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Optimization of Flow Parameters for Waste Lubricating Oil Combustion

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Abstract

The global energy demand has continued to skyrocket, exacerbating the already severe energy problem and environmental pollution, prompting researchers to look for alternative energy sources. Exploration of waste lubricating oil (WLO) as an alternative source of fuel has gained prominence among researchers due to its availability at low cost and the potential to generate energy while providing a safer means of disposal. The main challenge with WLO combustion is proper regulation of fuel and oxidizer during combustion to realize a near stoichiometric result. Additionally, WLO has high viscosity, hence preheating of the oil is necessary to lower the viscosity and enhance atomization, for a more efficient combustion process. This paper presents the optimization of flow parameters for combustion of WLO in a burner system by use of response surface methodology (RSM). The effects of air flow rate, injection pressure and fuel flow rate on combustion performance of a WLO burner were investigated. The highest flame temperature recorded was 1200˚C at an air flow rate of 1 m^3/min, fuel flow rate of 0.08 m^3/hr and injection pressure of 20 bar. Tests on physical and chemical properties of WLO were conducted and characterized according to ASTM standard to ascertain its potential as an alternative fuel. The calorific values of WLO from petrol and diesel engines were found to be 41.23 MJ/kg and 42.65 MJ/kg respectively. Therefore, recycling of WLO by utilizing it as a fuel for burners has double benefits of mitigating environmental pollution and harnessing energy for process heating and power generation.

Keywords

Waste Lubricating Oil, Combustion, Burner, Optimization, Flame Temperature, Response Surface Methodology

1. Introduction

Increased industrialization and population growth have led to an upsurge in global energy demand while conventional energy sources, mainly fossil fuels, have become scarce, unsustainable and are associated with environmental pollution and global warming [1] [2]. Renewable energy sources like wind, biofuels, solar and geothermal are a promising alternative, though they are yet to be fully embraced due to the capital-intensive nature of wind and solar power plants, unpredictability and intermittent nature of wind energy and the yet-to-be fully commercialized technologies for biofuels [3]. As such, researchers have continued to seek other potential sources of energy to meet the ever-growing energy demand.

Waste lubricating oil (WLO) has been proposed by different researchers as a potential alternative source of energy given its high energy content and local availability, hence, it can be used to supplement the energy mix. Combustion of WLO not only provides energy but also addresses its negative environmental impact which is attributed to gross mismanagement and poor disposal ethics. Poor handling of WLO leads to contamination of soil and water sources, endangering aquatic and terrestrial life [4] [5]. In harnessing energy, WLO combustion is necessary although it has a challenge of high viscosity and low volatility. Additionally, proper cleaning of the oil to remove contaminants is necessary to avoid blockage of the atomizing nozzle and fuel flow line [5]. Another challenge of WLO combustion is proper regulation of the fuel and oxidizer to achieve a near stoichiometric reaction. Safe and efficient combustion of WLO is necessary for it to suffice as an alternative source of energy. This can be achieved through proper mixing during combustion.

Several research studies have been carried out by different researchers to improve WLO burner combustion performance. Owiti *et al.* [4] designed and developed a manually ignited burner for WLO combustion for heating applications in small and medium enterprises. High levels of Carbon monoxide and unburned hydrocarbon were recorded, as well as challenges associated with manual ignition. Based on the findings of the study, optimization of the fuel and air flow parameters and re-design of the burner to incorporate automatic ignition system would significantly improve its performance.

Madu *et al.* [6] examined the performance of a WLO burner where WLO and kerosene were mixed to ease ignition and increase efficiency. The thermal efficiency of the burner was reported as 66%. However, high levels of emissions were recorded indicating the need to re-design the burner for improved efficiency.

Madhusudan *et al.* [7] designed and fabricated a WLO burner. Flame length and flame temperature were measured while varying the injection pressure and mass flow rate. Oil flow to the nozzle was via gravity hence poor fuel atomization was achieved. The study however recommended preheating of the WLO to improve atomization.

An experimental study was conducted by Arroyo *et al.* [8] on an emulsion burner using a blend of vegetable oils to optimize combustion performance and emissions characteristics of the burner. Investigation on the effect of air flow rate and fuel flow rate on combustion performance were conducted, as well as physicochemical analysis of the fuel. Interactions of fuel types, air flow and fuel flow rates by statistical technique, analysis of variance (ANOVA) indicated most factors to be significant. Fuel flow rate was more significant while air flow rate had no clear trend on combustion. Fuel type was seen to influence the unburned hydrocarbon (UHC) emissions. Emission measurements indicated low NOx emissions-below 44 ppm and absence of SOx emission. CO, CO_2 and UHC emissions were relatively high due to incomplete combustion.

In another study, a single burner mode for operation was optimized with an aim of increasing the system's efficiency. The air-fuel ratio was adjusted to optimal levels. At the end of the case study a 7% save on oil consumption was realized [9]. Recently, Madejski *et al.* [10] conducted an investigation both numerical and experimental on a combustion process to get optimal parameters for operation. The findings were that on proper control of air and fuel flow rates of the system, combustion process was at optimal level resulting in increased efficiency. Optimization was conducted through a proper control and monitoring system for distributing and optimizing the amount of air and fuel supplied with an aim of increasing thermal efficiency, prolonging the lifespan of the burner, and lowering emissions.

Dordic *et al.* [11] conducted a research study to combust waste engine oil blended with diesel fuel to determine its potential as an alternative fuel. Tests were conducted at a constant low heat output of 40kW to determine the combustion parameters and emission levels. The fuel blends were in four variations with waste oil weight varied between 20% and 50%. The findings indicated that waste engine oil blend had higher levels of NO, CO and CO_2 compared to diesel fuels.

A study carried out in Burkina Faso by Daho *et al.* [12] on characterization of domestic fuel oils (DFO) with other blends on overall combustion performance and emissions output by investigating the effect of fuel pressure and equivalent ratio on combustion in a non-modified DFO burner. Physicochemical property analysis was conducted on the various fuel blends and the results indicated that every blend had a specific property that prompted specific burner adjustment for its combustion. The optimal parameters for operation were found to be equivalence ratio of 0.86 and injection pressure of 20 bar for all blends. However, the results showed high SOx emissions at all pressures due to the physicochemical properties and presence of fatty acids in the blending fuels.

From the foregoing review, despite the concerted research efforts by different researchers, there has not been a conclusive approach to addressing the high viscosity of WLO and significant emissions reduction for adoption of WLO as an alternative source of energy. In response, there has been ongoing research on optimization of burner designs in addition to fuel properties to enhance improved combustion performance. Consequently, WLO characteristics affecting combustion still require extensive studies to comprehend how various factors affect them. This paper presents analysis of flow characteristics on combustion in a PLC controlled WLO burner system. The parameters investigated and their effects on combustion of WLO include the injection pressure, the volumetric rate of flow of air and the oil mass flow rate. Fuel preheating, was performed to lower the oil viscosity and enhance better atomization and facilitate improved combustion. Optimization is carried out by use of Response Surface Methodology (RSM) where the Box-Behnken Design approach is incorporated, and the analysis done by use of ANOVA.

2. Methodology

2.1. Experimental Setup

The waste lubricating oil (WLO) used in this study was sourced locally from service garages and used as fuel during combustion experiments without pre-treatment. The study involved design and fabrication of a WLO burner and combustion chamber, as well as analysis of flow parameters to establish optimum operating conditions for enhanced flame temperature and low emissions. Components of the designed burner system include: 1) a fuel injection system—which includes reservoir fitted with a preheating element, oil filters, flow control valves, fuel pump, fuel flow meter and nozzle; 2) air supply system consisting of a blower, regulating valve and air flow meter; 3) drive system consisting of a motor, couplings, belt and pulleys; 4) ignition system-comprising a transformer and two electrodes; 5) electronic control system consisting of burner controller and PLC Logo and 6) the combustion chamber. Table 1 describes the various components and their respective functions.

Figure 1 and Figure 2 show the schematic and pictorial views of the developed WLO burner, respectively. The burner was automated by incorporating a programmable logic controller (PLC) logo for controlling and monitoring the fuel and air supply.

The WLO reservoir mounted to the system was fitted with an immersion heater with an in-built thermostat for controlling the pre-heating temperature, initially set to a maximum of 80˚C. A PT100 sensor mounted to the system measures the pre-heat temperature of the fuel and relays to the PLC logo. The oil is passed through a series of filters including a Y-filter and two self-cleaning filters of 200 and 100 microns respectively before being pumped to the nozzle for atomization and combustion processes. The burner system is fitted with an electric motor to drive a pump and a blower system. The blower is connected via a pulley system from the main drive to give 3000 RPM. Both the fuel and air supply lines are fitted with regulating valves connected to the PLC logo for automatic control of the flow. Both the fuel and air supply lines are fitted with regulating valves connected to the PLC logo for automatic control of the flow. A pressure swirl nozzle is used for fuel atomization and the fuel is automatically ignited through an auto-ignition system with a photo-electric flame sensor to detect the flame and cut off the fuel supply in case the flame goes off. Flow of reactants is regulated using valves along the lines while monitoring on the flow meters fitted

Table 1. WLO burner components and their functions.

	Component	Function
1	Reservoir	Stores WLO fuel
2	Immersion heater	Preheating oil
3	Oil filters	Cleaning oil
4	Pump	Pump WLO to the atomizing nozzle
5	Flow control valves	Control the flow rates of both WLO and oxidizer
6	Nozzle	Atomize WLO fuel
7	Blower	Supply air under pressure
8	Air and fuel flow meters	Measure reactants' flow rates
9	Transformer	Enhance ignition
10	Ignition electrodes	Ignite the mixed reactants
11	PLC logo	Monitor and control the WLO combustion process
12	Copper tubes	Provide fuel flow lines
13	Combustion chamber	Provide space for reactants' combustion
14	Motor	Electrical drive system for various components
15	Couplings	Torque transmission from motor to pump

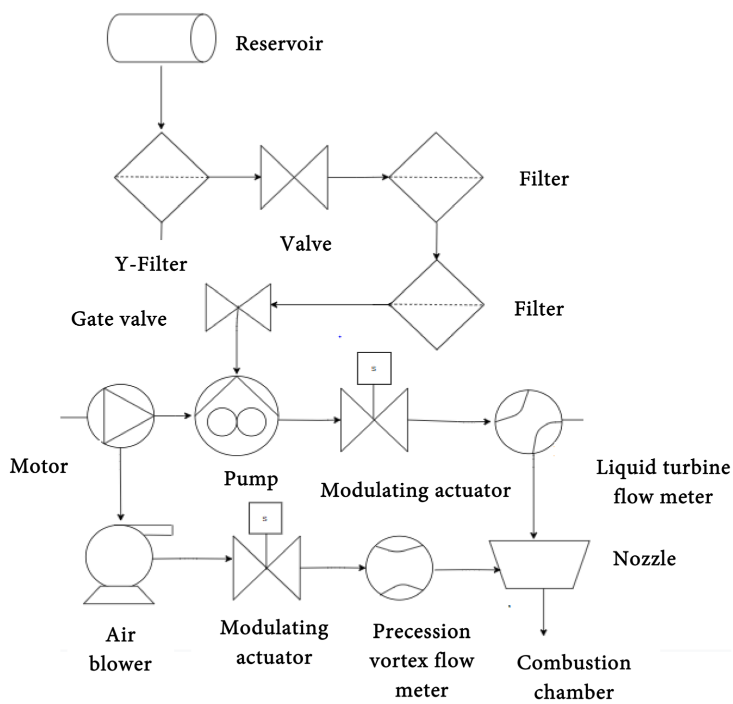

Figure 1. Schematic diagram of the WLO burner.

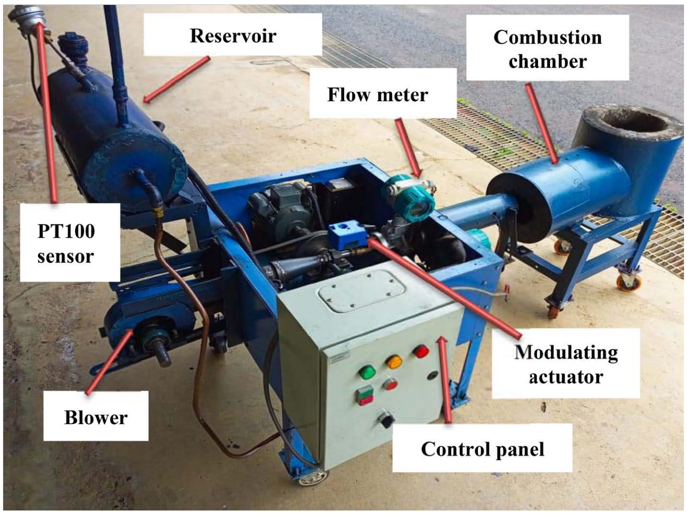

Figure 2. Pictorial view of the WLO burner system.

in the fuel and air supply lines.

2.2. Waste Lubricating Oil Property Analysis

Waste lubricating oil (WLO) from diesel and petrol engines was analyzed to establish their physical and chemical properties to justify their application as alternative fuel. The physical properties investigated include density, kinematic viscosity, and moisture content while chemical properties include the net calorific value and flashpoint. Density was determined using a glass hydrometer, where a measuring cylinder was filled with WLO sample, and the hydrometer was gently lowered into the sample until it floated freely. The point where the liquid's surface contacted the hydrometer's stem correlated to the relative density of the sample, with an accuracy of ±0.001 g/cm^3.

Kinematic viscosity was measured using a viscometer of accuracy ± 1%. The viscosity measurement was done by observing the duration it took for oil to go through the orifice of the viscometer tube under gravity and multiplying the value with a constant. The moisture content was measured using a water content tester that uses distillation principle with accuracy of ±0.1% volume. Flash point was analyzed using a PT-D92 3536 Cleveland open-cup flash point tester with accuracy of ±0.5%. WLO sample was put in a cup of Cleveland Open Tester then heated gradually but steadily at 3˚C to 5˚C temperature rise per minute. At predetermined intervals, a small test flame was evenly spread throughout the cup. The flashpoint was determined to be the lowest temperature at which the test flame application allowed the liquid's surface vapor to flash or ignite but not burn further.

WLO calorific value was determined by use of an adiabatic bomb calorimeter model NENKEN (7701) shown in Figure 3, with accuracy of ±0.01. The calorimeter consists of a reaction vessel (bomb) placed inside a copper vessel containing water and a stirring device for water agitation. The device is well lagged to reduce heat loss from the water when heated with the products of combustion.

(a) (b)

Figure 3. Adiabatic bomb calorimeter; (a)The front view of the adiabatic bomb calorimeter, (b) Pictorial view of the inner components of the adiabatic bomb calorimeter.

The oil pan inside the bomb was fed with 0.05 grams of WLO, then a nickel-chrome wire was weighed and connected to the two ends of the lead calorimetry and the wire extended to be in contact with oil in the pan. Oxygen was charged at 30 bars into the bomb. Water was filled in the outer cylinder and the calorimeter closed and switched on. The water temperature in the calorimeter was measured by a thermometer. The inner water bath was monitored and controlled by the outer water bath to ensure an adiabatic reaction until the temperature levelled off after 5 minutes. The results of the analyses, as well as the standard procedures used to establish each property, are presented in Table 4 and Table 5. Elemental analysis was obtained from literature as shown in Table 2 and used in the calculation of the required amount of air (oxidant) for combustion.

2.3. Design of the Burner System

Elemental analysis of the WLO was conducted on a sample unit mass of the waste oil to identify its constituent elements for calculating the quantity of air needed for complete combustion. A unit mass (1 kg) of WLO fuel is considered to contain 85.9% Carbon, 12% Hydrogen, 2% Sulphur, in determination of stoichiometric air for complete combustion [12]. Table 2 shows the constituent elements of WLO with their corresponding weight in percentage, the molecular weight and moles.

For a theoretically complete combustion, the sum of oil fuel and Stoichiometric air should be equal to the resulting combustion products with release of heat energy. The species information in Table 2 was used for calculating stoichiometric air needed for complete combustion and formulation of WLO chemical formulae. From calculation the amount of air was obtained as shown in Equations (1) and (2).

Table 2. WLO elemental constituents [14].

Species	Percentage weight	molecular mass (kg/kgmol)	Moles (kgmol)
Carbon	85.9	12	7.1583
Hydrogen	12	1	12
Oxygen	0.7	16	0.04375
Nitrogen	0.5	14	0.0357
Sulphur	0.5	32	0.0156
Ash	0.05		
Water	0.35	18	0.0194

Calculation of the stoichiometric air from Table 2 is as follows [12] [15],

Carbon

$$C + O_2 = CO_2$$
$$12 + 32 = 44$$

Therefore 0.859 kg of carbon needs

$$\frac{32}{12} \times 0.859 = 2.29 \text{ kg of oxygen}$$

For CO_2

$$\frac{44}{12} \times 0.859 = 3.15 \text{ kg}$$

Hydrogen

$$2H + 0.5O_2 = H_2O$$
$$2(1) + 16 = 18$$

For 0.12 kg of H_2, oxygen needed is

$$\frac{16}{2} \times 0.12 = 0.96 \text{ kg of oxygen}$$

Sulphur

$$S + O_2 = SO_2$$
$$32 + 32 = 64$$

Oxygen needed is

$$\frac{32}{32} \times 0.005 = 0.005 \text{ kg of oxygen}$$

Total oxygen needed is the summation which is (2.29 + 0.96 + 0.005) = 3.255 kg.

Oxygen required to burn 1 kg of WLO = 3.255 kg,

$$\begin{aligned}&\left(7.1583C + 12H + 0.04375O + 0.0357N + 0.0156S\right) + 0.0194H_2O \\ &+ a\left(O_2 + 3.76N_2\right) \rightarrow bCO_2 + cH_2 + dSO_2 + eN_2\end{aligned} \quad (1)$$

$$\frac{(1.42)(4.76)\,\text{kg}\cdot\text{mol} \times 29\left(\dfrac{\text{kg}}{\text{kg}\cdot\text{mol}}\right)}{1\,\text{kmol}(1\times 12)(1\times 1.68)(16\times 0.006)(32\times 0.002)(14\times 0.003)} = \frac{196.02}{13.882} \quad (2)$$

Air-fuel ratio: 14.12 (kg air/kg fuel).

The experiment was also conducted on excess air at 15%, 25% and 35%.

At 15% excess air the ratio of air to fuel was 16.24 (kg air/kg fuel),

$$\frac{(1.42)(1.15)(4.76)\,\text{kg}\cdot\text{mol}\times 29\left(\dfrac{\text{kg}}{\text{kg}\cdot\text{mol}}\right)}{1\,\text{kmol}(1\times 12)(1\times 1.68)(16\times 0.006)(32\times 0.002)(14\times 0.003)}=\frac{225.42}{13.882}=16.24 \quad (3)$$

At 25% excess air the ratio of air to fuel was 17.65 (kg air/kg fuel),

$$\frac{(1.42)(1.25)(4.76)\,\text{kg}\cdot\text{mol}\times 29\left(\dfrac{\text{kg}}{\text{kg}\cdot\text{mol}}\right)}{1\,\text{kmol}(1\times 12)(1\times 1.68)(16\times 0.006)(32\times 0.002)(14\times 0.003)}=\frac{245.021}{13.882}=17.65 \quad (4)$$

At 35% excess air the ratio of air to fuel was 19.06 (kg air/kg fuel),

$$\frac{(1.42)(1.15)(4.76)\,\text{kg}\cdot\text{mol}\times 29\left(\dfrac{\text{kg}}{\text{kg}\cdot\text{mol}}\right)}{1\,\text{kmol}(1\times 12)(1\times 1.68)(16\times 0.006)(32\times 0.002)(14\times 0.003)}=\frac{264.62}{13.882}=19.06 \quad (5)$$

According to Madhusudan *et al.* [7], a minimum of 2 cubic feet per meter (cfm) and a maximum of 4 cfm of air is needed to atomize any liquid fuel for complete combustion. The relationship of air mass flow rate in kg/s and volumetric flow rate in cubic feet per meter (cfm) is according to Equation (6) [16],

$$1\,\text{cfm} = 0.0283\,\text{kg/s} \quad (6)$$

For the blower design, a volume of 2 (cfm) which is an equivalent of 0.0574 kg/s was selected and used for blower design for this research. Using the relationship of mass flow rate of fuel and air flow rate with respect to air-fuel ratio shown in Equation (7), a fuel flow rate of 0.0041 kg/s was obtained.

The mass flow rate of fuel was determined using Equation (7).

$$m_a = m_f \times \left(\frac{\text{Air}}{\text{Fuel}}\right)\text{ratio} \quad (7)$$

where: m_a = Mass flow rate of air,

m_f = mass flow rate of fuel,

$$m_f = \frac{\text{B.C}\times 3.6}{\text{C.V}} \quad (8)$$

where: B.C is the burner capacity and C.V is the calorific value [17],

$$m = \rho_f A_f \sqrt{2gh} \quad [17] \quad (9)$$

ρ = density of oil = 885 kg/m^3, A m^2 = area of the nozzle orifice;

h = height of burner from ground level = 0.8 m;

g = acceleration due to gravity = 9.81 m/s^2;

The blower was designed based on the discharge air with the speed of 3000 rpm and a frequency of 50 Hz.

This is done using one of the blower (impeller) laws, using Equation (10) [6]:

$$Q = Nd^3 \quad (10)$$

Mass flow rate of air to the burner, is calculated as shown in Equation (11) [6]

$$m_a = \rho Au = \rho Nd^3 \tag{11}$$

where:

m_a = mass flow rate of air;

ρ = density of air = 1.225 kg/m^3;

A = cross-sectional area of the impeller;

u = velocity of air flow to the burner;

The diameter of the impeller is then determined as: 53 mm = 0.053 m.

The blower power can be obtained using Equation (12) [17]:

$$P = N^3 D^3 \tag{12}$$

Substituting for N and D in Equation (12), the power output of the blower was obtained as 4.62 Kw.

Calculation of the nozzle flow rate: Nozzle flow rate was obtained by multiplying the outlet area and oil velocity according to Equation (13) which was equated to the fuel flow rate of combustion from Equation (2), leading to the selection of a 4 GPH Danfoss nozzle and from Equations (10) and (11), an orifice diameter of 1.2 mm was obtained.

$$Q = AV \tag{13}$$

where V = Oil velocity (m/sec), A = Area of nozzle outlet (m^2) and Q = Discharge (m^3/s).

Equation (14) was used to calculate velocity of oil, V (m/s) where the head, h (m) is the distance from outlet of reservoir to top surface of the oil and g is acceleration due to gravity (9.81 m/s^2).

$$V = \sqrt{2gh} \tag{14}$$

2.4. Design of the Auto-Ignition System

The ignition system consists of an ignition transformer to step up the voltage from incoming 120 V to an output of 10,000 V which is supplied to the ignition electrodes [18]. The high voltage initiates a spark jump from the tip of one electrode to the other mounted at 3 mm horizontally and 5 mm vertically from the nozzle as shown in **Figure 4**, creating an electric arc for ignition of the atomized fuel. The ignition transformer is connected to the burner controller (BC) at short length ignition interval of 6 seconds for auto-ignition, with the BC connected to a power source.

2.5. Design of Experiments

Design of experiments was conducted using the design expert software to show multilevel interactions of flow parameters. First, response surface methodology (RSM) was selected as preferable design exploration method [19]. RSM is an engineering tool used for system and process development, improvement, and optimization. It evaluates and analyzes data from experiments to illustrate the

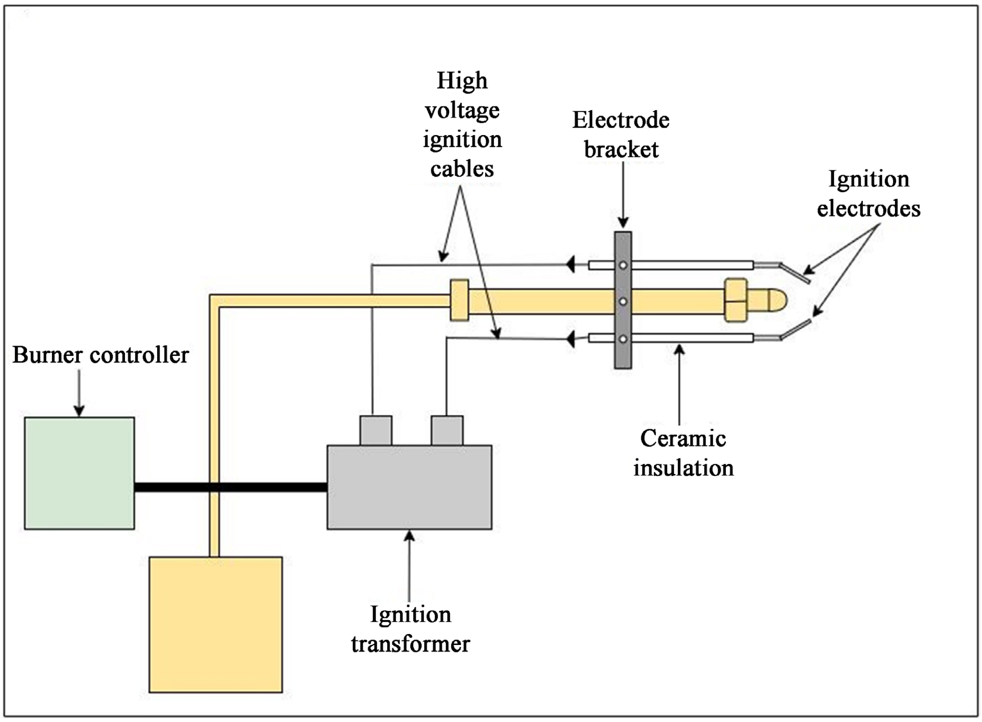

Figure 4. Fuel auto-ignition set-up.

effects of variables [20]. It employs statistical techniques such as ANOVA to determine the significance of variables in regression models.

The procedure for executing RSM includes selecting independent variables, responses, and experimental design; implementing experiments and data collection, mathematical modeling of experimental data by polynomial equations, with the best fitting response identified through analysis of variance, drawing response surfaces using 2D or 3D plots, and finally evaluating main and interactional effects of variables and identifying optimal conditions [20].

Under RSM, the Box-Behnken Design (BBD) as design of experiment method was selected. The Box-Behnken Design (BBD) approach was used to optimize the flame temperature for the air-flow rate, fuel mass flow rate, and injection pressure denoted in **Table 3**, by A, B, and C respectively, at which the experiments were to be conducted. BBD methodology was implemented to perform the least possible number of experiments and in turn lower the cost of the experiments. As a result, a total number of 17 experiments were conducted as per generated test points from the software [19] [20].

Equation (15), [21] shows a polynomial equation used to describe the effect of the chosen parameters and their interactions on the responses using the BBD for the experimental design.

$$\begin{aligned} Z = {} & Y_0 + Y_1 X_1 + Y_2 X_2 + Y_3 X_3 + Y_{11} X_1^2 + Y_{22} X_2^2 + Y_{33} X_3^2 \\ & + Y_{12} X_1 X_2 + Y_{13} X_1 X_3 + Y_{23} X_2 X_3 \end{aligned} \quad (15)$$

where Z is the response function and Y_0 the intercept coefficient (offset), while Y_1, Y_2, Y_3 parameters are linear terms coefficients, Y_{11}, Y_{22}, Y_{33} are unknown

Table 3. Physical and coded values for input factors.

Run	A: Air flow rate (m^3/min)	B: Fuel flow rate (m^3/hr)	C: Pressure (Bar)
I	5.5	0.08	13
2	5.5	0.01	20
3	5.5	0.01	6
4	5.5	0.08	13
5	5.5	0.15	6
6	5.5	0.08	13
7	1	0.08	6
8	1	0.08	20
9	10	0.08	6
10	10	0.01	13
11	1	0.15	13
12	10	0.15	13
13	5.5	0.08	13
14	1	0.01	13
15	5.5	0.15	20
16	10	0.08	20
17	5.5	0.08	13

quadratic coefficients for main effects, and Y_{12}, Y_{13}, Y_{23} are coefficients for two variable interaction effects, which can be obtained through the least squares technique. Interaction terms X_1, X_2 and X_3 are uncoded independent variables [22].

All factors were fed at three equally spaced points (−1, 0, +1), as required by BBD. The injection pressure, the air-mass flow rate and the fuel mas flow rate were the input factors in the experiments while flame temperature was the response. Design-Expert 13 software package was used to generate the experimental test points according to the methodology of BBD as shown in **Table 3**.

3. Result and Discussion

Physicochemical properties of WLO obtained from petrol and diesel engines are shown in **Table 4** and **Table 5**, respectively. The measured property values showed slightly higher viscosity, flashpoint, water content and calorific values for WLO from diesel engine as compared to that from petrol engine, except for specific gravity. There is however no significant difference in calorific values of the waste oil from diesel engine and that from petrol engine.

3.1. Flame Temperature

The effect of air flow rate, fuel flow rate and injection pressure on flame temperature

Table 4. Physicochemical properties for WLO from petrol engine.

Test property	Results	Test method
Viscosity at 50˚C	34 Cst	ASTM D2170
Flashpoint	198˚C	ASTM D92
Water content	1.3	ASTM D95
Specific Gravity	0.885 (g/cc)	ASTM D 1298-12b
Calorific values	4 1.23 (MJ/kg)	ASTM 0240-IP 12

Table 5. Physicochemical properties for WLO from diesel engine.

Test property	Results	Test method
Viscosity at 50˚C	40 Cst	ASTM D2170
Flashpoint	205˚C	ASTM D92
Water content	1.8	ASTMD95
Specific Gravity	0.880 (g/cc)	ASTM D 1298-12b
Calorific values	42.53 (MJ/kg)	ASTM 0240-IP 12

(a) (b) (c)

Figure 5. Flame temperature measurements; (a) Thermocouple setting for temperature detection, (b) Flame temperature captured by data logger, (c) Flame obtained from the burner.

was investigated by varying the three parameters while measuring the flame temperature. Two K-type thermocouples were used to record the flame temperature through a digital data logger, as indicated by Figure 5(a). Figure 5(b) shows readings captured at steady state during experimental measurements on the data logger set to record temperature at intervals of 5 seconds while Figure 5(c) shows the flame at steady state operating condition. A maximum flame temperature of 1200˚C was recorded at an air flow rate of 1 m^3/min, fuel flow rate of 0.08 m^3/hr and injection pressure of 20 bar. Flame temperature corresponding to different air flow rate, fuel flow rate and injection pressure is presented in Figures 6-8.

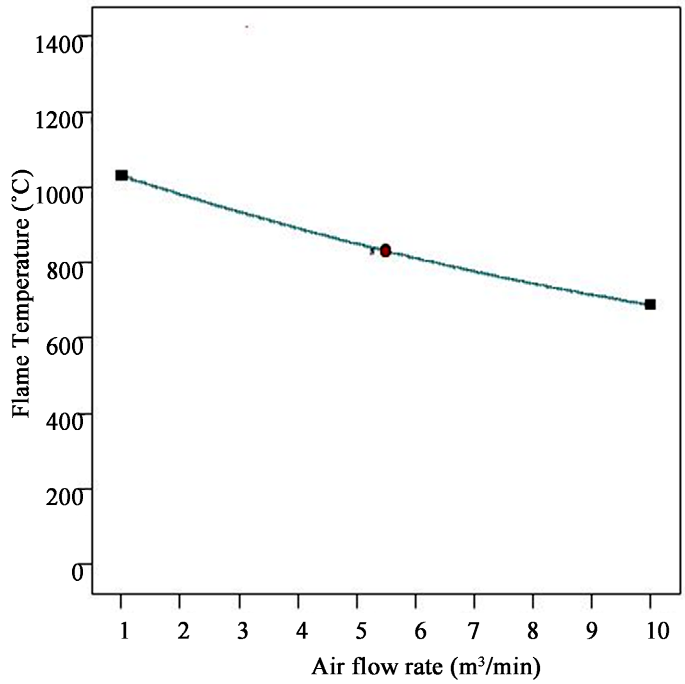

Figure 6. Effect of air flow rate on flame temperature.

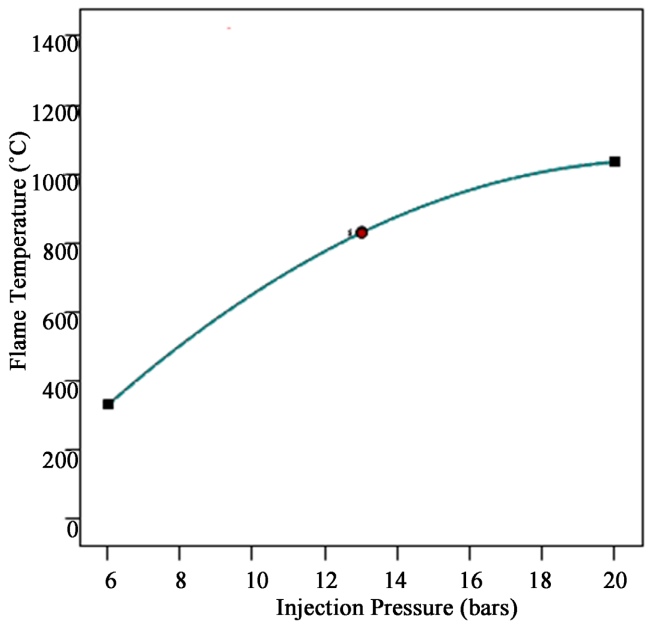

Figure 7. Effects of injection pressure on flame temperature.

From **Figure 6**, it is observed that the flame temperature decreases with air flow rate. From calculation, the allowable excess air should not be more than 3 m^3/min. It's observed that within that range, excess air is attributed to increase turbulent improving mixing of air and fuel hence, improved combustion because a limited amount of excess air ensures that each fuel molecule is surrounded by sufficient number of Oxygen molecules for reaction. However, beyond a certain limit, large quantities of excess air leads to flame quenching, as excess air carries with it some heat to the exhaust.

Figure 7 shows variation of flame temperature with fuel injection pressure. From the figure, it is observed that flame temperature increases with injection pressure. Increased injection pressure leads to high spray velocity and consequently better atomization due to the increased relative motion between the fuel and air particles, causing shearing of the fuel jet and finer droplets [23], hence improved combustion and higher flame temperature. The results are in agreement with related previous studies by Owiti *et al.* [4] on influence of injection pressure on flame temperature in a manually ignited low capacity WLO burner.

Figure 8 shows variation of flame temperature with fuel flowrate. Flame temperature increases with increase in fuel flow rate, due to increased quantity of fuel.

Increased fuel amount implies higher energy available for conversion from chemical to thermal energy, leading to higher flame temperature. The trend is in agreement with related previous studies by Owiti *et al.* [4].

3.2. Optimization of Burner Performance

3D surface response plots are used to show interaction of the parameters under investigation and the combination that gives optimal combustion results. The parameters include, air flow rate, fuel flow rate and the injection pressure. At the normal 0.01 and 0.05 significance thresholds, all factors and their interactions were significant. For statistical significance, p-value was used to evaluate the ANOVA results in where, for a value less than 0.05 the model was considered significant for analysis. Small p-values were found in all the cases with a confidence level of 95%. Table 6 shows the ANOVA results indicating the significant and insignificant parameters.

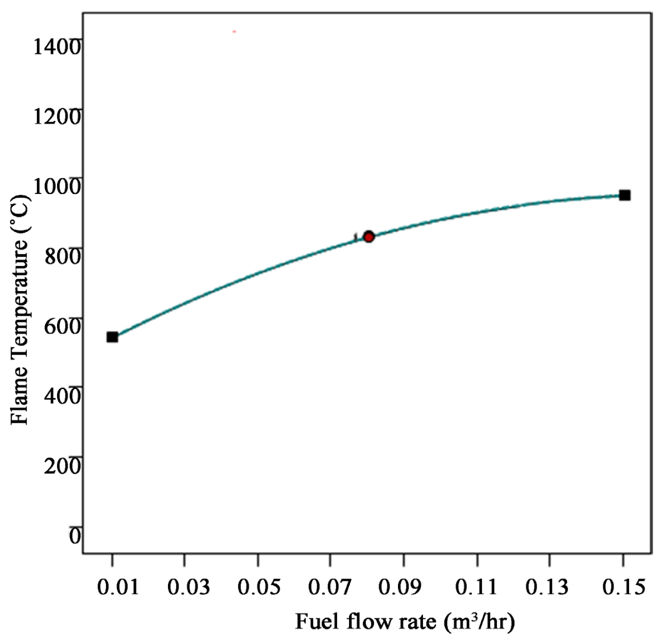

Figure 8. Effect of fuel flow rate on flame temperature.

Table 6. ANOVA results for flame temperature response.

SOURCES	Sum of squares	df	Mean squares	F-value	P-value	
Model	1.721E + 06	9	1.912E + 05	70603.99	<0.0001	significant
A-Injection Pressure	9.868E + 05	1	9.868E + 05	3.644E + 05	<0.0001	
B-Air flow rate	2.346E + 05	1	2.346E + 05	86628.17	<0.0001	
C-Fuel flow rate	3.314E + 05	1	3.314E + 05	1.224E + 05	<0.0001	
AB	4654.65	1	4654.65	1718.86	<0.0001	
AC	4705.27	1	4705.27	1737.55	<0.0001	
BC	30,775.68	1	30,775.68	11,364.76	<0.0001	
A^2	90,514.24	1	90,514.24	33,424.83	<0.0001	
B^2	3399.27	1	3399.27	1255.27	<0.0001	
C^2	30,382.77	1	30,382.77	11,219.66	<0.0001	
Residual	18.96	7	2.71			
Lack of Fit	4.37	3	1.46	0.3996	0.7614	not significant
Pure Error	14.58	4	3.65			
Cor Total	1.721E + 06	16				

$R^2 = 1$; $R^2_{adj} = 1$.

Table 6 shows ANOVA results indicating that all factors were significant hence analysis of the interactions to get the optimal combinations of input factors could easily be achieved. Additionally, it indicates that the average flame temperature significant model terms are the A, B, C, AB, AC, BC, A^2, B^2 and C^2. The expression governing this combustion property is given by Equation (16) which is the optimization function. The equation obtained is a quadratic polynomial correlating the independent variables with the response.

$$\begin{aligned} &\text{flame temperature} \\ &= -146.70370 + 116.41567\text{A} - 89.84310\text{B} + 3239.99427\text{C} + 1.08294\text{AB} \\ &\quad + 69.99490\text{AC} + 278.46032\text{BC} - 2.99222\text{A}^2 + 1.40314\text{B}^2 - 17336.02041\text{C}^2 \end{aligned} \tag{16}$$

Equation (16) shows that B, A^2, and C^2 had a negative impact on the flame temperature implying that with increase in the magnitude of the coefficients the flame temperature decreases.

Figure 9 shows variation of flame temperature with fuel flow rate and injection pressure. From the figure, it can be observed that the lowest flame temperature was attained at the lowest fuel flow rate of 0.01 m^3/hr and pressure of 6 bar. It is also observed that the maximum flame temperature of 1200˚C is recorded at a pressure of 20 bars and a fuel flow rate of 0.01 m^3/hr.

Effect of air flow rate and injection pressure on flame temperature is shown in Figure 10. From the figure, flame temperature is observed to increase with

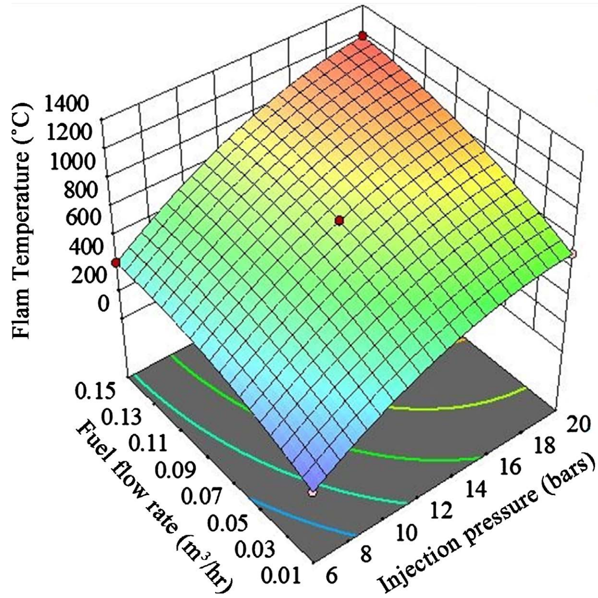

Figure 9. Effect of fuel flow rate and injection pressure on flame temperature.

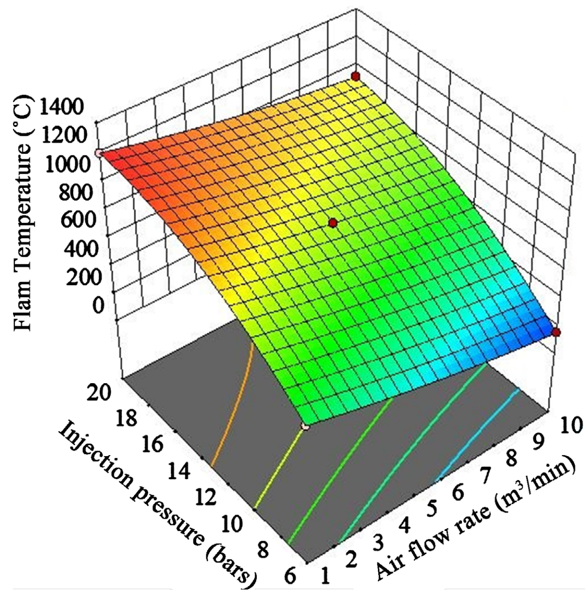

Figure 10. Effect of air flow rate and injection pressure on flame temperature.

increasing air flow rate and injection pressure. However, it is observed that injection pressure has greater influence on the flame temperature than air flow rate. It is also observed that the maximum flame temperature of 1200˚C is recorded at a pressure of 20 bars and air flow rate of 1 m^3/min. Improved combustion due to high injection pressure can be attributed to the fact that at higher pressures the fuel particles atomize into finer droplets which combine with air particles increasing the surface area of contact causing the fuel particles to vaporize hence the ease to ignite and burn.

The effect of fuel flow rate and air flow rate on flame temperature is shown in **Figure 11**, where the flame temperature increases with fuel flow rate and decreases

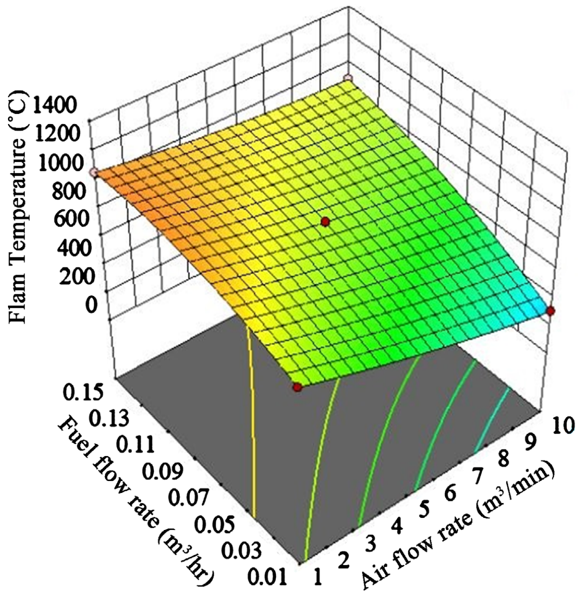

Figure 11. Effect of fuel flow rate and air flow rate on flame temperature.

with air flow rate. However, it is observed that at the lowest air flow rate the flame temperature is maximum, and this could be attributed to the fact that the air flow rate is slightly in excess of the stoichiometric value. A maximum flame temperature of 1066˚C was recorded at an air flow rate of 1 m^3/min and fuel flow rate 0.15 m^3/hr. From the experiment the maximum flame temperature of 1200 was obtained at injection pressure of 20 bar, air flow rate of 1 m^3/min and fuel flow rate of 0.08 m^3/hr.

4. Conclusion

The study was conducted to establish physicochemical properties of WLO and performance of a WLO burner. The results of the fuel property analysis indicate that WLO has high calorific value and can therefore be used as fuel to generate energy. Additionally, preheating results in significant improvement in flow properties and hence ease of ignition and combustion. Comparison of properties of WLO from petrol and diesel engines however reveals no significant difference in calorific value and other chemical properties of the WLO. Combustion performance analysis indicates that proper control and balancing of the oxidizer and fuel improves the performance of the WLO burner. Optimal conditions for the highest flame temperature were attained when the burner was subjected to maximum injection pressure of 20 bar, moderate fuel flow rate of 0.08 m^3/hr and minimum air flow rate of 1 m^3/min. In establishing optimum conditions, ANOVA was applied to the combustion of the WLO burner and an optimal flame temperature of 830˚C was obtained at air flow rate of 5.5 m^3/min, fuel flow rate of 0.08 m^3/hr and injection pressure of 13 bar. Combustion of WLO is an effective and reliable process in recycling and disposal of this waste. It has economic and environmental benefits in that it reduces environmental pollution by offering a safer mode of disposal and due to its high energy content, it can be used for heat and power generation.

5. Recommendations

Study and analysis of emissions and particulate matter was not conducted hence can be recommended since it favors char burnout with the flame hence has a significant impact on flame temperatures.

Preheating the air slightly is encouraged to increase combustion efficiency and also suppress the NOx generation.

Simulation of the burner can be conducted and used to give more insight into the burner design improvements.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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