fuel, palm oil methyl ester (PME), coconut oil methyl ester (CME), and the gas oil were also used as test fuels. From the fuel property analyses and the engine experimental results; the pour point of PKME was the same as that of CME and the pour point of PK-B20, the brake thermal efficiency of PKME was the same as the other test fuels, the ignition ability of PKME was better than that of the gas oil and the exhaust emissions (CO, HC, NO_x and smoke) from PKME were almost the same as those of CME and lower than those of the gas oil.

Bennadji et al. (2009) studied the autoignition delay times of methyl crotonate, methyl acrylate, ethyl butanoate, ethyl crotonate, and ethyl acrylate in shock tube experiments [19]. A series of mixtures diluted with argon, of varying fuel/oxygen equivalence were measured behind reflected shock waves at temperatures of 1280-1930 K, and pressures 7-9.65 atm, and found that the ignition delay time decreases as temperature rises. Feng et al. (2010) studied in a stagnation-flow reactor configuration, which allows for the systematic evaluation of fundamental combustion and emission characteristics, the oxidation characteristics of biodiesel fuels of pure fatty acid methyl-esters (FAME,) that can serve as surrogate compounds for real biodiesels, [44]. The focus was on the pollutant emission characteristics of two low carbon fuels: C4 FAMES: ethyl-butanoate and methyl-crotonate, whose behavior is compared with that of n-butane and n-pentane. The effects of chain length and degree of saturation on the fundamental flame properties of these fuels were evaluated. NO_x concentration profiles were measured in

stagnation flow flames by sampling using a quartz micro-probe followed by chemiluminescence analysis.

Knothe et al. (1998) injected into a constant-volume combustion apparatus, fatty acids of C18 chain length, as well as their methyl, ethyl, n-propyl, and n-butyl esters that were suitable for collecting material from the fuel spray prior to the onset of ignition [20]. The collected material from this precombustion phase of the injection event was analyzed by gas chromatography-mass spectrometry (GEMS). Compounds identified as forming during the precombustion phase were straight-chain and branched alkanes, alkenes, and cyclic hydrocarbons, as well as aldehydes, ketones, esters, substituted benzenes. Some of the compounds formed during precombustion have low cetane numbers (CN) more prominently for more unsaturated fatty compounds.

McCormick et al. (1997) investigated 1% oxygen in diesel using a 6V-92TA DDEC II engine. Oxygen was added as a C8 (n-octanol), C12 (decanoic acid), and C17 (methyl soyester) [21]. Relative to the base diesel, the NO_x changes were 1-2.29%. This study also examined the effect of n-octanol and methyl soyester at 2% oxygen on NO_x emissions. Octanol reduced NO_x by 2.9% while methyl soyester increased NO_x by 2.53%. The data suggest that lower molecular weight or lower boiling point oxygenates might not affect NO_x as greatly as methyl soyester.

Williams et al. (2010) investigated which biodiesel fuel properties impact reactivity [22]. Three fuel properties in this study included fuel oxygen content and functionality, fuel aromatic content, and the presence of alkali metals. Results showed no dependence on the aromatic content or the presence of alkali metals in the fuel. The presence and form of fuel oxygen proved to be the dominant contributor to faster DPF regeneration times and soot reactivity. The form of the oxygen functional group proved to play a role in DPF performance, and a long-chain alcohol (a carbon bonded to a single oxygen atom) provided a more effective form of oxygen than the methyl-esters of biodiesel (a carbon bonded to two oxygen atoms) for improving soot reactivity. Ban-Weiss et al. (2007) evaluate proposed theories for slight NO_x increase, including based on biodiesel's cetane number, which leads to differing amounts of charge preheating, and theories based on the fuel's bulk modulus, which affects injection timing [23]. They propose an additional theory for the slight NO_x increase of biodiesel. Biodiesel typically contains more double bonded molecules than petroleum derived diesel and these double bonded molecules have a slightly higher adiabatic flame temperature, which leads to the increase in NO_x production for biodiesel. The theory was verified using numerical simulations to show a NO_x increase, due to the double bonded molecules, that is consistent with observation and the numerical simulations show that NO_x is predominantly due to the Zeldovich mechanism.

Sun et al. (2010) investigated the differences in properties between biodiesel and petroleum diesel fuels that create several changes to system and combustion behaviors of diesel engines [24]. They found that combined, these effects lead to several complex and interacting mechanisms that make it difficult to fundamentally identify how biodiesel affects NO_x emissions. Instead, several parameters seem to influence on the observed differences in NO_x emissions with biodiesel, thus introducing several possibilities for inconsistency in the trends. These parameters are injection timing, adiabatic flame temperature, radiation heat transfer, and ignition delay.

Detailed analysis shows that ignition delay and exhaust emissions are affected by the proportion of biodiesel. Biodiesel's higher surface tension may contribute to an advance in injection timing; its influence on ignition delay is complex due to competing interactions with atomization, droplet size, penetration, and evaporation [25]. Biodiesel's lower heat capacity may allow its temperature to rise at a faster rate once injected, and droplets evaporate sooner than petroleum diesel, contributing to shorter ignition delay. In terms of chemical properties, the literature tends to identify the increased double-bonding of biodiesel as contributing to shorter ignition delays [23, 26, 27]. Thermal cracking of double-bonds associated with unsaturated fatty acids during injection results in breakdown of high molecular weight species to lower molecular weight species on the periphery of the fuel spray, allowing their mixing and eventual ignition with air. These mechanisms are believed to allow shorter ignition delay compared to more saturated fuel structures. However, Ryan et al. [26] note that increased viscosity with biodiesel decreases atomization, mixing rate, and cone angle, which should contribute to increased ignition delay. They conclude that the balance between chemical and physical mechanisms results in a net decrease in ignition delay.

This literature review shows that over the last two decades, researchers have reported very complex, sometimes contradictory, interactions in biodiesel, and most remain to be clarified for combustion in a diesel engine.

FUELS SPECIFICATIONS

The enrichment of vegetable oils using methyl oleate is typically performed with technical-grade level, 60-90% purity. Technical grade methyl oleate with 78% purity was purchased from TCI America (Portland, OR). As previously stated, methyl oleate has been suggested in the past as a compound for enrichment in biodiesel fuels to improve biodiesel fuel properties [28, 29]. As seen from previous studies, oleic acid is definitely a suitable fatty acid for enrichment in a fatty acid profile. The melting point of -20 °C would suffice for most cold climate environments; however, for extreme conditions, an even lower melting point would be desired. As reported the kinematic viscosity of methyl oleate increases from 4.50 mm²/s at 40 °C to 21.50

mm²/s at -10 °C, with the latter value being nearly the kinematic viscosity of some vegetable oils at 40 °C. The oxidation stability, of less than 3 hr (per Rancimat test at 110 °C), for methyl oleate does not meet either the ASTM or EN standards. The oxidative stability of methyl oleate is considerably greater than that of the polyunsaturated esters methyl linoleate and methyl linolenate, but still require an additive for these materials to meet the specifications in biodiesel standards. The methyl oleate used in this research was tested using gas chromatography mass spectrometry (GC-MS) to determine the exact purity of the methyl oleate and the composition of the remaining 22%. The results from the testing were determined to be the methyl esters of stearic, palmitic, palmitoleic, and myristic acid. All of these methyl esters have densities that are within 5% of the methyl oleate, therefore it was assumed that the methyl oleate's density would be the standard value, 0.88 g/cm³, ± 2.5%. The density of diesel No.2 and methyl oleate mixtures varies with the mass participation of the fatty acid into the mixture having values from 0.85 g/cm³ to 0.88 g/cm³ for O100 shown in Figure 1. The cetane number of methyl oleate exceeds the minimum biodiesel standards (51 in EN 14214 and 47 in ASTM D6751) as seen in Table 2. The value of Cetane number for diesel in this study was 47 and that of O100 was 56 as presented in Table 2 and Figure 2.

Table 2. Properties of reference fuels

Property	Diesel No.2	Methyl Oleate	Biodiesel
Cetane Number	40-55	56	47 min
Density	0.85 g/cm ³	0.88 g/cm ³	0.88 g/cm ³
Viscosity @40°C	1.9 - 4.1 mm ² /s	4.51 mm ² /s	1.9-6.0 mm ² /s
LHV	42.6 MJ/kg	39.93 MJ/kg	37.53 MJ/kg
MW	233 g (EPA)	296.5 g	~292 g
Saturation Degree	NA	saturated	NA
Flash Pt.	100°C min	163°C	130°C min
Cloud Pt.	-16.1°C	-12.8°C	0°C
Acid Number	NA	NA	0.8 mg KOH/g max

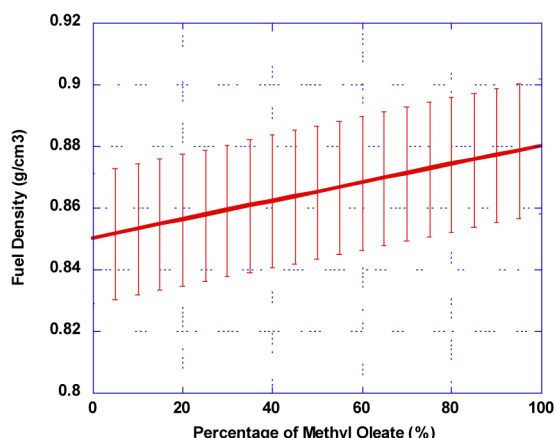


Figure 1. Fuels density versus methyl oleate content

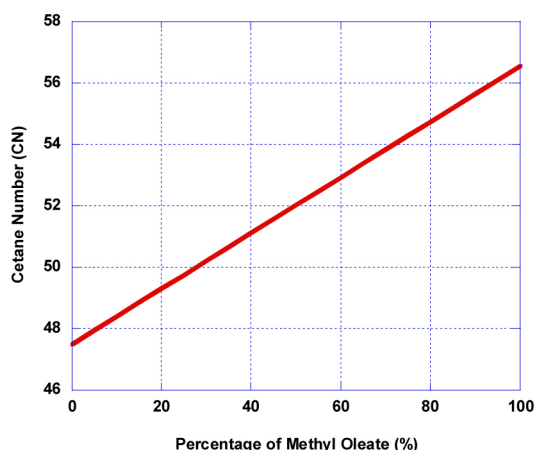


Figure 2. Cetane number versus methyl oleate content

DYNAMIC VISCOSITY STUDY

The dynamic viscosity of fatty compounds is considerably influenced by the structure of the compound. Influencing factors are chain length, double bond position, number of double bonds, and nature of double bonds. Usually, the hydrocarbons in petroleum diesel exhibit lower viscosity that would affect the fuel spray atomization and ultimately, the formation of carbon deposits in the engine [30]. The viscosity is one of the most important properties of biodiesel because of its pronounced affect based on the operation of the fuel injection equipment, in particular at low temperatures where the increase in viscosity can lead to poor spray due to injector clogging and inadequate fuel atomization [31]. Poor atomization leads to increased carbon deposits causing increased wear to develop which effects performance, with respect to mechanical efficiency and power output. However, the higher viscosity range of biodiesel has been seen to help to reduce barrel/plunger leakage and increase injector efficiency in the engine [30].

According to Knothe and Steidlty the viscosity of biodiesel is slightly higher than that of diesel, but of less magnitude than the original vegetable oil of fat [32]. Generally the aliphatic and aromatic hydrocarbons, which are the major components of petroleum diesel, display a smaller viscosity range with lower viscosities due to their lack of oxygen [30]. The length of the chain with the same number of carbon atoms and the difference in increasing the viscosity hydrocarbons are smaller for the esters of the fatty acids. For the same number of carbon atoms, composed of fatty acids are more viscous. Double bonds reduce kinematic viscosity in fatty compounds and aliphatic hydrocarbons. The viscosity-lowering effect is greater in the fatty compounds, which may be a result of the double bond position. However, varying the double bond position towards the middle of the chain has comparatively little effect on viscosity, so that double bond within the region should not be of significance for biodiesel [5].

Viscosity increases with chain length (number of carbon atoms) and with increasing degree of saturation. This holds also for the alcohol moiety as the viscosity of ethyl esters is slightly higher than that of methyl esters. Factors such as double bond configuration influence viscosity (cis double bond configuration giving a lower viscosity than trans) while double bond position effects viscosity less. Branching in the ester moiety, however, has little or no influence on viscosity, again showing that this is a technically promising approach for improving low-temperature properties without significantly affecting other fuel properties. Values for dynamic viscosity and kinematic viscosity of neat fatty acid alkyl esters are included in Table 2 [5].

For all the fuel mixtures developed in the viscosity studies (0-50% Methyl Oleate), the viscosity was investigated at various speeds (shear stress), Figure 3, with a Brookfield Viscometer DV II Pro type. Fitted with the Small Sample Adapter attachment the instrument selection came from the conditions that the viscometer had to operate from 0-100 °C, handle low viscosity liquids, ease of maintenance, and resistant to contamination. The results showed that viscosity increases in proportion with the percentage weight of the methyl oleate to petroleum diesel used to produce the fuel samples. The viscosities of the samples were measured at temperatures between 25°C and 30°C as seen in Figure 4. For the diesel engines, the fuels' viscosity is essential since it has influence on the droplet size, penetration, and mixing rate with the air, vaporization, emissions, smoke, and wall deposits. As a result, engine efficiency and emissions characteristics are determined. The diesel engines require a fuel kinematic viscosity between 1-20 cSt with a maximum for very large bore engines of about 100 cSt. The dynamic viscosity study of the methyl oleate and diesel blends, took place at various viscometer spindle speeds ranging from 1.5-100 rpm and 26°–30°C, verifying that the viscosity of the Oleic FAME (fatty acid methyl ester) diesel blends are