Environmental and Climate Technologies
2020, vol. 24, no. 1, pp. 545–561
https://doi.org/10.2478/rtuect-2020-0034
https://content.sciendo.com

Effect of Diesel Fuel Blend on Flame and Emission Characteristics of Used Engine Oil as Heating Fuel Using Swirl Waste Oil Burner

Bobby Shekarau LUKA[1]*, Robinson Ichakpa EJILAH[2], Sampson Chisa OWHOR[3], Joseph Ajiya JAPHET[4], Tanimu Kogi IBRAHIM[5], Paul Okon UDOM[6]

[1]*Department of Agricultural Engineering, Federal University Wukari, Taraba State, Nigeria*

[2]*Department of Mechanical/ Production Engineering, Abubakar Tafawa Balewa University, Bauchi, Bauchi State, Nigeria*

[3, 6]*Department of Mechanical Engineering, Federal University of Agriculture Makurdi, Benue State, Nigeria*

[4]*Department of Mechanical Engineering University of Jos, Plateau State, Nigeria*

[5]*Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Kaduna State, Nigeria*

Abstract **– Highly viscous fuels present combustion challenges due to poor atomization and consequent inefficient air-fuel mixture, however, due to the demand for cheap heating fuels; burner design and fuel properties are continually optimized to enhance their combustion and emission performance. In this study, used engine oil was drained from the sump of a compression ignition engine; the oil was pre-treated to remove particulate matter, water and ferromagnetic materials. The oil samples were then blended with diesel fuel at different volumetric proportions and were characterized according to ASTM standard. The fuel samples were then combusted using atomizing swirl waste oil burner; flame temperature and flame size were measured using infrared thermometer and direct photography respectively. The burner was then mounted to a combustion chamber and the emission gases and flue gas temperatures were measured using a flue gas analyser and digital thermometer respectively. It was revealed that increasing diesel fuel blend decreases the density and viscosity of the fuel samples. All the blended fuel samples were found to form a homogenous mixture and generated flame temperature higher than the unblended oil sample (B0), B20 generated the highest flame temperature of 1400 °C with flame size of 340 × 210 mm and the lowest carbon monoxide (CO) emission of 0.49 %, unburned hydrocarbon (HC) of 249 ppm and the highest carbon dioxide (CO_2) of 12.87 % levels. In view of this, diesel fuel can be used as a good blending candidate to used engine oil to improve flame temperature and decrease emission levels in swirl waste oil burners.**

Keywords **– Emission gases; fuel oils; oil burner; waste oil, waste to energy.**

Nomenclature		
ΔP	Pressure drop	N/m^2
ρ_{bf}	Density of the blended fuel samples	kg/m^3
ρ_f	Density of the fuel sample	kg/m^3
V	Escape velocity of fuel samples	m/s

---

* Corresponding author.
E-mail address: bobbylukas5@gmail.com

©2020 Bobby Shekarau Luka, Robinson Ichakpa Ejilah, Sampson Chisa Owhor, Joseph Ajiya Japhet, Tanimu Kogi Ibrahim, Paul Okon Udom. This is an open access article licensed under the Creative Commons Attribution License (http://creativecommons.org/ licenses/by/4.0), in the manner agreed with Sciendo.

A	Nozzle cross sectional area	m^2
δ	Standard deviation	–
$\bar{X}$	Mean values	–

1. INTRODUCTION

Used engine oil has high energy content like any other petroleum derived fuel [1], [2] but its combustion as a heating fuel has been underutilized due to the challenges of cleaning the contaminants found in the oil and surmounting its high viscosity and density for proper atomization into fine spray and efficient fuel-air mixing [3]. The constituents of used engine oil depend on the engine starter systems, used engine oils drained from the sump of compression ignition engines are more viscous than their counterpart from the sump of spark ignition engines, due to higher additives per volume and combustion by products such as soot that find their way into the crankcase [4], [5].

In external combustion devices such as oil burners, combustion and emission performance of viscous fuels are enhanced with the help of pre-heaters to surmount high oil viscosity and swirlers to tailor turbulent secondary air in a vortex form into the combustion zone to promote efficient spray characteristics and mixing characteristics [6], [7]. However, despite the introduction of pre-heaters in burners, the challenges of thinning out viscosity of oils in oil burners has not been fully addressed, as preheating the oil above certain temperatures has been reported to cause vapour lock in burners and consequent flame failure and formation of carbon deposits at the nozzle [6], [8] thus a non-thermal approach of further thinning out the oil viscosity via blending with other fuels of lower viscosity and density to supplement the thermal approach is a worthwhile endeavour.

Although re-refining and re-processing of used engine oil are considered more environmentally helpful, burning used engine oil that meets the quality specification for heat recovery is another option that is environmentally and economically beneficial [9]. Used engine oil is utilized as heating fuel as single fuel or blended fuel for many heating applications; in ceramic kilns, used engine oil is utilized as firing fuels during hardening and glazing under reduction firing conditions [10], [11], in home heaters, foundry shops and more prominently in cement kilns, used engine oil is adopted as supplementary or surrogate heating fuel [12].

Potential pollutants from the combustion of used engine oil includes carbon monoxide (CO), oxides of sulphur (SO_X), oxides of nitrogen (NO_X), particulate matter (PM), toxic metals, organic compounds, hydrogen chloride, greenhouse gases such as; carbon dioxide (CO_2) and methane (CH_4), as well as heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg) and nickel (Ni) among others [13].

Studies carried out on the combustion of used engine oil are documented in Luka and Ejilah [2], Al-Omar [14], Aji *et al.* [15], Yahaya and Diso [1], Madu *et al.* [16], all reported the drawback of high viscosity of used engine oil when subjected to atomization and combustion and impressive calorific value, and where blending was employed with kerosene, it presented the challenges of heterogeneity in the mixture. At the moment, no research evidence has been reported on the flame and emission characteristics of blended diesel-used engine oil drained from the crankcase of a compression ignition engine thus the investigation of the impact of diesel fuel blend on the thermo-physical properties, stability, flame characteristics and emission profile of used engine oil using swirl waste oil burner forms the basis of this study.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Swirl Waste Oil Burner

The swirl waste oil burner (STW-120P) used is of atomizing type (Fig. 1). The burner has an oil tank connected to an oil pump to an oil filter and to the burner oil preheating tank. The oil pump, pumps the oil from the oil tank through an oil filter of 10 microns size into the burner preheating tank, inside the burner is a thermostat which controls the preheating temperature and sends a signal to the spark electrode and motor which drives the compressor and immediately activates them when the required preheating temperature has been attained. The burner is equipped with a suction nozzle connected to the compressor and oil preheating tank, which pulls out the oil and atomizes it into droplet spray, the spark electrode ignites the fuel and establishes a combustion flame, a CAD cell positioned inside the burner blast tube senses the flame combustion quality, and trips off the burner when it does not see the flame properly in case of poor combustion.

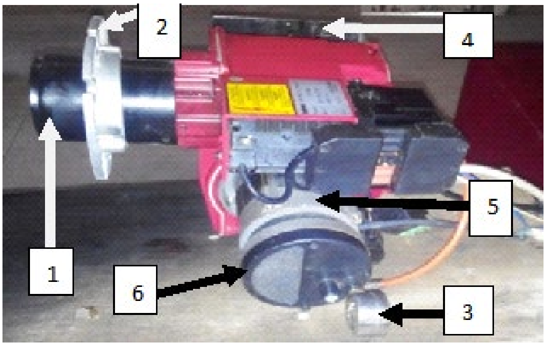

Fig. 1. Atomizing swirl waste oil burner. 1 – Blast tube; 2 – Flange; 3 – Pressure gauge; 4 – Oil preheating tank; 5 – Motor; 6 – Air compressor.

2.2. Fuel Collection, Pre-Treatment and Preparation

Used engine oil was drained from crankcase of the compression ignition engine, the oil was poured into a container and allowed to stratify under gravity for a period of 5 days to rid it of large and heavier particulate matters in the form of sludge formed at the bottom of the container, the upper layer was then decanted and pieces of neodymium magnets (nickel plated) were placed in the oil to attract ferrite materials that may be present in the oil according to the procedure of Abu-Elella *et al.* [17], the oil was then heated in an open container under a control temperature of 90 ºC to avoid reaching ignition temperature and gasification of volatile components of the oil for 45 minutes to rid it of the water held in emulsion by detergent in the oil. The oil sample was filtered thrice using an UBS-177 stainless steel mesh screen to further remove larger particulate matter in accordance with the procedure adopted by Owolabi *et al.* [18]. The diesel fuel was purchased from a government approved retail outlet. The oil sample was blended with diesel fuel, at the following volumetric proportions, that is; B0 (unblended pre-treated primary oil sample), B10 (90 % pre-treated primary oil samples, and 10 % secondary diesel fuel sample), B20, B30, B40 and B50.

2.3. Characterization of Fuel Samples

The thermos-physical properties of the fuel samples were determined according to the modified ASTM standard with the exception of the fuel calorific value which was determined using a bomb calorimeter. The properties determined are flash point, pour point, density, kinematic viscosity, ash content, calorific value, self-ignition temperature, final boiling point, ignition delay period and flame propagation. The fuel viscosities measured were double checked using Refutas algorithm. The results are presented in Table 1 and Table 2.

2.4. Determination of Flow Rate, Stoichiometric Ratio and Combustion Air Volumetric Flow Rate of the Blended Fuels

The flow rates of the fuel blends were estimated using the Bernoulli equation according to the approach of Ejilah *et al.* [19]:

$$p_1 + \frac{1}{2}\rho_{bf} v_1^2 + \rho_{bf} g h_1 = p_2 + \frac{1}{2}\rho_{bf} v_2^2 + \rho_{bf} g h_2 \,. \tag{1}$$

Assuming $v_1 = v_2$, $h_1 = h_2$:

$$v = \sqrt{\left(\frac{2\Delta P}{\rho_{bf}}\right)}, \tag{2}$$

where ΔP is the pressure drop at the burner nozzle and ρ_{bf} is the density of the blended fuel samples. Assuming the pressure dropped by 50 % at the nozzle [20], the burner was fired at 0.4 bar ($0.4 \cdot 10^5$ N/m^2), burner nozzle diameter is 0.00004 m and the calculated cross-sectional area is $1.257 \cdot 10^{-9}$ m^2.

Mass flow rate:

$$\dot{m} = \rho_f v A \,, \tag{3}$$

where

ρ_f Density of the fuel sample, kg/m^3;
v Escape velocity of fuel samples, m/s;
A Nozzle cross sectional area, m^2.

The calculated flow rates (kg/s) were converted to US gallon per hour (GPH) using the expression; 1 GPH → 0.0011 kg/s. The time required for the burner nozzle to discharge 1 kg of each blended fuel sample was determined.

The required oxygen to mass ratio of the combusted fuel samples were calculated from the following combustion chemical equations.

The combustion equation of diesel fuel is given in Eq. (4).

$$C_{13}H_{28} + 20\ O_2 \rightarrow 13\ CO_2 + 14\ H_2O \tag{4}$$

The oxygen-fuel mass ratio of diesel fuel was found to be 3.47 kg; the oxygen-fuel mass ratio of used engine oil is 2.66 kg [16].

In order to avoid flame over ventilation and under ventilation, the secondary combustion air must be tailored at the required stoichiometric ratio; the combustion air was calculated considering 20 % excess air for the combustion of fuel oils as reported in the Engineering Tool Box [21]. The estimation was done using the calculated mass of oxygen according to the method reported by Stephen [22] and Williams and Rothamer [23]. The calculated combustion air mass flow rate (kg/s) was converted to volumetric flow rate, cubic feet per meter (cfm) using the relationship Eq. (5).

$$1 \text{ cfm} = 0.0283 \text{ kg/s} \tag{5}$$

The combustion secondary air volumetric flow rate estimated for all the blended fuel samples fall within the range of 0.296 cfm to 0.341 cfm, the burner secondary combustion air valve is calibrated to deliver 0.25, 0.50 and 0.75 cfm of air through the blast tube, hence, 0.25 cfm was selected for all the blended fuel samples with the view that atomizing air from the compressor will supplement the inadequacy to overcome the challenges that may be posed by over-ventilation.

3. EXPERIMENTAL METHOD

B0 oil sample was poured into the oil tank and the burner was connected to a power source, the burner preheating temperature was set at 100 °C, and atomizing air pressure of 0.4 bar, when the burner was switched on, the oil pump pumps the oil into the oil filter and to the burner oil preheating tank. When the oil preheating temperature was reached, the motor was activated simultaneously with the spark electrodes and ignite the atomized fuel samples to generate combustion flame. An infrared thermometer (infrared pyrometer with laser sighting) was used to measure the flame temperature. Flame length and flame width were measured by taking three direct photographs of the flame from a fixed point through a transparent acrylic plate marked in horizontal and vertical order using a digital camera and their average was computed. The burner was then mounted to a ceramic fibre combustion chamber enclosed in a lagged steel box; flue gas analyser (SV-5Q) was used to analyse the emission gases i.e., carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (HC) and oxygen (O_2) and the excess air coefficient (λ) at 0.40 m stack height and the flue gas temperature was also measured using a digital thermometer (MexTech) at the stack base. The experiment was replicated for all the blended fuel samples. The combustion efficiency was estimated using a combustion efficiency chart for fuel oils.

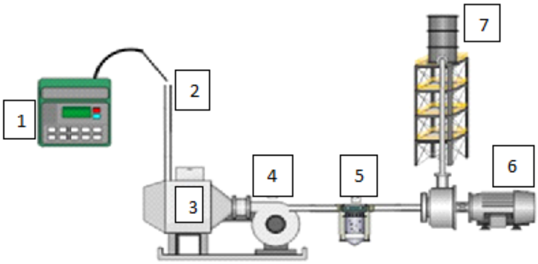

Fig. 2. Experimental setup. 1 – Flue gas analyser; 2 – Stack; 3 – Combustion chamber; 4 – Swirl oil burner; 5 – Oil filter; 6 – Oil pump; 7 – Oil tank.

4. RESULTS AND DISCUSSION

4.1. Thermo-Physical Properties of the Fuel Samples

It is clearly revealed that blending used engine oil with diesel fuel influences its viscosity and density, as both properties decrease with increasing diesel fuel proportion, the thermo-physical properties of used engine oil determined and presented in Table 1 are closely similar to the ones reported by Yahaya and Diso [1] and Lockwood *et al.* [24]; diesel fuel has higher calorific value and lower density and viscosity than used engine oil (Table 2) which makes it a good blending candidate to used engine oil in atomizing oil burners.

TABLE 1. THERMO-PHYSICAL PROPERTIES OF THE FUEL SAMPLES

Fuel blends	**Calorific value, kJ/kg**	**Flash point, °C**	**Viscosity at 40 °C, cSt**	**Viscosity at 100 °C, cSt**	**Pour point, °C**	**Density, kg/m^3**	**Ash content, %**
B0	44.277	95	156.41	15.26	–11	880	1.025
B10	44.283	–	140.04	13.00	–	875	–
B20	44.320	–	125.22	10.61	–	870	–
B30	44.345	–	110.30	8.84	–	863	–
B40	44.678	–	92.89	6.44	–	859	–
B50	44.902	–	79.35	6.42	–	854	–

TABLE 2. PROPERTIES OF DIESEL FUEL

Properties	**Unit**	**Diesel**
Chemical formula	–	$C_{12}H_{26}$
Calorific value	kJ/kg	45.400
Self-ignition temperature	°C	725
Final boiling point	°C	369
Ignition delay period	S	0.0002
Flame propagation rate	cm/s	10.5
Kinematic viscosity at 39 °C	mm^2/s	2.7
Density at 15.6/15.5 °C	kg/m^3	893

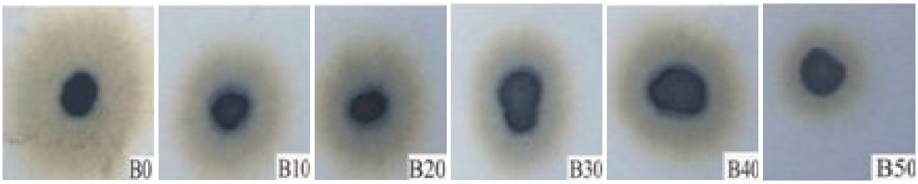

Fig. 3. Result of homogeneity test.

The result of the homogeneity test presented in Fig. 3 was compared to modified ASTM D4740 reference spot sheet [25], as it can be seen, there is no visible inner ring in the spots formed in B10-B40 but faintly appears in B50, this indicates that there will rarely be a possibility of forming degradation product leading to increase in fuel viscosity during storage and formation of stratified layers and droplet size irregularities during atomization.

4.2. *Influence of Diesel Fuel Blend on Flame Characteristics*

The result of the influence of diesel fuel blend on flame width, flame length and flame temperature of blended used engine oil is presented in Table 3 and discussed accordingly.

TABLE 3. FLAME CHARACTERISTICS OF USED ENGINE OIL AND DIESEL BLENDS

Fuel sample	**Flame structure**	**Mean Flame Length, mm**	**Mean Flame width, mm**	**Flame temperature, °C**
B0		110	80	1305
B10		160	100	1376
B20		340	110	1400
B30		310	105	1333
B40		310	130	1314
B50		345	130	1310

4.2.1. *Influence of Fuel Blend on Flame Length*

The flame length of B10, B20, B30, B40 and B50 are 45.45 %, 209.09 %, 181.81 %, 181.81 % and 213.64 % higher than B0 (110 mm), taking B0 as the benchmark. The increase in flame length by all the flames with increasing diesel fuel blend above B0 could be ascribed to decrease in kinematic viscosity (Table 1) and consequent higher degree of fuel atomization of the blended fuel samples. According to Presser *et al.* [26] lower fuel viscosity generates smaller fuel droplet size; smaller droplet size tends to have higher velocities hence longer flame length and vice versa. The higher excess air coefficient in B0 when compared to its counterparts could also be a contributing factor to its shorter flame length as documented in Elorf and Sar [27]. However, the decrease in flame length by B30 and B40 could be as a result of puffing and micro explosions, Wang and Law [28] and Wang *et al.* [29] explain that a lower volumetric proportion of less volatile fuel components in fuel blends and variation in boiling point causes fewer site nucleation which results in tiny bubbles, these bubbles break down to develop secondary droplets at the nozzle, thereafter, the secondary droplets further disintegrate into smaller droplets as they travel, this is peculiar to these blends due to increasing volatile diesel fuel against less volatile used engine oil. Presser *et al.* [26] reported that decrease in fuel droplet size shortens the life span of the fuel droplet thus decreasing the flame length. The increase in flame length by B50 could be due to decreased condition of homogeneity in the fuel blend (Fig. 3), such could cause irregular fuel droplet diameters with smaller ones traveling faster [30] such behaviour can result in shorter resident time by some of the fuel droplets within the combustion zone, this is evident by decreasing flame temperature (Table 3) and increasing CO level (Fig. 4).

4.2.2. Influence of Fuel Blend on Flame Width

The flame width of the diesel blended fuel samples; B10, B20, B30, B40 and B50 are 20.00 %, 37.50 %, 31.25 %, 62.50 % and 62.50 % higher than the benchmark (80 mm). The consequent increase in flame width with increasing diesel fuel blends above B0 could be attributed to decrease in kinematic viscosity of the blended fuel samples (Table 1) and decreasing excess air coefficient as revealed in the work of Elorf and Sar [27]. According to Delevan [20], the lower the fuels kinematic viscosity, the wider the nozzle's spray angle hence wider flame width. A similar result was reported by Luka and Ejilah [2] from combusted used engine oil sourced from spark ignition engine sump blended with diesel and kerosene fuel.

4.2.3. Influence of Fuel Blend on Flame Temperature

The flame temperature of the diesel blended fuel samples B10, B20, B30, B40 and B50 are 5.44 %, 7.30 %, 21.15 %, 0.70 %, and 0.51 % higher than B0 (1305 °C, B20 gave the highest flame temperature of 1400 °C. The increase in flame temperature by all the fuel blends above B0 could be explained in terms of mixture homogeneity (Fig. 3) and decreasing viscosity which improves fuel atomization at the nozzle and facilitates air-fuel mixture due to swirler effect. The highest temperature generated by B20 could be attributed to consumption of most oxygen supplied [31], [32] as presented in Fig. 1. However, the decrease in flame temperature by B30-B50 could occur because diesel has a higher proportion of hydrogen and at a higher blending ratio, it will bring about higher water vapour and consequently lower the flame temperature due to higher specific heat capacity of water [33].

4.2.4. Experimental Uncertainty Analysis

Photographs of the flame were taken three times and the values of the flame length and flame width are shown in Table 4 and Table 5. The mean and standard deviation were calculated according to Chen *et al.* [34] and Beckwith, Marangoni and Lienhard [35] using the Eqs (6)–(8).

Mean Value:

$$\underline{\overline{X}} = \frac{1}{n}\sum_{i=1}^{n} X_i \text{ , } i = 1, 2, 3, \ldots, n \tag{6}$$

Standard deviation:

$$\delta = \left[\frac{1}{n-1}\sum_{n-1}(X-\overline{X})^2\right]^{\frac{1}{2}} \tag{7}$$

Uncertainty error:

$$\% = \frac{\delta}{X} \cdot 100, \tag{8}$$

where X is the measured flame length and flame width.

Guassian for bell shape probability density function at 95 % uncertainty range was used to estimate the expanded uncertainty as adopted by Cakmak *et al.* using Eq. (9)–(12) [36].

Since the linear scale on the acrylic plate has an interval of 0.1 mm, calibration uncertainty Δd is twice smaller, and that is equal to 0.05 mm.

To calculate B-type uncertainty, Eq. (9) was used.

$$u(d) = \frac{\Delta d}{\sqrt{3}} \tag{9}$$

Since result distribution was observed in A-type, standard uncertainty was calculated using Eq. (10).

$$u(d) = \sqrt{s_X^2} = \left[\frac{1}{n(n-1)} \Sigma_{i=1}^{n} (X_i - \overline{X})^2 \right]^{\frac{1}{2}} \tag{10}$$

Also, since the magnitude of A-type and B-type is the same, combine uncertainty was calculated using Eq. (11).

$$u(d) = \sqrt{s_X^2 + \frac{\Delta d}{\sqrt{3}}} \tag{11}$$

To calculate expanded uncertainty at 95 % confidence interval, $k = 1.96$, Eq. (12) was employed.

$$U(d) = k \cdot u(d) \tag{12}$$

Table 4. Uncertainty Error Analysis of Measured Flame Length of Diesel Blended Used Engine Oil Sourced From Compression Ignition Engine Sump

Fuel blends	**FL1, mm**	**FL2, mm**	**FL3, mm**	**Mean, $\overline{X}$**	**Standard deviation, δ**	**Error %**	**Expanded Uncertainty ($U_{(d)}$), mm**
B0	108	111	111	110	1.73	1.5727	±1.9608
B10	159	159	162	160	2.45	1.5313	±1.9608
B20	339	342	339	340	2.45	0.7206	±1.9608
B30	310	309	311	310	1.41	0.4548	±1.1330
B40	309	312	309	310	2.45	0.7903	±1.9608
B50	345	347	343	345	2.83	0.8203	±2.2639

TABLE 5. UNCERTAINTY ERROR ANALYSIS OF MEASURED FLAME WIDTH OF DIESEL BLENDED USED ENGINE OIL SOURCED FROM COMPRESSION IGNITION ENGINE SUMP

Fuel blends	FW1, mm	FW2, mm	FW3, mm	Mean, $\bar{X}$	Standard deviation, δ	Error, %	Expanded Uncertainty ($U_{(d)}$), mm
B0	80	81	79	80	1.41	1.7625	±1.13302
B10	111	108	111	110	2.24	2.0364	±1.96081
B20	110	111	109	110	1.41	1.2818	±1.13302
B30	114	115	116	115	1.41	1.2261	±1.13302
B40	112	110	108	110	2.83	2.5727	±2.26392
B50	130	131	129	130	1.41	1.0846	±1.13302

The measured percentage error and expanded uncertainty for both flame length and flame width fall below the 5 % threshold; this substantiates reliability in all measurements.

4.3. Influence of Fuel Blending Ratio on Emission Gases

The influence of fuel blend on the emission profile of CO, CO_2, HC and O_2 is presented in Fig. 4 and are discussed accordingly.

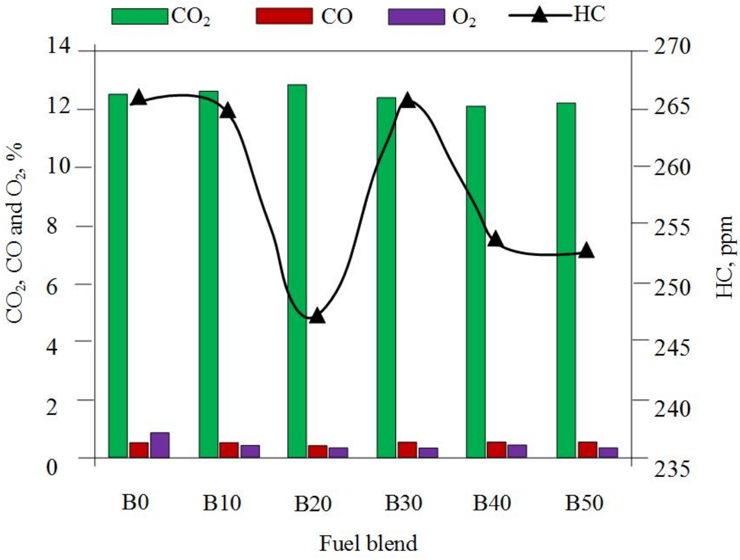

Fig. 4. Emission profile of combusted fuel samples.

4.3.1. Influence of Fuel Blend on CO_2 Emission

The emission profile of CO_2 from combusted B10 and B20 are 0.72 % and 2.80 % higher than the B0 benchmark, for B30, B40 and B50 it is 0.64 %, 2.72 % and 2.40 % lower than the B0 (12.52 %) reference blend. B20 gave the highest and B40 gave the lowest CO_2 emission level. The increase in CO_2 by B10 and B20 can be explained in terms of increasing combustion efficiency, which could be attributed to corresponding increase in flame temperature (Table 3). However, the decrease in CO_2 concentration observed in B30, B40 and B50 could be ascribed to decreasing flame temperature (Table 3) this point was further explained by Mohammed *et al.* [37] and Bergmann [38], that the formation of CO_2 from CO and O_2 as well as decomposition is kinetically constrained and sensitive to high flame temperature due to elevated activation energy.

4.3.2. Influence of Fuel Blend on CO Emission

CO emission decrease below that of B0, (0.56 %) in some fuel blends. At B10 and B20, the CO emission decrease by 3.79 % and 12.50 % below the B0 benchmark, for B30 and B40, CO increase by 1.79 % and 1.79 % above the B0 and then decrease by 1.79 % at B50. B20 gave the lowest CO emission. The decrease in CO emission by B10 and B20 could be attributed to higher flame temperature (Table 3) and lower carbon content of diesel fuel blends when compared to unblended used engine oil (B0), Jon *et al.* [39] reported that viscous fuels produce more CO emission profile due to their higher carbon content and atomization challenges due to high viscosity and density. The increase above B0 observed in B30 and B40 could be imputed to the formation of CO by dissociation of CO_2 at high flame temperature and efficient utilization of oxygen [37].

4.3.3. Influence of Fuel Blend on HC Emission

The HC emission from combusted B10 and B20 are 1.51 % and 9.23 % lower than B0 (266 ppm). B30 is 1.52 % higher than the B0 benchmark, and B40 and B50 are 18.18 % and 19.70 % lower than the B0 benchmark. B20 gave the lowest HC emission level. The decrease in HC emission could be directly correlated with the decreasing CO emission and increasing flame temperature, this suggests increase in combustion efficiency, however; this was possible owing to decreasing oil viscosity and density and different chemical composition of used engine oil and diesel fuel as explained by Ahmed *et al.* [31].

4.3.4. Influence of Fuel Blend on O_2 Emission

The O_2 emission from combusted B10, B20, B30, B40 and B50 are 48.89 %, 91.41 %, 63.41 %, 36.72 % and 86.11 % lower than the B0 (0.67 %). There is a direct relationship between the flame temperature and O_2 emission profile; the decrease in O_2 emission level by B10-B50 below the B0 benchmark could be imputed to the consumption of oxygen atoms in converting CO to CO_2 during combustion which translates into higher flame temperature [31], [32]. It could also be seen that where O_2 emission level are lower, flame temperature and combustion efficiency are higher, this further corroborates the literature by Bhatia [40] that decrease in stack O_2 emissions result in an increase in combustion efficiency and thermal efficiency and vice versa, this behaviour could also be possible in all the blends owing to homogeneity in the blended fuels (Fig. 3). Frank [30] reported that in homogeneous fuel blends, atomized fuels droplet diameters are relatively equal and travel with relatively equal velocities and have sufficient contact with the air which facilitates efficient utilization of oxygen atoms for combustion.

4.4. Combustion Efficiency

Combustion efficiency gain can bring about significant annual cost saving. The aim of every combustion device is to convert all fuels into useful energy. The combustion efficiency of the fuel samples studied was not significantly different as presented in Table 6; the highest value was recorded by B20 and the lowest by B30.

TABLE 6. COMBUSTION EFFICIENCY OF THE BLENDED FUELS

Fuel blend	λ	FGT, °C	CE, %
B0	0.94	287.80	81.4
B10	0.87	297.06	81.3
B20	0.82	275.44	82.2
B30	0.81	316.00	80.3
B40	0.81	299.00	81.3
B50	0.79	298.37	80.8

λ: Excess air coefficient, FGT: Flue gas temperature, CE: Combustion efficiency

This is because B20 utilized most of the supplied combustion oxygen releasing out lower heat via the stack but such could not be effectively replicated by B30 despite a higher flame temperature than B40 and B50, thus the unusual drop in combustion efficiency. Generally, the excess air coefficient is below the theoretical value calculated to be 1.2 for the mixture to be stoichiometric, nevertheless, changes in excess air coefficient show a positive correlation with combustion efficiency; this was corroborated in a study by Gong *et al* [41].

4.5. Statistical Validation of the Influence Tested Fuel Properties on Emission Gases and Combustion Efficiency

To validate the effect of tested fuel properties on the combustion characteristics and efficiency, multivariate regression analysis was carried out using STATA 14. The results of the analysis are presented in Tables 7, 8 and 9.

TABLE 7. REGRESSION PERFORMANCE

Equation	Observations	Parms	RMSE	*R*-Sq	*F*	*p*
CO_2	6	3	0.2125484	0.9999	6889.216	0.0000
CO	6	3	0.0369354	0.9977	438.2244	0.0002
HC	6	3	12.41383	0.9989	880.8394	0.0001
CE	6	3	0.6543254	1.0000	30813.49	0.0000

From Table 7, it could be seen that CO_2, CO, HC and CE has R^2 value of 0.9999, 0.9977, 0.9989 and 1.0000, respectively, this implies that 99.99 %, 99.77 %, 99.89 % and 100 % changes in CO_2, CO, HC and CE profile can be attributed to changes in the calorific value, viscosity and density of the tested fuels. The p-values of all the dependent variables fall below 0.05 at 95 % confidence interval, this infers that all the fuel properties significantly influenced the emission profile and the combustion efficiency of the tested fuel samples.

Table 8 shows the coefficient of estimation of the regression equation, this shows the fuel property that prominently influences the changes in CO_2, CO, HC and CE profile the most, from their coefficient, changes in CO_2, CO, HC and CE level were more influenced by changes in fuel density, viscosity, density and density respectively, in other words, every unit change in the response variables is attributed by change in the regression coefficient of the corresponding fuel property.

TABLE 8. REGRESSION COEFFICIENTS

Parameter	**CO_2**	**CO**	**HC**	**CE**
	Coefficient	Coefficient	Coefficient	Coefficient
Calorific value	–0.0004175	0.0000389	–0.0036089	–0.0000537
Viscosity	–0.0797685	0.0045129	–0.4917646	–0.2092389
Density	0.367343	–0.0014153	0.4913728	0.0988843

The regression equations for all the dependent variables are presented as:

$$CO_2 = -0.0004175CV - 0.0797685V + 0.0367343D, \tag{13}$$

$$CO = 0.0000389CV + 0.0045129V - 0.0014153D, \tag{14}$$

$$HC = -0.0036089CV - 0.4917646V + 0.4913728D, \tag{15}$$

$$CE = -0.0000537CV - 0.2092389V + 0.988843D, \tag{16}$$

where

CV	Calorific value;
V	Viscosity;
D	Density.

The performance of the models was tested to ascertain their capability to effectively predict all the response variables, the result is presented in Table 9.

TABLE 9. MODELS PERFORMANCE

Fuel samples	**CO_2 Exp.**	**CO_2 Pred.**	**CO Exp.**	**CO Pred.**	**HC Exp.**	**HC Pred.**	**CE Exp.**	**CE Pred.**
B0	12.52	12.62	0.56	0.55	266.00	265.11	81.40	81.45
B10	12.61	12.62	0.54	0.54	265.00	263.75	81.30	81.43
B20	12.87	12.61	0.49	0.54	249.00	262.33	82.20	81.43
B30	12.44	12.48	0.57	0.54	276.00	259.67	80.30	81.11
B40	12.18	12.39	0.57	0.55	254.00	257.68	81.30	81.19
B50	12.22	12.11	0.55	0.57	253.00	254.42	80.80	80.69

TABLE 10. REGRESSION TEST ON FUEL PROPERTIES

	Calorific value	**Viscosity**	**Density**
F (4, 3)	1001.89	$2.30 \cdot 10^5$	$1.10 \cdot 10^6$
Prob.>F	0.0001	0.0000	0.0000

The regression test was carried out at 95 % confidence interval, to ascertain the significance of each test variable; we divided 5 % by the number of independent variables (3) which gives us 0.017. from Table 10, it could be seen that the p-value of all the tested fuel properties fall below 0.017, thus it can be deduced that all the fuel test parameters significantly influenced CO_2, CO, HC and CE profile of the tested fuel samples.

5. CONCLUSION

Experimental investigation of the effect of diesel fuel blend on the flame and emission performance of used engine oil has been carried out; the work draws the following conclusions:

- The blended fuel samples were found to be homogeneous and will form a good and stabilized mixture with no problem of stratification;
- Addition of diesel fuel reduces fuel viscosity and density of used engine oil; thus, diesel fuel blending can be used to supplement the inadequacy of oil viscosity thinning via preheating with no compromise to combustion quality;
- Variation in fuel blending ratio was found to prominently influence the flame temperature by enhancing its thermal performance, with optimum blending ratio of B20 (20/80 %) Diesel-Used engine oil outperforming its counterparts and improve the combustion temperature above B0 by 7.23 %;
- At optimum blending ratio of B20, CO and HC were reduced by 12.51 % and 6.39 %, respectively.

REFERENCES

[1] Yahaya D. B., Diso I. S. Thermo-physical properties of Nigerian used engine oil. *Journal of Emerging Trends in Engineering and Applied Sciences* 2012:3(2):244–246.

[2] Luka B. S., Ejilah R. I. The Influence of Waste Crankcase Oil Blended Fuel Samples on the Flame and Thermal Behaviour of Atomising Swirl Oil Burner. *European Journal of Advances in Engineering and Technology* 2017:4(10):770–787.

[3] Baukal E. C. The john zink hamworth combustion book: Design and operation. 2nd Edition. NY, Ohio: CRC Press, 2014.

[4] Grimmer G. PAH kumulierung im Motor schmier S1; PAH emission aus Ottomotoren ErdS1 Erdgas. (PAH accumulation in engine lubrication S1; PAH emission from petrol engines ErdS1 natural gas). *Petrochem.* 2008:33(19):135. (in German)

[5] Brown M. C. Understanding the difference in engine oils, machinery lubrication. [Online]. [Accessed 23.04.2019]. Available: www.machinerylubrication.com

[6] Daniel B. J. Waste oil burner pre-heater design. US patent no. US WO 20130206046 A1, 2012.

[7] Baukal E. C. *Industrial combustion testing*. NY, Ohio: CRC Press, Tailor and Francis Group, 2010.

[8] Bairan W. Waste Oil Burner Manual. Bairan Wenling Company. Burner manual. 2015.

[9] Tailor E. Turning used motor oil into heat with a used oil furnace. National rural transit assistance program. 2014.

[10] Hansen T. Reduction firing. Digital fire. [Online]. [Accessed 22.07.2018]. Available: http://digitalfire.com/4sight/glossary_reduction_firing.html

[11] Zakin R. A guide to the ceramic kiln and various firing methods. ceramic arts Network Daily. [Online]. [Accessed 10.10.2018]. Available: http://ceramicartsnetwork.org/daily/clay-tool/ceramic-kiln/guide-ceramic-kiln-various-firing-methods/

[12] Speight J. G., Exall D. I. *Refining Used Lubricating Oils*. NY, Ohio: CRS Press, 2014.

[13] USEPA. Waste Oil Combustion. [Online]. [Accessed 11.09.2018]. Available: www.epa.gov/ttnchie1/le/pompta.pdf

[14] Al-Omar S. B. Used engine lubrication oil as a renewable supplementary fuel for furnaces. *Energy Conversion and Management* 2008:49(12):3648–3653. https://doi.org/10.1016/j.enconman.2008.07.011

[15] Aji I. S., El-Jummah A. M., Aji M. A., Ifeanyi N. D. Admixture of used engine oil blended with kerosene as a substitute for industrial fuel. *Continental Journal of Engineering Sciences* 2008:3(6):64–71.

[16] Madu M. J., Aji I. S. Martin, B. Design, construction and testing of a burner that uses an admixture of used engine oil and kerosene for foundry application. *International Journal of Innovative Research in Science and Engineering Technology* 2011:6(2)23–31. https://doi.orh/10.15680/IJIRSET.2014.0309036

[17] Abu-Elella R., Ossman M. E., Farouq R., Abd-Elfatah M. Used motor oil treatment: turning waste oil into valuable products. *International Journal of Chemical and Biochemical Science* 2015:4(4):57–67.

[18] Owolabi R. U., Alabi K. A., Oke O. B. Reclamation of spent automobile engine lubricating oil. *Fountain Journal of Natural and Applied Science* 2013:2(1):11–16.

[19] Ejilah I. R., Olorunnisola A. A. G., Enyejo L. A. Comparative analysis of the combustion behavior of adulterated kerosene fuel samples in a pressurized kerosene stove. *Global Journal of Researches in Engineering* 2013:13(6):15–29.

[20] DELEVAN. A Total Look at Oil Burner Nozzles. A Reference Guide for Burner Service Technicians. [Online]. [Accessed 16.01.2017]. Available: www.delevaninc.com/pdf/total_look.pdf

[21] The Engineering ToolBox. Combustion Efficiency and Excess Air. [Online]. [Accessed 03.03.2019]. Available: http://engineeringtoolbox.com/boiler-combustion-efficiency-d_271.html

[22] Stephen B., Londervill F., Charles E., Baukal J. R. *The Coen and Hamsworthy combustion handbook, fundamental of power, marine and industrial application*. NY, Ohio: CRC Press, 2013.

[23] Williams M. L., Rothamer D. P. The ideal ratio: Stoichiometry of combustion in the chemistry of class room. Great Lake Bio Energy Research Centre. [Online]. [Accessed 11.07.2019]. Available: http://www.glbrc.org

[24] Lockwood F. E., Zhang Z. G., Choi S. U. S., Wang J. C. Thermal characteristics of new and used diesel engine oils. [Online]. [Accessed 17.08.2019]. Available: http://www.oeg.at/fileadmin/Dokumente/oetg/Proceedings/WTTC_2001_files/html/M-21-27-729

[25] ASTM. Standard parts 17 and 18. American Society of Testing and Materials. Philadelphia, Pennsylvania, U.S.A.: ASTM, 1990.

[26] Presser C., Gupta A. K., Avedisian C. T., Semerjian H. G. Fuel property effects on the structure of spray flames. *Symposiums (international) on Combustion* 1991:23(1):1361–1337. https://doi.org/10.1016/S0082-0784(06)80401-7

[27] Elorf A., Sar B. Excess air ratio effects of flow and combustion characteristics of pulverized biomass (olive cake*). Case Studies in Thermal Engineering* 2019:13:24–32. http://doi.org/10.1016/j.csite.2018.100367

[28] Wang C. H., Liu X. Q., Law C. K. Combustion and micro explosion of freely falling multi-component droplet. *Combustion and Flame* 1984:56(2):75–97. https://doi.org/10.1016/0010-2180(84)90036-1

[29] Wang C. H., Law C. K. Microexplosion of fuel under high pressure. *Combustion and Flame* 1985:59(1):53–62. https://doi.org/10.1016/0010-2180(85)90057-4

[30] Frank B. A Guide to Assist in Evaluating Liquid Fuel Flames. [Online]. [Accessed 14.09.2016] Available: https://www.scribd.com/document/153939006/A-Guide-to-Assist-in-Evaluating-Liquid-Fuel-Flames

[31] Ahmed M., Ahmed M., Gad M. S., Ahmed E. F. Effect of waste cooking-diesel oils blends on the performance, emission and combustion characteristics of industrial oil burners. *International Journal for Research in Applied Science and Engineering Technology* 2017:5:9:1264–1274.

[32] TSI. Combustion analysis: Combustion Analysis Basic. [Online]. [Accessed 10.04.2018]. Available: www.tsi.com

[33] Chu H. Flame temperature. [Online]. [Accessed 11.06.2017]. Available: myweb.ncku.edu.tw/~chuhsin/ppt/combustion%20principles%20and%20control/04-Flame%20Temperature.ppt

[34] Chen W. H., Liao C. Y., Hung C. I., Huang W. L. Experimental study on thermoelectric modules for power generation at various operating conditions. *Energy* 2012:45(1):874–881. https://doi.org/10.1016/j.energy.2012.06.076

[35] Beckwith T. G., Marangoni R. D., Lienhard J. H. *Mechanical Measurements*. New Jersey: Prentice Hall, 2007.

[36] Cakmak A., Kapusuz M., Ganiyev O., Ozcan H. Effects of Methyl Acetate as Oxygenated Fuel Blending on Performance and Emissions of SI Engine. *Environmental and Climate Technologies* 2018:22:55–6. https://doi.org/10.2478/rtuect-2018-0004

[37] Shehata M. S., Elkotb M. M., Salem H. Combustion Characteristics for Turbulent Prevaporized Premixed Flame Using Commercial Light Diesel and Kerosene Fuels. *Journal of Combustion* 2014:363465. http://dx.doi.org/10.1155/2014/363465

[38] Bergmann J. Performing a combustion analysis. [Online]. [Accessed 11.7.2018]. Available: www.achrnews.com/articles/106070-performing-a-combustion-analysis

[39] Jon H., Van G., Charles L. P., Carroll E. G. Biodiesel: An Alternative Fuel for Compression Ignition Engines. ASABE Distinguished Lecture Series No. 31, ASABE, 2007.

[40] Bhatia A. Improving Energy Efficiency of Boiler Systems. PDH online Course M166 (4 PDH). [Online]. [Accessed 01.11.2017]. Available: https://www.pdhonline.com/courses/m166/m166content.pdf

[41] Gong X., Liu Z., Jiang H. Emission and thermal efficiency investigation of a pulverized submerged combustion evaporator. *International Journal of Low-Carbon Technology* 2012:7(4):257–263. https://doi.org/10.1093/ijlct/cts059

Bobby Shekarau Luka holds M. Eng. in Power and Process Engineering. He is a lecturer in the Department of Agricultural Engineering, Federal University Wukari, Nigeria. He has published research articles in the area of Waste management, Environmental management, Biofuels, Artificial intelligence and Food processing. He is a multiple Academic and Professional Award winner and a registered member of the Council for the Regulation of Engineers in Nigeria (COREN).
E-mail: bobbylukas5@gmail.com
ORCID iD: http://orchid.org/0000-0002-4410-5934

Dr Robinson Ichakpa Ejilah holds PhD in Energy studies. He is an Associate Professor in the Department of Mechanical/Production Engineering, Abubakar Tafawa Balewa University Bauchi. He has published many research articles in the area of energy security, alternative fuels, renewable energy, waste to energy, biofuels, and metallurgy among others. He is the National Chairman of The Nigerian Institution of Mechanical Engineers (NIMechE), a member of the Nigerian Society of Engineers (NSE) and registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN).
E-mail: rejilah@gmail.com
ORCID iD: http://orcid.org/0000-0002-6941-3570

Sampson Owhor Chisa holds M. Eng. in Production Engineering. He has published research articles in the area biofuels, combustion and renewable energy. He is a registered member of International Association of Engineers (IAENG), Council for the Regulation of Engineering in Nigeria (COREN) and The Nigerian Institution of Mechanical Engineers (NIMechE).
E-mail: owhorchisa@gmail.com
ORCID iD: https://orcid.org/0000-0003-2126-7903

Tanimu Kogi Ibrahim holds MSc in Production Engineering, and currently a PhD student. He is a lecturer. He has published many research articles in the area of Material science, Metallurgy and Energy. He is a member of the Nigerian Society of Engineers (NSE) and registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN).
E-mail: terrytanimu@yahoo.com
ORCID iD: https://orcid.org/0000-0002-3657-0422

Joseph Ajiya Japhet holds M. Eng in Power and Process Engineering, He is a lecturer in the Department of Mechanical Engineering, University of Jos. He has published many research articles in the area of Bio-energy, Waste management and Renewable energy. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN).
E-mail: suyidam@yahoo.com
ORCID Id: https://orcid.org/0000-0001-8325-4011

Paul Okon Udom holds M. Eng in Production Engineering. He has published many research articles in the area of renewable energy, combustion process and metallurgy. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN).
E-mail: udompaul2011@gmail.com