Experimental Study of Adding Kerosene to the Recycled Lubricating Oil in a Diesel Engine Fuel

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ABSTRACT - *A pressurized injector chamber was used to test the effect of using pure petroleum diesel (denoted by W0), RWLO (Recycled Waste Lubricating Oil)-diesel blends (20 % RWLO + 80 % diesel fuel (denoted by W20), 40 % RWLO + 60 % diesel fuel (denoted by W40)) and RWLO-diesel-kerosene blends on spray characteristics.*

Using RWLO as a fuel affected the spray characteristics due to the difference in its physical properties as RWLO has higher viscosity when compared to diesel fuel. Experiments showed that spray penetration is increased by about 27 % while cone angle showed an opposite behavior as it decreased by about 47 % when compared by pure diesel. The brake specific fuel consumption (BSFC) is increased by about 14 % while the brake thermal efficiency showed an opposite behavior as it reduced by about 12 % when compared to W0. Tail pipe emissions are increased upon switching from diesel fuel to diesel/RWLO blends as unburned hydrocarbons and carbon monoxide emissions are increased by about 60 and 22 % respectively when compared to diesel fuel

Kerosene was added as an additive due to its low viscosity in addition to its high calorific value when compared to diesel fuel. Such changes in physical and chemical properties for the blend when kerosene is added as an additive improved the engine performance and emissions significantly as shown in the following sections.

Keywords: Recycled Waste Lubricating Oil, RWLO-diesel-kerosene blends, Spray characteristics, Engine performance, High viscosity Fuel

1- INTRODUCTION

It is becoming increasingly difficult to ignore the increasing impact of air pollution caused by using fossil fuels, fossil fuels depletion, being concentrated in certain places in the world and their high costs [1, 2, 3]. One of the most significant current discussions is how to make alternative fuel sources more attractive. Therefore, alternative energy resources and energy from waste material such as waste frying cooking oils, waste lubricating oils, plastics, and tires are grapping the attention these days. However, a major problem with this kind of waste materials is it cannot be used as an engine fuel directly. Several processing includes filtration and purification to remove undesirable particles which may harm the fueling system of an engine.

Waste engine oil loses its physical properties due to its exposure to high temperatures in addition to the fact that it holds many suspended matters resulted from the engine operation. About 40 million metric tons per year of waste lubricating oils are produced all over the world, and around 60% of the production becomes waste and most of them, which is improper, disposed or lost in use [4]. One liter of waste lubricating oil being improperly disposed to the environment contaminates about 810,000 liters of water and about 5,000,000 tons of clean water not usable. Such numbers show the importance of converting the waste oil into a usable fuel [5]. The issue has grown in importance in light of recent numbers. The new technologies developed during the last years made it possible to produce diesel fuel from recycled waste lubricating oils with an added attractive advantage of being lower in price.

The availability of waste lubricating oil and its higher flash and fire point which makes it safer to handle and store compared to diesel fuel are some of the advantages of using RWLO as a fuel. Their disadvantages, however, include the higher viscosity in addition to its lower calorific value and volatility. Most studies in this field have only focused on using oil directly without applying any changes on its physical structure. Some major drawbacks of this approach is that using high viscosity fuels may lead to problems such as severe engine deposits, injector cooking, piston ring sticking and blockage of fuel lines and filters which act as a key problem for using waste lubricating oil as a fuel. One question that needs to be asked, however, is how to lower the viscosity of the oil in order to make it suitable for engines.

In order to compromise such conflicting features to run diesel engines without modification, blending of RWLO and kerosene with the petroleum diesel fuel was the aim of this study. The production of a fuel which can be used to operate diesel engines from waste lubricating oil offers a triple-facet solution: economical, environmental and waste management. The main issues addressed in this paper are:

- Examining the physical properties for the blends in order to determine the best mixture with properties similar to diesel fuel after adding kerosene as an additive.
- The effect of using different blends on fuel on spray characteristics, engine performance and emissions.

The main of the present work is to ensure simultaneous reduction in the tailpipe exhaust emissions specially carbon monoxide and unburned hydrocarbons emissions while enhancing the performance by improving the thermal efficiency and reducing the fuel consumption.

2- MATERIALS AND METHODS

Firstly, the RWLO has passed through several filters in order to ensure that there are no suspended particles or metals inside it which may cause damage to the injection circuit when used as a fuel engine. Then, the filtered oil was heated to 200 °C for one hour, to evaporate the water. Sulphuric acid was then added with a percentage of 10 % by volume of the oil while the whole mixture was stirred for 10 minutes. The mixture was left for 24 hours in order to allow the additives to settle down at the bottom of the container forming a semi solid substance (sludge). Thus useful oil was easily extracted. Such process helps to lower the viscosity of oil to appropriate level as shown in section 5.1.1. in order be used as a fuel in diesel engines. A 10 % by weight of sodium hydroxide was add to the extracted oil to neutralize the effect of any remaining acid to avoid any damage to the injection system. Finally, kerosene was added as an additive in order to investigate its effect on the spray behavior, engine performance and emissions [6].

3- SPRAY CHARACTERISTICS EXPERIMENTAL PROCEDURES

A pressurized chamber was fabricated to characterize the spray pattern of different blends of RWLO and kerosene with the petroleum diesel fuel. . The chamber consists of 4 sides of steel, 2 sides of acrylic glass, air valve and a typical Diesel injector as shown in Figure 1, Figure 2 and Figure 3. The steel walls are 4 mm thick while the acrylic walls are 10 mm thick in order to withstand such pressure and to visualize the spray length penetration and cone angle. The chamber can be pressurized up to 7 bar all the results obtained were compared to W0 in order to find the optimal blend. Canon EOS Rebel T5 18MP DSLR digital camera was used to take pictures for the spray behavior when different blends were used.

4- ENGINE PERFROMANCE EXPERIMENTAL PROCEDURES

A Twin-cylinder, air-cooled, four-stroke, diesel engine type DEUTZ F2L-511 operating at a constant speed of 1500 rpm was used in the experiments. The basic specifications of the engine are shown in Table 1. The engine is connected to a 3-phase electric generator used to supply electricity to three rows of lamps (3L), each containing three lamps (100W each) and three rows of heaters (3H), each containing three heaters (≈ 1200 W each) representing about 90 % of full load.

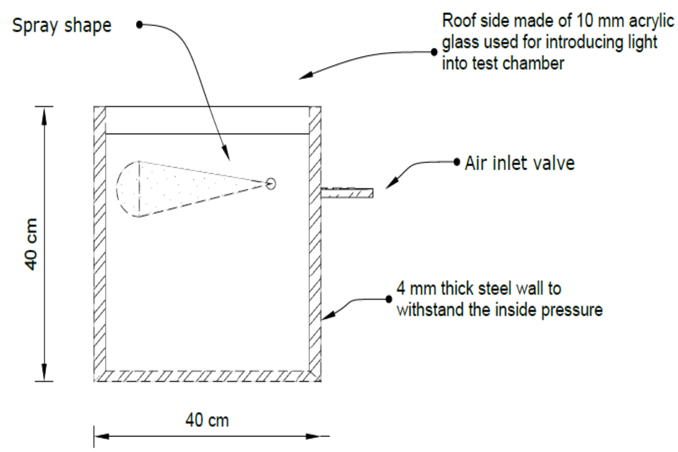

Fig-1: Front view of the pressurized chamber

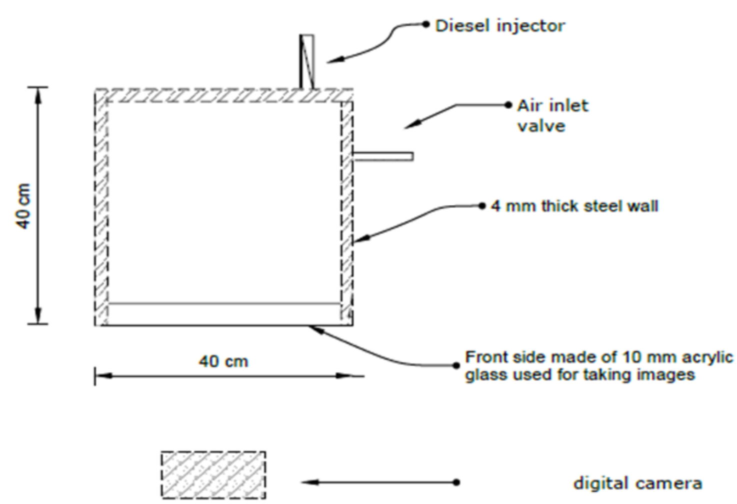

Fig-2: Plan view of the pressurized chamber

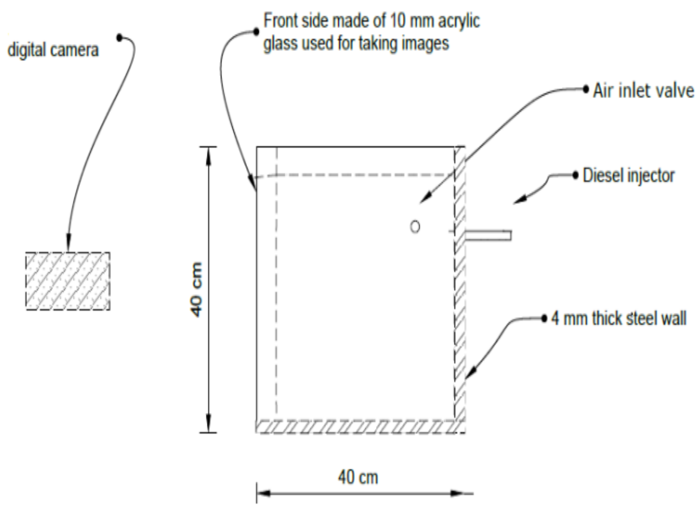

Fig-3: Side view of the pressurized chamber

An exhaust gas analyzer integrated with a K-type thermocouple probe was employed to measure the exhaust gas species concentrations for NOx, HC and CO as well as the exhaust gas temperature. To ensure the accuracy of the measured values, the gas analyzer was calibrated before the measurement. The exhaust gas suction probe was made with a tapered end to minimize the flow disturbances and it was confined by a cooling water jacket to keep the species concentrations at their levels at the point of measurement.

Table 1: Detailed Specifications of the test engine

Engine Model	DEUTZ F2L-511 , four-Stroke, Naturally-Aspirated
Max Power	13.6 kW
Max Toque	88 N.m.
Displacement	1650 cm^3
Number of Cylinders	2
Bore	100 mm
Stroke	105 mm
Rated Injection Pressure	165 bar
Type of injection system	Direct injection
Compression ratio	17:1
Cooling type	Air cooled

The temperature readings were corrected for the radiation, convection, and conduction heat transfer from the thermocouple bead whose diameter is 0.5 mm. Data were recorded after reaching a steady state as indicated by the exhaust gas and cooling water temperatures utilizing K-type thermocouples. Table 2 shows the uncertainty values corresponding to the systematic errors of the respective quantities measured.

Table 2: Uncertainty analysis due to systematic errors.

Variable	Uncertainty due to systematic errors (%)
Spray penetration length	0.30
Spray cone angle	2.40
Engine brake power	0.24
Brake-specific fuel consumption	4.47
Exhaust gas temperature	0.34
HC concentration	1.51
CO concentration	0.15
NOx concentration	0.17
CO2 concentration	0.26

The fuel consumption was calculated by measuring the time during which the engine consumed a certain quantity of fuel. The experiments were carried out by using W0 as the base line fuel at fifteen different engine loads. Kerosene was added as an additive to W40 fuel with concentrations of 5, 10, 20 and 30 %. The density of RWLO which was produced from waste engine oil was measured by dividing the mass of a known volume by that volume.

To evaluate the engine performance, the important operating parameters such as power output, fuel consumption and exhaust emissions were measured. Significant engine performance parameters such as the BSFC and BTE when using RWLO and its blends were calculated.

5- RESULTS AND DISCUSSION

Spray analysis, engine performance and emissions while using kerosene as an additive are discussed in details in the following sections

5.1. FUEL PHYSICAL PROPERTIES

5.1.1. Viscosity Measurement

The Engler viscometer was used to measure the viscosity of the fuels used in the experiments. It has been observed that as the content of waste lubricating oil in diesel-RWLO blends increase, the mixture viscosity increased as shown in Chart 1. The increased viscosity of the fuel mixture will raise significantly the Ohnesorge number. This effect will be counteracted by the increased liquid density and surface tension of the mixture. On the other hand, the increased values of surface tension will lead to lower Weber numbers, resulting in poor atomization which is reflected on reducing the combustion efficiency and increasing the tail pipe emissions such as carbon monoxide and unburned hydrocarbons emissions [7-10]. Higher density and bulk modulus of RWLO result in an injection pressure increase in the conventional injection system, which is reflected in advanced injection, higher spray velocity, narrower spray cone, and larger penetration length [11].

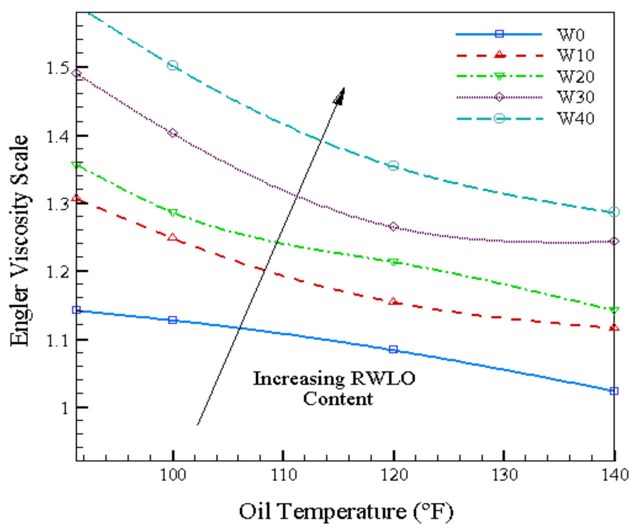

Chart-1: Engler viscosity scale for diesel-RWLO blends

In order to overcome the undesirable effect of using RWLO on engine parts, performance and emissions, the viscosity of the mixture was reduced by adding a low viscosity material as an additive to the mixture such as kerosene as shown in Chart 2., Kerosene was added gradually in order to reach to the right mixture that does not only enhance the viscosity of the mixture but also restore it to values close to diesel fuel.

Using 30 % kerosene as an additive to 40 % RWLO + 30 % diesel fuel lowered the viscosity of the mixture to values almost the same to those obtained when using diesel at different temperatures as shown in Chart 1 and Chart 2. This combination with such percentages introduced a new fuel capable of solving one the problems occurred when using diesel-RWLO blend which is the high viscosity. Lowering the viscosity of the mixture will automatically enhance both engine performance and emissions.

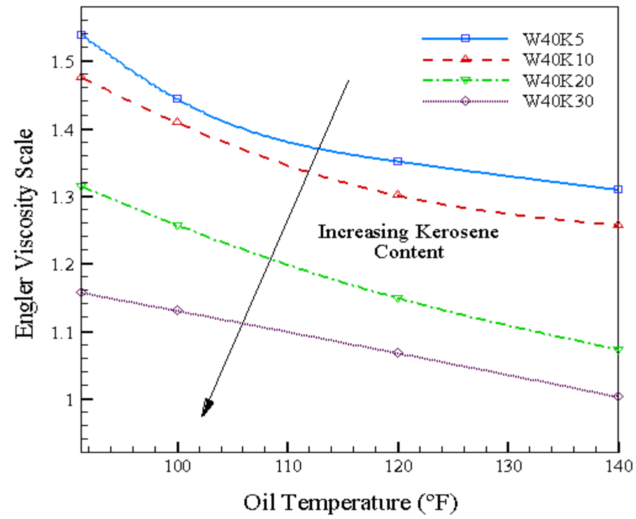

Chart-2: Engler viscosity scale for diesel-RWLO-kerosene

5.1.2. Flash Point and Fire Point

Chart 3 shows the flash and fire point for different concentrations of fuels when using closed cup method [15]. Chart 4 shows the flash and fire point for different concentrations of fuels when using open cup method. As illustrated, diesel-RWLO blends show an increasing trend for the flash point when increasing the RWLO content in the fuel which indicates a successive decrease in the volatility of the fuel which is consequent to lowering the mixture viscosity. Flash and fire points are directly proportional with the distillation temperature of the fuel which means as the flash and fire points increase, it can be predicted that this will eventually cause the evaporation temperature to increase as well.

Such behavior means that more energy is required to evaporate the fuel droplets thus increasing the fuel consumption which is reflected on lowering the combustion efficiency. High evaporation temperatures will lower the possibility for enhancing the spray atomization which will cause engine deposits, injector cooking, piston ring sticking, blockage of fuel lines and filters, and high nozzle valve opening pressures as well as longer spray penetration and reducing the cone angle which proofs the results found during the viscosity measurement. The fuel's volatility also has a significant influence on ignition delay time. Ignition delay period starts with the injection of fuel and consists of physical and chemical delay periods until the auto-ignition occurs.

Adding kerosene as an additive showed an opposite behavior as both flash and fire point started to decrease when the content of kerosene increased in the fuel mixture. Although adding kerosene added an advantage of lowering the viscosity of the fuel which will enhance the combustion but the mixture become less safe to be handled and should be handled carefully. Lowering both flash and fire points will lower the evaporation temperature thus enhancing the atomization of the fuel which reduces the fuel consumption which by turn enhance the combustion efficiency and reduce the tail pipe emissions. The reduction in the flash and fire points when using kerosene as an additive will be reflected positively on the fuel cetane number. Using W40K30 as a fuel lowered both flash and fire point when compared to diesel/RWLO blends but it still higher than those obtained when using pure diesel which means it's safer to handle and store then diesel fuel.

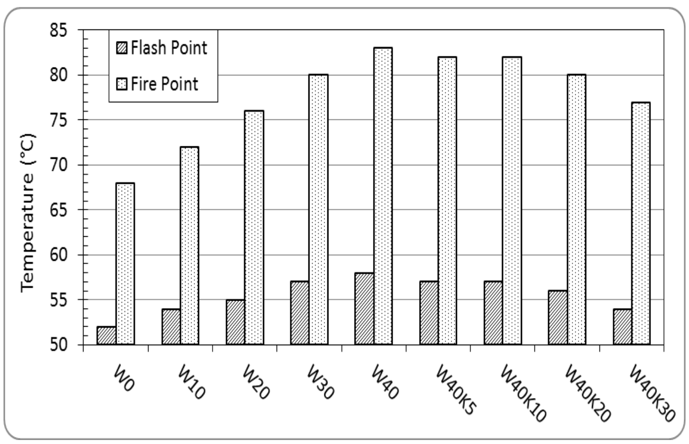

Chart-3: Closed cup method for measuring flash and fire point

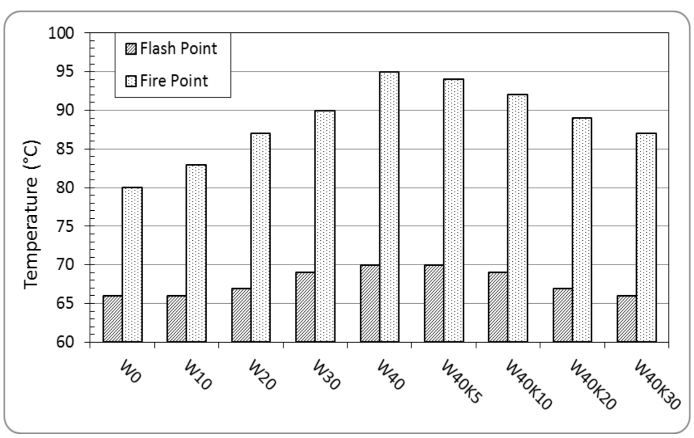

Chart-4 :Open cup method for measuring flash and fire point

5.1.3. CALORIFIC VALUE

The net calorific value was then obtained by subtracting the latent heat of the water present from the gross calorific value. The latent heat of vaporization of water is 2.5 MJ/kg [18].

The heating values of diesel, RWEO and kerosene were measured by using the bomb calorimeter while the heating value of W10, W20, W30, W40, W40K5, W40K10, W40K20 and W40K30 was calculated by using equation (1). The calorific values (C.V.) are shown in Table 3

Calorific Value of the mixture = (% diesel × C.V. of diesel) + (% RWEO × C.V. of RWEO) + (% kerosene × C.V. of kerosene) (1)

Fuel	Calorific Value of the	Fuel	Calorific Value of
Diesel	43120	W40	42714
RWLO	42105	W40K5	42824
Kerosene	45320	W40K10	42934
W10	43018.5	W40K20	43137
W20	42917	W40K30	43154
W30	42815.5		

Table- 3: Experimental and numerical results of calorific value for diesel, RWEO, blends and RWEO – Kerosene blend

As illustrated in Table 3, the calorific value of RWLO is lower that of diesel fuel. Adding kerosene to the blends increased the total calorific value of the mixture which will in turn reduce the fuel consumption and enhance the combustion efficiency.

Using W40K30 introduced a fuel with higher calorific value then pure diesel and diesel/RWLO blends. Such advantage will help to lower the fuel consumption due to the increase occurred in the energy content of the fuel which means enhancing the thermal efficiency.

5.2. COMPARATIVE SPRAY CHARACTERISTICS

It was observed that the spray penetration length of injector (1) was about 17.1, 20.3 and 21.7 cm for W0, W20 and W40 respectively. W20 and W40 showed a percentage increase by about 19 and 27% respectively when compared to W0. The cone angle was 17°, 10° and 9° cm for W0, W20 and W40 respectively. W20 and W40 showed a percentage decrease by about 41 and 47 % respectively when compared to W0 as shown in Figure 4-a, Figure 4-b and Figure 4-c.

Figure 4-a: Injector (1) –W0 spray development

Figure 4-b: Injector (1) –W20 spray development

Figure 4-c: Injector (1) –W40 spray development

Figure 5-a: Injector (1) –W40K5 spray development

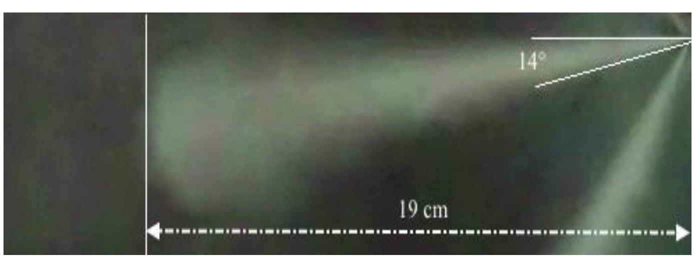

Figure 5-b: Injector (1) –W40K10 spray development

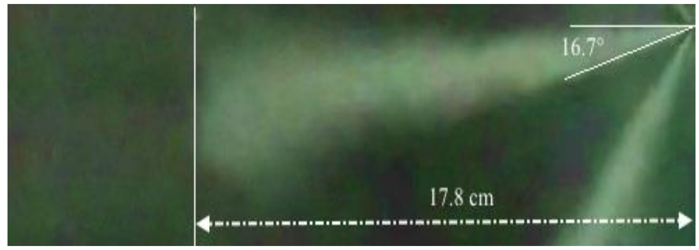

Figure 5-c: Injector (1) –W40K20 spray development

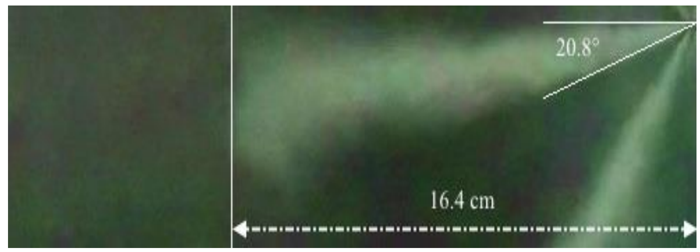

Figure 5-d: Injector (1) –W40K30 spray development

Such behavior was found by Heilig et al., Kuti et al., Jaafar el al. and Pogorevc et al. [12-16]. The reason for such behavior is due to the difference in the fuel physical properties which is reflected in the spray characteristics. The higher density and bulk modulus of RWLO result in an injection pressure increase in the conventional injection system, which is reflected in advanced injection, higher spray velocity, narrower spray cone, and larger penetration length.

Adding kerosene as an additive showed an opposite behavior as the spray penetration started to decrease. The spray penetration was about 19.6, 19 and 17.8 cm for W40K5, W40K10 and W40K20 respectively with a percentage increase of about 15, 11 and 4 % when compared to W0. The spray penetration of W40K30 decreased as it reached about 16.4 cm with a percentage reduction of about 4 % when compared to W0. The spray angle was about 10°, 14° and 16.7° for W40K5, W40K10 and W40K20 respectively with a percentage decrease of about 41, 17 and 1.7 % when compared to W0. Using W40K30 increased the spray angle further beyond W0 to about 20.8° with a percentage increase of about 22 %. Figure 5-a, Figure 5-b, Figure 5-c and Figure 5-d show the spray development of injector (1) for W40K5, W40K10, W40K20 and W40K30 respectively.

Such behavior is due to decreasing the viscosity of the mixture when using kerosene leading to a reduction of the penetration length and increase of the spray angle. It is noted that when using W40K30, the spray characteristics were enhanced further more when compared to diesel fuel leading to a conclusion that this fuel is the required mixture as it did not only eliminate the effect of using a high viscosity fuel such as RWLO but it enhanced it when compared to W0.

5.3. ENGINE PERFORMANCE AND EMISSIONS

It was observed that W40K30 showed an enhancement in the spray behavior when compared to W0. The same four blends were used (W40K5, W40K10, W40K20 and W40K30) to run a diesel engine.

5.3.1. BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)

Chart 5 shows the variation of BSFC of the RWLO-diesel blends versus the brake power of the engine when compared to W0. It was observed that as the RWLO content increase, the BSFC increases. The highest percentage increase in BSFC was about 14 % at 0.53 kW engine power when using W40 as a fuel when compared to W0. This is due to the low calorific value of RWLO compared to diesel fuel which means that the engine needs to consume more fuel in order to compensate such loss in order to produce the same output power. Low cetane number will contribute as well in increasing the fuel consumption.

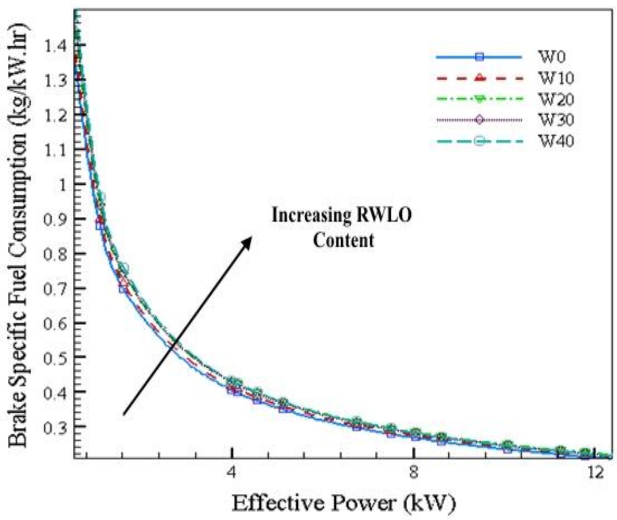

Chart 5: Variation of BSFC versus brake power for RWLO-diesel blends

Chart 6 shows the percentage difference of BSFC of W40, W40K5, W40K10, W40K20 and W40K30 when compared to W0. In general, it was observed that the BSFC values of the RWLO-diesel-kerosene blends were lower than those of W40 fuel all over the range of engine loads which is similar to results obtained by Obodeh and Isaac [16] and Kadhim [27]. It has been observed that using W40K30 reduced the BSFC beyond diesel fuel which agrees with the results obtained from the spray analysis. The percentage reduction in BSFC was about 7% at 8.05 kW engine power when compared to W0. The BSFC of diesel engine depends on the fuel injection system, fuel density, viscosity and lower heating value. Such reduction is due to the higher calorific value and low latent heat of vaporization of kerosene when compared to diesel fuel.

The low volatility of the fuel mixture when using kerosene as an additive improves the cetane number of the fuel. Increasing fuel CN reduces BSFC, although it is still high at low loads. Increasing fuel's CN improves combustion and raises combustion chamber temperatures. Increasing combustion chamber temperatures gives low fuel delay period, and gives better ignition. Reducing the load reduces temperatures inside combustion chamber, and increases fuel delay period, resulting in bad combustion that needs more fuel to compensate the lost power [17].

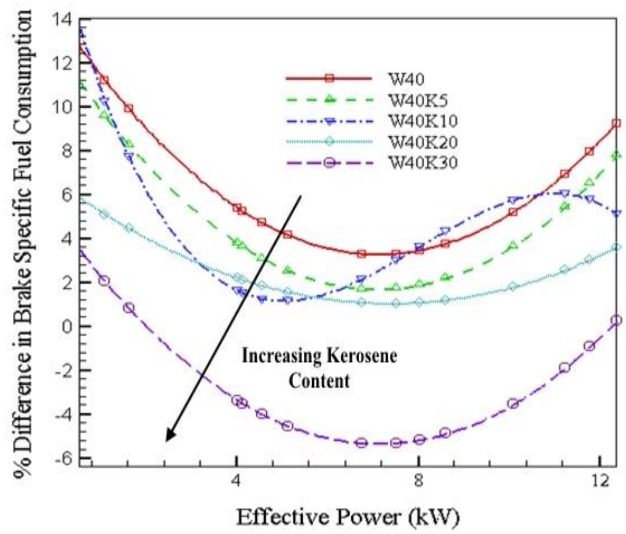

Chart 6: Percentage difference of BSFC for RWLO-diesel-kerosene blends

5.3.2. BRAKE THERMAL EFFICICENCY

The BTE values calculated for RWLO blends with the diesel fuel are shown in Chart 7. It was observed that as the RWLO content increased, the BTE decreased. The highest percentage reduction for BTE was 11 % for the W40 blend at 0.53 kW engine power when compared to W0. Such reduction is due to low calorific value of RWLO when compared to diesel in addition to the increase in fuel consumption and the incomplete combustion occurred due to the high viscosity of the fuel and low cetane number when compared to diesel fuel.

When kerosene was added to W40, it increased the BTE at all engine loads as shown in Chart 8. Such results were similar to the results obtained by Obodeh and Isaac [16], Venkanna1 [26] and Kadhim [27]. Chart 8 shows the percentage difference of the BTE versus the brake power for W40, W40K5, W40K10, W40K20 and W40K30 when compared to W0. Using W40K30 as a fuel increased BTE by about 7 % when compared to W0. Such increase is due to the reduction in BSFC and the increase in the calorific value in addition to higher cetane number when compared to other blends.

5.3.3. EXHAUST GAE TEMPERATURE

The EGT indicates the effective use of the heat energy of a fuel. It was observed that when the RWLO content in the fuel blend increased, the EGT increased as shown in Chart 9. The results obtained match the results found by Arpa et al [18-19]. The reason for such increase is due to the following factors:

a) Injection timing advance: The higher bulk modulus of RWLO causes an advance in the start of injection. Such behavior leads to an earlier start of combustion, yielding higher in-cylinder temperatures during expansion.

b) High distillation temperatures for RWLO results in higher values in exhaust gas temperature for the RWLO. As a result of the higher combustion temperature, EGT will increase. [20-22]

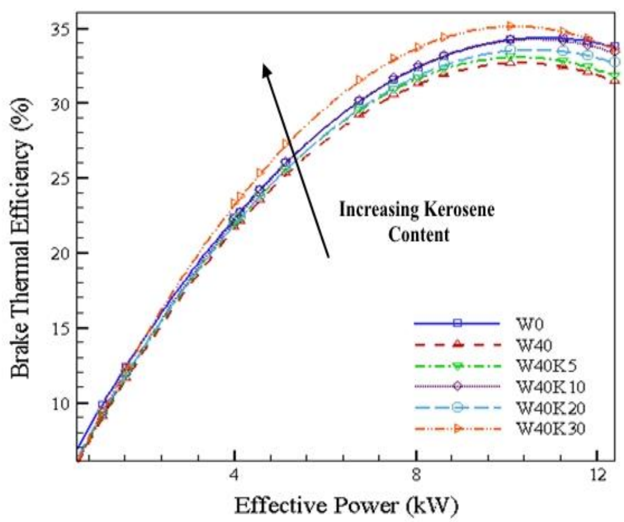

Chart 7: Variation of BTE versus brake power for RWLO-diesel-kerosene blends

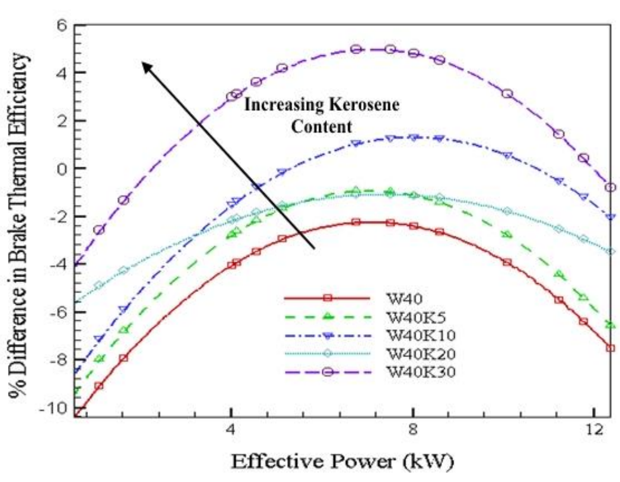

Chart 8: Percentage difference of BTE for RWLO-diesel-kerosene blends

When kerosene was added as an additive, the EGT increased as shown in Figure 14. Such behavior is similar the trend observed by Kadhim [27].The reason for such trend is due to the higher calorific value and cetane number of kerosene when compared to diesel or is due to that the air cooling system was not able to dissipate heat fast enough specially at high loads. Increasing the fuel cetane number improves combustion and raises combustion chamber temperatures.

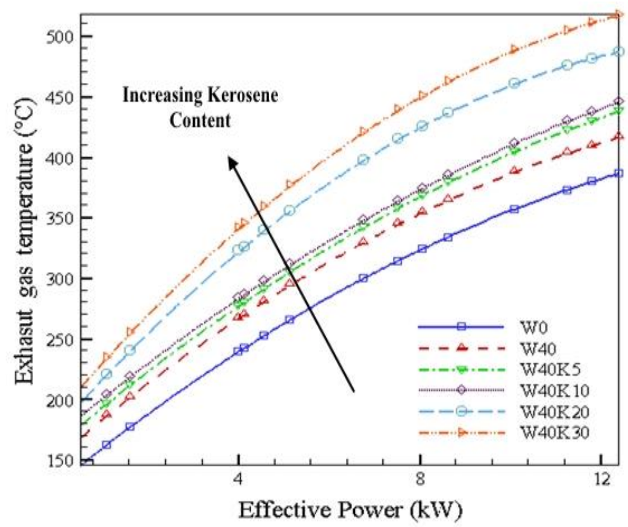

Chart 9: Variation of EGT versus brake power for RWLO-diesel-kerosene blends

5.3.4. UNBURNED HYDROCARNONS EMISSIONS

When using RWLO as a fuel, HC emissions increased when compared to W0 as shown in Chart 10. Such behavior is observed by Cataluña1 and Da Silva [22]. The use of high viscosity fuels delays vaporization, favoring the formation of large diameter droplets and causing incomplete combustion due to the high penetration of the fuel jet, delaying cold starts and increasing the emission of unburned hydrocarbons. RWLO has a low cetane number compared to diesel leading to longer ignition delay and hence incomplete combustion occurs as more fuel is burned in the expansion stroke. Lowering the CN reduces the maximum pressure after TDC, reducing the torque and the maximum temperature in the chamber, which directly affects the emissions unburned hydrocarbons.

When kerosene was added, the unburned hydrocarbon emissions were reduced as shown in Chart 11. Such behavior meets with the results obtained by Sethi and Salariyas [24] and Venkanna1 [26]. As kerosene concentration increased, the viscosity of the mixture decreased leading to decrease the droplet size and improve atomization as well as the heat released by the fuel also increased and which improved combustion and promoted the combustion efficiency, thus, decreasing the emissions of the unburned hydrocarbons.

Using W40K30 as a fuel reduced the emissions by about 10 % at 8.05 kW engine power when compared to W0 which proves that this mixture is the suitable one to be used.

5.3.5. CARBON MONOXIDE EMISSIONS

Chart 12 shows the variation of the CO emissions corresponding to W40 W40K5, W40K10, W40K20 and W40K30 with respect to standard diesel versus engine power. It was observed that when RWLO content increased in the fuel blend, the CO emissions increased. Such behavior assembles the behavior found by Cumali and Hüseyin [25] and Arpa et al. [18-19]. The reason for such behavior is due to the poor atomization, lower cetane number and longer ignition delay.

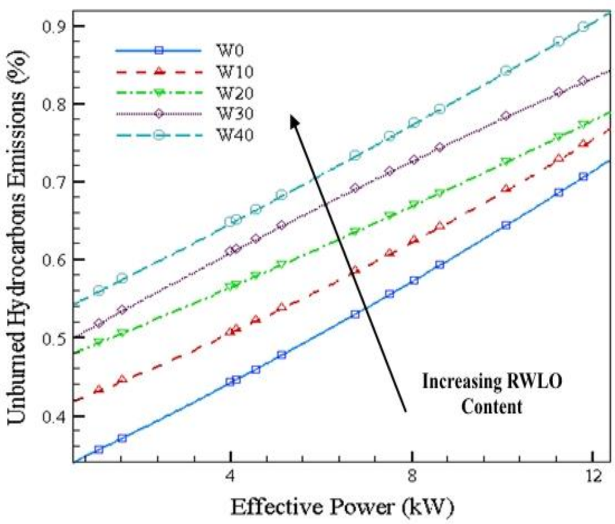

Chart 10: Variation of HC emissions versus brake power for RWLO-diesel blend

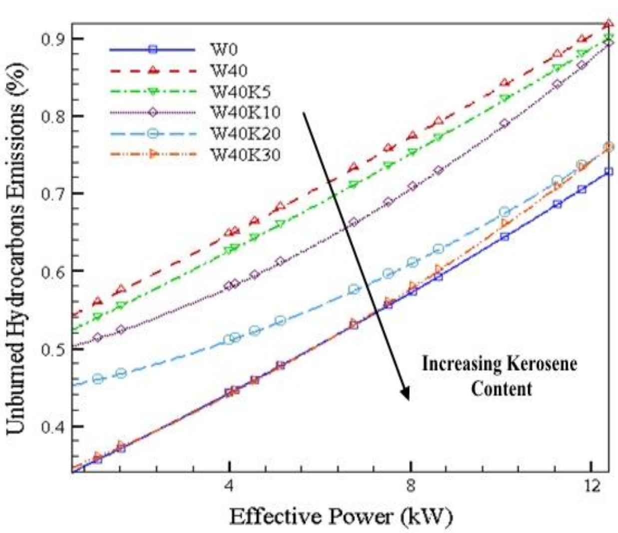

Chart 11: Variation of HC emissions versus brake power for RWLO-diesel-kerosene blend

It was observed that using kerosene as an additive decreased the CO emissions when compared to W0 as shown in Chart 12. These results meet with the results observed by Sethi and Salariya [24] and Venkanna1 [26]. The reason for such behavior is due to the improved combustion because kerosene has lower self-ignition temperature and has higher volatility compared to diesel that reduces ignition delay period. Using W40K30 helped to reduce the CO emissions to the same levels as W0.

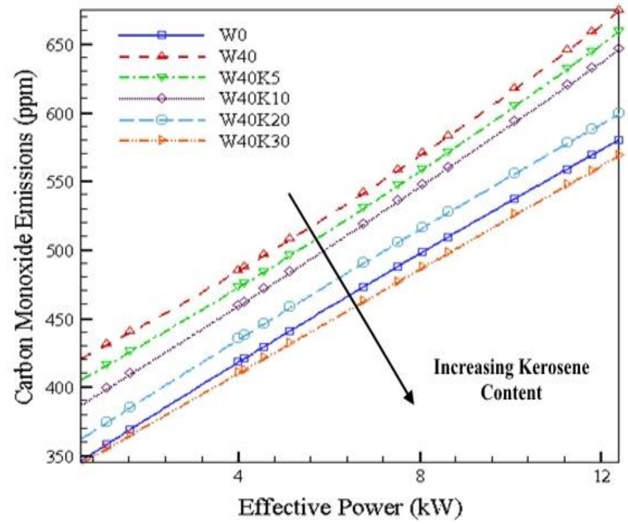

Chart 12: Variation of CO emissions versus brake power for RWLO-diesel-kerosene blends

5.3.6. CARBON DIOXIDE EMISSIONS

Increasing when the RWLO content increase, the hydrocarbons emissions increase. Such behavior is due to the presence of incomplete combustion which decreased the combustion efficiency hence lowering the emissions of CO_2. Chart 13 shows the variation of CO_2 emissions versus brake power for various RWLO blends. The highest percentage decrease was found to be for W40 while operating on 12.39 kW engine power.

When kerosene was added to the fuel, the CO_2 emissions increased as shown in Chart 13. This agrees with the results of Sethi and Salariya [24] and Kadhim [27]. Higher percentage of CO_2 in the exhaust indicates higher oxidation of the fuel at constant engine speed and release of more heat for power conversion which helps in decreasing the possibility of incomplete combustion which eventually decreases the emissions of CO and unburned hydrocarbons which increases the CO_2 emissions. Using W40K30 increased the CO_2 emissions by about 2 % at 8.62 kW engine power compared to W0.

5.3.7. NITROGEN OXIDES EMISSIONS

When the RWLO content in the fuel increased, the nitrogen oxide emissions increased as shown in Chart 14. Such behavior meets with the results obtained by Arpa et al [18-19], Cumali and Hüseyin [25] and Venkanna1 [26]. The reason for such behavior is due to the high EGT which is resulted from the high distillation temperature of waste lubricating oil leading to increase the nitrogen oxide emission in addition to the slower combustion of the RWLO blends that result in a longer period of combustion.

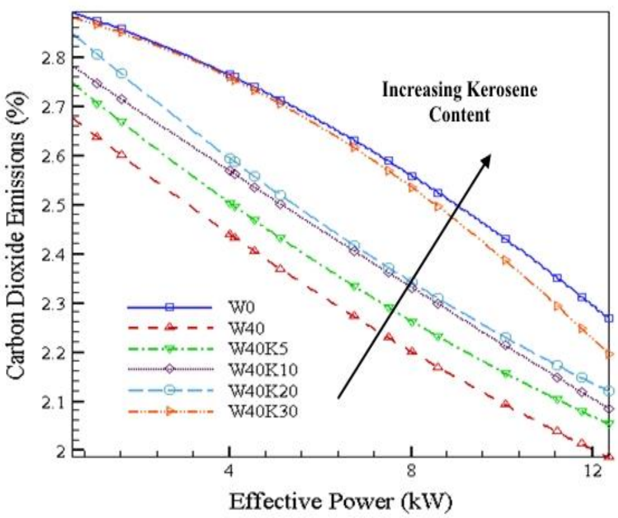

Chart 13: Variation of CO_2 emissions versus brake power for RWLO-diesel-kerosene blends

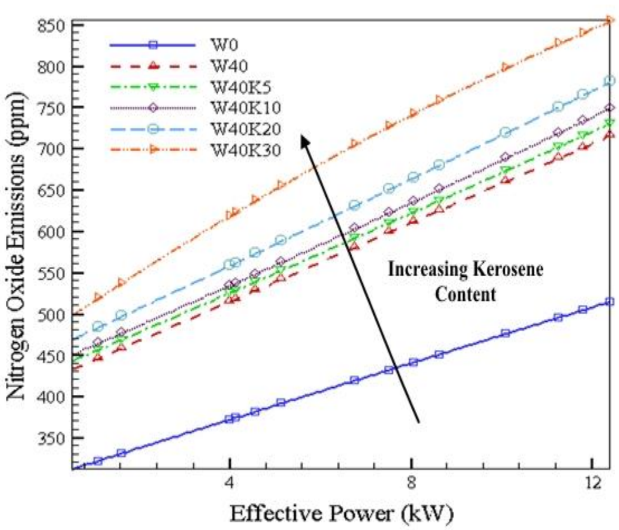

Chart 14: Variation of NO_x emissions versus brake power for RWLO-diesel-kerosene blend

NO_x emissions increased further more when kerosene was added to the blend as shown in Chart 14. This is similar to the results of Sethi and Salariya [24] and Kadhim [27]. Increasing the exhaust gas temperature as shown in Figure 14 when kerosene is added as an additive increased the NO_x emissions.

6. CONCLUSIONS

RWLO produced from waste lubricating oil represents a source of energy. Though, using it leads to some undesirable results such as lowering BTE and increasing BSFC and HC emissions. 13 After performing spray analysis and engine performance experiment, it has been observed that W40K30 is the most appropriate mixture to be used. The following general conclusions could be drawn according to analysis:

A higher RWLO density and bulk modulus result in an injection pressure increase in the conventional injection system, which is reflected in advanced injection, higher spray velocity, narrower spray cone, and larger penetration lengths as well as better performance at the start of combustion but at the end the combustion started to become incomplete leading to increase the tail pipe emissions especially unburned hydrocarbons. The spray characteristics showed that using a mixture consisting of 40 % RWLO + 30 % diesel fuel + 30% kerosene (W40K30) enhanced both the spray angle and penetration by overcoming the unsatisfactory results obtained while blending RWLO with pure diesel.

- The fuel consumption decreased by about 7 % when the kerosene content increased in the fuel. This is due to the high calorific value of kerosene when compared to RWLO-diesel blend.
- The use of kerosene increased the BTE by about 7 %, which is due to the reduction in BSFC and the increase in the calorific value in addition to higher cetane number when compared to the other blends.
- HC emissions decreased by about 10 % when kerosene is used as an additive to RWLO-diesel blend.
- CO emissions decreased by about 3 % when using kerosene as an additive.
- CO_2 emissions increased by about 2 % as the kerosene content in the fuel increased, which is due to the reduction on both CO and unburned hydrocarbons emissions.
- NOx emissions increased when using kerosene, which is due to the increase in EGT.
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