

Analysis of Soot Suppressing Effect of Bio-Diesel in a Compression Ignition Internal Combustion Engine

S. D. Rasika Perera

¹Department of Mechanical Engineering, The Open University of Sri Lanka, Nawala, Nugegoda, Sri Lanka.

*Corresponding Author: email: sdper@ou.ac.lk Tele: +94112881386

Abstract – Out of many pollutants, diesel particulates (soot) play a major role when it comes to emission controlling in the transport sector. Fine particles of soot can irritate various respiratory and cardiovascular health problems to human beings.

The addition of oxygenated fuels has taken a significant attention to reduce harmful emissions from petroleum-based fuels. The objective of the current study was to investigate the effect on soot formation of biodiesel produced for this experimental study.

The contribution of different hydrocarbon classes on soot formation, soot formation models and the contribution of hydrocarbon saturation on soot formation were studied. Hydrocarbons with higher amount of saturation has a higher tendency to form soot. For the current study, coconut oil was used to produce biodiesel. Out of many vegetable oils, coconut oil has the lowest concentration of unsaturated hydrocarbons. Biodiesel has a lower calorific value but a higher cetane index compared to that of diesel fuel.

The experiment was carried out on a vehicle fitted with diesel engine. A separate opacity meter was used to measure the soot concentration of diesel emissions.

Tests were carried out with 11 fuel samples which included 100% diesel fuel, 100% biodiesel samples and nine other blends of biodiesel in diesel fuel with compositions varying between 90 % (10% biodiesel) and 10% diesel fuel (90% biodiesel).

During the experimental investigation, the lowest soot concentration was observed when the vehicle was fueled with 100% biodiesel and the highest amount was observed when the vehicle was fueled with pure diesel fuel. At higher concentration of biodiesel blends, a significant reduction of soot concentration was observed. At low concentrations of biodiesel, the reduction of soot concentration was not significant. The results obtained during the research are in comparison with the outcome of previous research.

Keywords: soot, soot formation, oxygenated fuels, bio diesel

1 INTRODUCTION

Despite advancements made with respect to electricity, Hydrogen and other alternatives such as Bio Diesel, fossil fuels are very likely to be the main supplier of energy for the transportation system for the next 4 to 5 decades (Lei Xu et.al., 2022).

It is well known that fossil fuel used in the transport sector emit much of the harmful emissions to the atmosphere. Out of many harmful emissions, diesel particulates play a major role when it comes to emission controlling in the transport sector.

Due to the absence of a throttle body by nature, compression ignition engines operate in a lean region of air fuel ratio. However, even if the fuel is burned in the presence of more than enough oxygen, soot may form due to poor fuel quality, fuel system component malfunction or non availability of time to complete the ignition etc.

Diesel particulates from automobiles powered by CI Engines results in direct exposure to human beings. Especially, the fine particles of soot can have various respiratory and cardiovascular health problems in human beings (Lighty et.al., 2011).

Although the total oxygen content within the combustion chamber of a diesel engine may be sufficient for complete combustion, due to uneven mixture formation, localized rich mixtures exist (see Fig. 1).

If it is assumed that a four stroke engine is operating at 3000 rev/min, and diesel fuel is injected 20° before TDC and combustion process continue further 20° after TDC, only 22 ms is available for the whole process to occur.

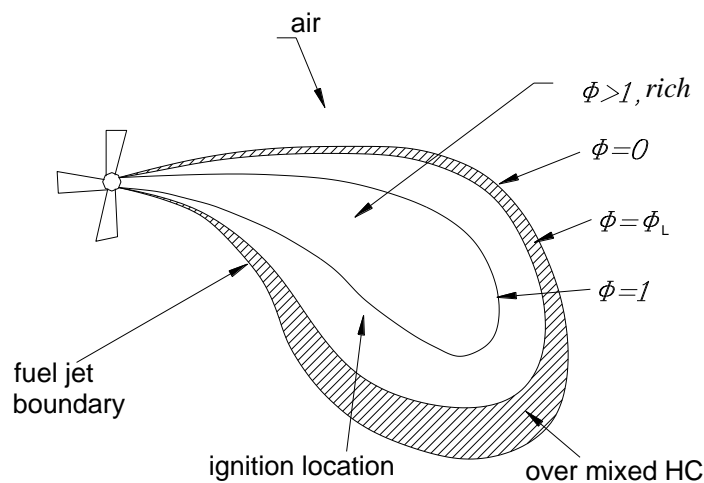


Fig. 1 - Equivalence ratio distribution at the beginning of combustion (Heywood 1981)

The ignition starts at a point in the slightly lean region downstream of the spray core, where the fuel air mixture has spent more time in the combustion chamber. In the mixing mechanism, the degree of mixing of fuel with air varies with equivalence ratio, Φ , and this value reaches the combustible limit Φ_L and approaches a limit of zero. At the middle of the spray core is a rich mixture of fuel.

In order to reduce the harmful effects of soot produced by diesel fuel combustion, various alternatives such as after treatment, modifications to the fuel injection system, fuel additives have been proposed. Out of many alternatives the addition of oxygenated fuels also has taken a significant attention. Fuels such as alcohols, vegetable oil, and bio diesel are considered as alternatives for oxygenated fuels (Shigeru Tosaka and Yasuhiro Fujiwara., 2000). The objective of the current study is to investigate the effect on soot formation of biodiesel produced for this experimental study.

2 EFFECT OF FUEL STRUCTURE ON SOOT FORMATION

Soot is formed from unburned fuel, which nucleates from the vapor phase to a solid

phase in fuel-rich regions at high temperatures. Out of the major hydrocarbon classes, unsaturated hydrocarbons, aromatics and polycyclic aromatic hydrocarbons have the greatest influence on soot formation. Shigeru Tosaka and Yasuhiro Fujiwara (2000), have carried out a series of tests to investigate the soot formation mechanisms of different hydrocarbon classes. It was revealed by Shigeru Tosaka and Yasuhiro Fujiwara, (2000) that different hydrocarbon classes start to form soot at different temperatures. Benzene starts to form soot at the lowest temperature and is increased in the order 1-hexane, cyclohexane and n-hexane. The fuel which starts to form particulate matter at lower temperatures emits higher amounts of particulate matter. It was further observed that benzene does not decompose and formation of soot took place through polymerisation and formation of polycyclic aromatic hydrocarbons.

Tao et. al. (2009) have explained in detail and validated a soot formation model. According to Tao et. al. the soot formation process can be explained in nine steps as shown in Fig. 2.

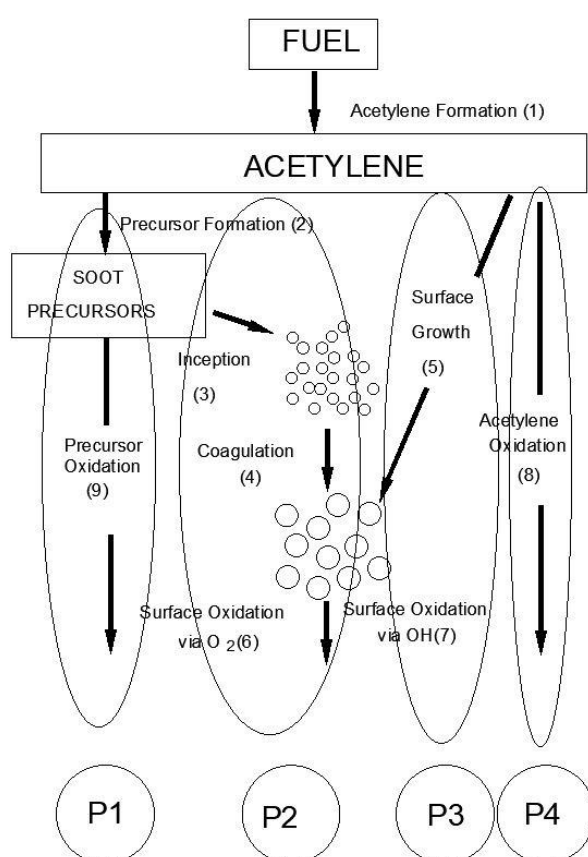


Fig. 2 - Soot formation model [Tao et.al (2009)]

According to Tao et. al. there are four main paths (P1- P4) for soot formation and the first step is fuel pyrolysis leading to the formation of acetylene which is a gas phase soot precursor. According to the model, soot can be formed by formation of precursors and soot formation by precursor oxidation (P 1).

The second path (P2) is via process 2, 3, 4 and 6 where, acetylene is formed via pyrolysis and soot precursors are formed. These soot precursors form young soot particles that

contain significant amount of carbon.

The developing soot particles are assumed to have a diameter of 1.28 nm, which corresponds to about 100 carbon atoms. These developing (budding) particles are coagulated and oxidized via OH to form final soot particles.

The third path (P3) is by formation of acetylene and direct surface growth and coagulation to form soot. The fourth path (P4) is direct acetylene oxidation.

Regardless of the path that the fuel particle follows, the general process can be summarised as:

- a) formation of gas-phase soot precursors,
- b) soot nucleation,
- c) surface growth and coagulations,
- d) soot oxidation.

According to the model, the local deficiency of oxygen favours the soot formation. Formation of soot precursors, inception and surface growth of soot is accommodated because of the deficiency of local oxygen. Based on the argument that soot is formed due to lack of local oxygen within the fuel core, the effect of oxygenated fuels (biodiesel) is investigated.

The formation of gas phase precursors involves the formation of Acetylene and involves the well-known hydrogen-abstraction-carbon-addition reactions (Zhang., 2016). The main soot precursors are considered to be acetylene, benzene and un-saturated Polycyclic Aromatic Hydrocarbons.

Although, the latest research has been able to elaborate more on the details, the above model remains valid up-to-date (Lei Xu et.al., 2022).

3 PRODUCTION OF BIODIESEL

All naturally existing fats and oils are esters of glycerol, consisting of three long-chain fatty acids that are bonded to a single glycerol molecule. With few exceptions, fatty acids, from which the fats and oils are derived, are straight chain compounds ranging in size from three to eighteen carbon atoms.

Since three long chain fatty acids are bonded together to form a glycerol molecule, such a compound is called a triglyceride. Triglycerides are heavy in molecular weight and low in cetane number compared to that of average diesel hydrocarbon. The length of carbon chains, as well as the number, orientation, and position of double bonds in these chains vary from one triglyceride to another. If the triglycerides are cracked and separated from the glycerol molecule by a suitable method, a hydrocarbon with the carbon number, which is almost equivalent to Cetane (hexa decane), can be obtained.

TRANSESTERIFICATION PROCESS

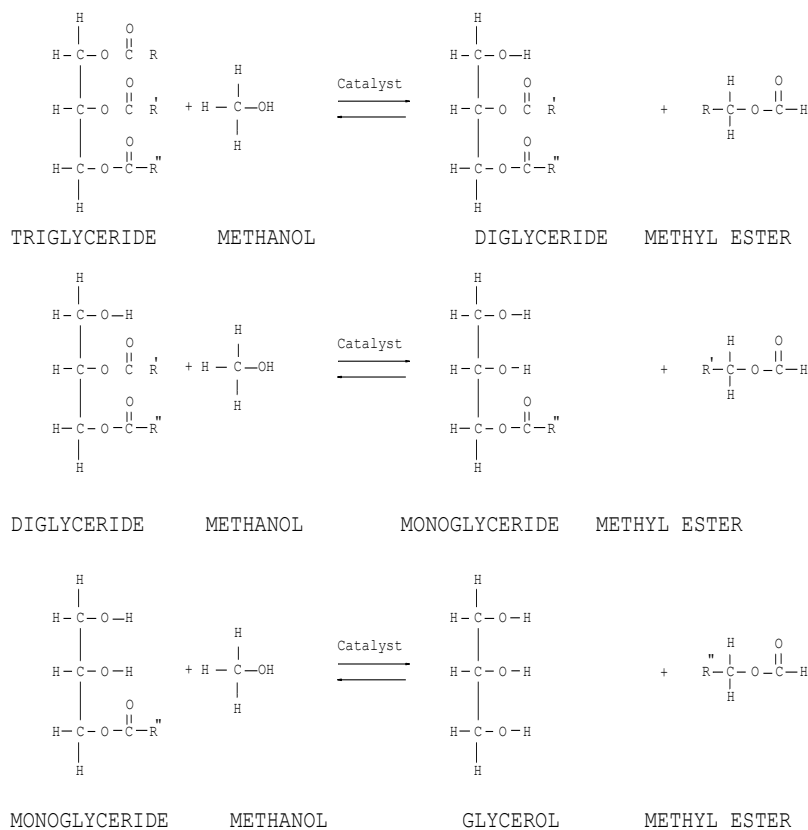


Fig. 3 - The process of biodiesel preparation

The bio diesel is prepared by breaking fatty acids from the glycerol molecule and joining an alcohol to the fatty acid as shown in Fig. 3. First the tri-glyceride is converted to a dy-glyceride by releasing a fatty acid molecule from the triglyceride to form a fatty acid ester. Then the dy-glyceride is converted to a mono-glyceride by liberating another fatty acid molecule. Finally, the mono-glyceride is converted to glycerol by liberating the third fatty acid molecule.

A catalyst is used to improve the reaction rate. Since the reaction is reversible, excess alcohol is used to shift the reaction to obtain the maximum yield of biodiesel.

After trans esterification, the mixture separates into fatty-acid methyl ester and glycerol (see Fig. 4). The fatty acid methyl ester is separated from glycerol by gravity and is washed. The neutral fatty-acid ester is called "biodiesel".

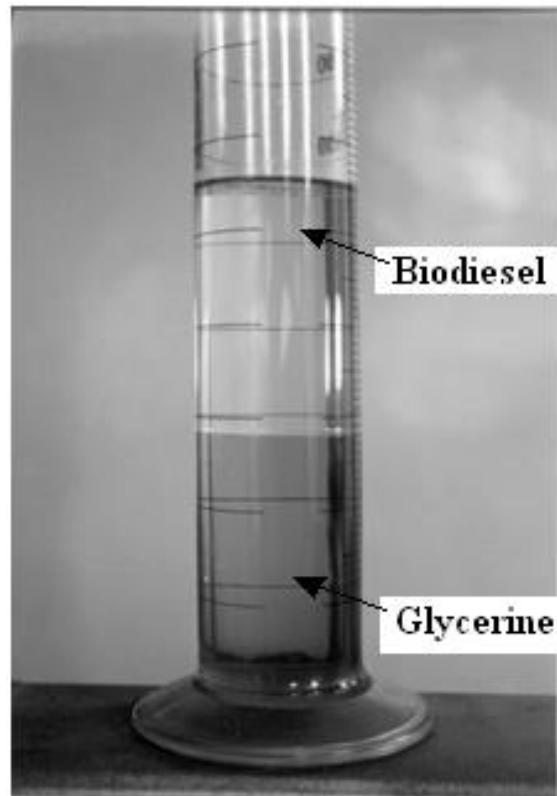


Fig. 4 - Separation of biodiesel

For the current study, coconut oil has been used with methyl alcohol to produce biodiesel. Biodiesel is an oxygenated fuel with a higher cetane number. The conversion of triglycerides into methyl or ethyl esters through the transesterification process reduces the molecular weight to one-third that of the triglyceride. Further, this reaction reduces the viscosity of vegetable oil and the final viscosity is almost similar to that of diesel fuel. These esters contain 10 to 11% oxygen by weight, which may encourage complete combustion than hydrocarbon-based diesel fuels in an engine.

Table 1 - Physical and Chemical Properties of Biodiesel and Diesel Fuel

Property	Diesel fuel	Biodiesel
Viscosity (cSt)	2.82	4.2
Flashpoint (°C)	83	113
Calorific value (kJ/kg)	45, 000	38,000
Cetane Index	40	60

The cetane number of biodiesel is around 60. Biodiesel has volumetric heating values about 12% less than diesel fuels, but has a high cetane number and high flash point. A comparison of physical properties of biodiesel and diesel fuel is given in table 1.

From the review on soot formation, two main factors contributing to the soot formation can be identified. (a) Polycyclic aromatic hydro carbons act as precursors for soot formation (b) Soot is formed in the fuel rich region of the fuel spray.

If biodiesel is used as a fuel or mixed with diesel fuel, major portion of fuel will consist of straight chain paraffin hydro carbons and this will reduce the tendency to form soot as the precursors are less. Further, biodiesel contain 10% - 11% Oxygen by mass which can help the combustion process within the fuel rich region.

4. FATTY ACID COMPOSITION ON SOOT FORMATION

Biodiesel is made from natural feedstock which consists of three long chain fatty acids that are bonded together to form a glycerol molecule. The hydrocarbon chain length of the fatty acid and the degree of saturation depends on the raw material used.

Table 2 - The composition, total saturated and total un saturated fatty acids by weight for some of the vegetable oils (Folayan 2019).

Fatty Acid	Formulae	Coconut oil	Palm oil	Soybean oil	Corn oil	Olive oil	Canola oil
Saturated components							
Caproic	C ₆ H ₁₂ O ₂	0.59	0.4	-	-	-	-
Caprylic	C ₈ H ₁₆ O ₂	8.1	3.8	-	-	-	-
Capric	C ₁₀ H ₂₀ O ₂	6.5	4	-	-	-	-
Lauric	C ₁₂ H ₂₄ O ₂	47	49.5	0.1	-	-	-
Myristic	C ₁₄ H ₂₈ O ₂	18.6	14.9	0.2	0.17	0.01	0.18
Palmitic	C ₁₆ H ₃₂ O ₂	8.4	7.8	10.5	12.1	13.6	4.35
Stearic	C ₁₈ H ₃₆ O ₂	2.6	2.5	3.8	2.3	2.7	2
Arachidic	C ₂₀ H ₄₀ O ₂	0.1	0.1	0.3	-	0.5	0.5
Behenic	C ₂₂ H ₄₄ O ₂	-	-	0.28	-	0.12	-
Ligoceric	C ₂₄ H ₄₈ O ₂	-	-	-	-	0.6	-
Total saturated		91.89	83	15.18	14.57	17.53	7.03
Unsaturated							
Palmitoleic	C ₁₆ H ₃₀ O ₂	-	-	-	0.12	1.65	0.275
Oleic	C ₁₈ H ₃₄ O ₂	6.4	14.7	23.7	30.9	68.2	59.4
Linoleic	C ₁₈ H ₃₂ O ₂	1.6	2.2	54.5	53.3	11.5	21.15
Linolenic	C ₁₈ H ₃₀ O ₂	0.1	-	6.3	1.1	0.9	10.35
Eicosenoic	C ₂₀ H ₃₈ O ₂	-	-	-	-	0.2	0.8
Erucic	C ₂₂ H ₄₂ O ₂	-	-	0.25	-	-	0.78
Total unsaturated		8.1	16.9	84.75	85.42	82.45	92.75

Wang et.al., (2016) have also observed that Biodiesels produce lower soot compared to diesel fuel because of the oxygen atoms in the fuel. Further Wang et. al., (2016) have observed that during the combustion, higher saturated biodiesel fuel produces less acetylene and soot precursors than un-saturated biodiesel and the acetylene production is proportional to the number of carbon-carbon double bonds in the Fatty Acid Methyl Ester structure. The net soot production is the result of the combined effect of acetylene and precursor species formation. Biodiesel fuels with a lower fraction of unsaturated Fatty Acid Methyl Esters result in lower soot emissions. Sarathy et.al., (2007) have concluded that unsaturated Fatty Acid Methyl Esters would have a greater tendency to soot than a saturated Fatty Acid Methyl Esters.

The fatty acid, formulae and the composition total saturated and total un-saturated fatty acids by weight for some of the commonly used vegetable oils to produce biodiesel is given in Table 2.

Out of the six oils compared in table 2, Canola oil has the highest un saturated content of 92.75% by mass and the lowest unsaturated content is for Coconut oil. The total unsaturated hydrocarbon content of coconut oil is 8.1% by mass. As it was observed by other researchers that lower the unsaturated fat, lower the soot concentration. It is expected that biodiesel produced from coconut oil would produce less amount of soot.

5. PROCEDURE

The experiment was carried out on a vehicle fitted with an engine of specifications given in Table 3. A separate MAHA LPS 200 opacity meter was used to measure the soot concentration of diesel emissions. The measurement of the opacity meter is based on the amount of light extincted during its travel when a gas containing certain amount of soot particles (Wang et.al., 2016). The smoke density is expressed on a per meter basis (m^{-1}) also known as the K factor. The zero and full scale readings of the smoke meter has been calibrated to display $0.0 \pm 1.0\%$ and $100.0 \pm 1.0\%$. Optical sensors were cleaned using purge air system of the opacity meter as per the manufacturer recommendation. Each test was repeated three times and average was taken. If the maximum deviation between three readings was more than 5%, the test was repeated. During operation, the accelerator pedal was moved to the fully open position as rapidly and held until the engine reaches tje maximum speed and the emission meter take a reading.

Table 3 -Test Engine Specifications

Type of engine	Four cylinder four stroke
Bore diameter	86 mm
Stroke	85 mm
Total displacement	1974 cm ³
Compression ratio	23:1
Turbocharger	None
Rated power	55 kW @ 4700 rpm
Peak torque	97 Nm@ 2600 rpm

Prior to the investigation, the injector pump was serviced and calibrated to manufacturers' specifications. A new set of injectors with correct injection pressure was fitted. In order to ensure that all fuel sediments were expelled from the system, the fuel system was completely flushed out before the engine was charged with a new fuel blend. The filter too was replaced for the same reason with the same frequency. Tests were carried out with 11 fuel samples which included 100% diesel fuel, 100% biodiesel samples and nine other blends of biodiesel in diesel fuel with compositions varying between 90 % (10% biodiesel) and 10% diesel fuel (90% biodiesel). The blend reference number and composition are given in table 4.

Table 4- Blends of fuels used for the experiment

Blend reference number	1	2	3	4	5	6	7	8	9	10	11
Diesel composition	100	90	80	70	60	50	40	30	20	10	0
Bio diesel composition	0	10	20	30	40	50	60	70	80	90	100

6. RESULTS

The engine was started and warmed up to the operating temperature. The K factor was measured for different fuel blends starting from blend 1 to blend 11 at full throttle position of the engine at snap acceleration as per the SAE J1667 standard test procedure (SAE J1667., 1996). The K factor for various biodiesel blends with diesel fuel was measured. Fig. 5 depicts the variation of opacity for various fuel blends.

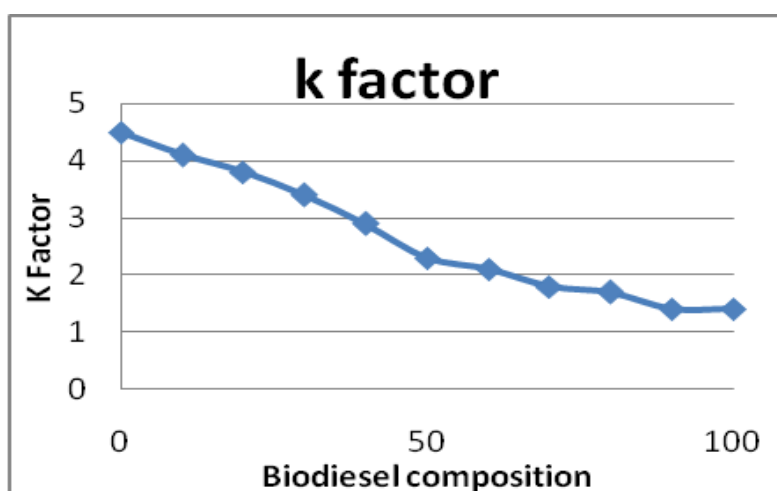


Fig. 5 - Soot Level for Various Biodiesel Blends with Diesel Fuel

From Fig.5, it is clear that the soot emission level of the engine has reduced with the increase of biodiesel concentration in the fuel. The lowest level of soot is recorded for 100% biodiesel. The K factor for diesel fuel was 4.5 and it has reduced to 1.4 when the test was carried out for pure biodiesel. When the engine was fuelled with 100% biodiesel, the soot level was reduced by 3.2 times compared to the soot concentration for 100% diesel fuel.

7. DISCUSSION

Biodiesel contains 10%-12% oxygen by mass and therefore it is a good oxygenator, which may help to burn hydrocarbons especially in fuel rich region of the diesel spray. Since the cetane number is high for biodiesel compared to that of diesel fuel, the ignition delay period is shorter for biodiesel, which results in less soot emissions. Absence of aromatic hydrocarbon and polycyclic aromatic hydrocarbon classes in biodiesel is the greatest advantage. Since aromatic and polycyclic aromatic hydrocarbons are acted as precursors for soot in flames, biodiesel does not provide necessary precursors for the process of soot formation. Low concentration of soot have been observed by Schobing et.al., (2018) when the biodiesel concentration was increased. Further they have observed that high concentration of bio diesel in diesel fuel have increased the oxygen concentration and ash content in soot. They have attributed this phenomena to better oxidation of soot with the increased amounts of biodiesel. Abbouda et.al., (2018) have carried out Soot volume fraction measurements for three different methyl ester compounds as Methyl butanoate, methyl octanoate and methyl decanoate. They also have observed a reduction in soot concentration with the increase of Biodiesel concentration. Further, they have observed a decreasing carbon formation with decreasing the carbon chain length of methyl ester. Tian et. Al. (2019) have applied Extinction calibrated laser induced incandescence (LII) to measure the soot volume fraction in laminar pool fires. They have observed that the peak soot volume fraction produced by neat biofuels are 10.6 to 32.6% that of diesel fuel. Further, they have observed slower reduction in total soot amount for blending of small quantities of biodiesel and faster decrease towards neat biodiesel.

8. CONCLUSION

It was revealed in the experimental investigation that biodiesel has a significant soot suppressing effect and biodiesel can be used as a soot inhibitor.

During the experimental investigation, the soot concentration varied between 4.5 and 1.3. The lowest soot concentration was observed when the vehicle was fueled with 100% bio diesel (blend 11) and the highest amount was observed when the vehicle was fueled with pure diesel fuel (blend 1). The difference is a 71,1% reduction in soot concentration from that of pure diesel fuel. At higher concentration of biodiesel blends such as 90%(blend 10) - 70% (blend 8), the soot concentration remained below 2 and the percentage reduction of soot concentration was more than 57% of that for pure diesel fuel. At low concentrations of biodiesel, the reduction of soot concentration was not significant. When the biodiesel concentration varied from 10% - 30% (blend 2 and blend 4), the soot concentration varied between 4.1 and 3.4 which is only a 17% reduction from that of the pure diesel fuel. The results obtained during the research are in comparison with the outcome of other researchers.

7. ACKNOWLEDGEMENT

The authors wish to acknowledge the contribution of Mr KCK Deraniyagala in conducting this research.

REFERENCES

1. Lei Xu , Yu Wang c, Dong Liu (2022) Effects of oxygenated biofuel additives on soot formation: A comprehensive review of laboratory-scale studies *Fuel* 313 122635
2. Lighty J S, Veranth JM, Sarofim A F(2011) Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health. *J Air Waste Manage* 2011;50:1565–61
3. John B. Heywood, (1981). *Internal combustion engine fundamentals* - New York: McGraw-Hill.
4. Shigeru Tosaka and Yasuhiro Fujiwara (2000), *The characteristics of chemical reaction of diesel fuel*. Society of Automotive Engineers of Japan.
5. Feng Tao, Rolf D. Reitz, David E. Foster and Yi Liu, (2009) Nine-step phenomenological diesel soot model validated over a wide range of engine conditions. *International Journal of Thermal Sciences* 48 1223–1234
6. Hong-Bo Zhang, Dingyu Hou, Dingyu Hou, Chung K Law, Xiaoqing You Xiaoqing You (2016) The Role of Carbon-Addition and Hydrogen-Migration Reactions in Soot Surface Growth *The Journal of Physical Chemistry A* 120(5)
7. Society of Automotive Engineers (SAE) J1667 Recommended Practice, 1996, Snap Acceleration Smoke Test Procedure for Heavy-Duty Powered Vehicles.
8. Julie Schobing, Valerie Tschamber, Alain Brillard, Gontrand Leysens, Eduard Iojoiu, Vincent Lauga (2018), Impact of engine operating cycle, biodiesel blends and fuel impurities on soot production and soot characteristics; *Combustion and Flame* 198 (2018) 1–13
9. Johnny Abbouda, Julie Schobingb, Guillaume Legrosa, Alexis Matyniaa, Jérôme Bonnetya, Valérie Tschamberb, Alain Brillardb, Gontrand Leysensb, Patrick Da Costaa (2018) Impacts of ester's carbon chain length and concentration on sooting propensities and soot oxidative reactivity: Application to Diesel and Biodiesel surrogates; *Fuel* 222 (2018) 586–598.
10. B. Tian, C.T. Chong, L. Fan, J.H. Ng, C. Zhang, S. Hochgreb (2019); Soot volume fraction measurements over laminar pool flames of biofuels, diesel and blends; *Proceedings of the Combustion Institute* 37 (2019) 877–884
11. Zhi Wang, Li Li, Jianxin Wang, Rolf D. Reitz(2016) Effect of biodiesel saturation on soot formation in diesel engines; *Fuel* 175 (2016) 240–248
12. S.M. Sarathy, S. Gail, S.A. Syed, M.J. Thomson, P. Dagaut;(2007) A comparison of saturated and unsaturated C4 fatty acid methyl esters in an opposed flow diffusion flame and a jet stirred reactor, *Proceedings of the Combustion Institute* 31 (2007) 1015–1022.
13. Adewale Johnson Folayan, Paul Apeye Lucky Anawe , Adeyemi Emman Aladejare , Augustine Omoniyi Ayeni (2019), Experimental investigation of the effect of fatty acids configuration, hain length, branching and degree of unsaturation on biodiesel fuel properties obtained from lauric oils, high-oleic and high-linoleic vegetable oil biomass *Energy Reports* 5 (2019) 793–806
14. Zhi Wang, Li Li a, Jianxin Wang, Rolf D. Reitz (2016), Effect of biodiesel saturation on soot formation in diesel engines *Fuel* 175 (2016) 240–248