

BRAKE THERMAL EFFICIENCY AND HEAT ANALYSIS OF A DIESEL ENGINE POWERED BY *Khaya-senegalensis* BIODIESEL FUEL BLENDS

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Abstract

In this study, the brake thermal efficiency and heat analysis of a compression ignition engine powered by Khaya senegalensis biodiesel and its blends were experimentally investigated. The performance of the engine was evaluated by running a 2.5 kW, single cylinder, 4 stroke, air cooled, diesel engine test rig model TD111 (Petter AA1) with Khaya senegalensis biodiesel (B100) and its blends with diesel fuel (D100) of varying proportion from 10% to 50% (B10 to B50) at different engine load levels from 25% to 100% of the engine capacity (1000 g to 4000 g) at constant speed of 1500 rpm. The time taken by the engine to consume 8ml of the fuel was recorded, the torque produced by the engine, exhaust gas temperature, engine block surface temperature, barometric pressure and the ambient temperatures were also recorded. Other performance parameters of the engine were calculated from the experimental values. The maximum value of BTE was obtained at 75% engine load, with Khaya senegalensis biodiesel fuel blend (B10) having the highest value of 29.65% followed by B20 with 29.53%. The maximum value of heat supplied by the fuel (Q_f) to the engine occur at 100% engine load with Khaya senegalensis biodiesel fuel blend (B30) having the highest value of 23.34MW followed by B20 with 23.20 MW. The heat lost through the exhaust gas is at its lowest value at 100% engine load with B10 having the lowest value of 21.94% followed by B30 with 22.21% and the lowest value of heat loss to friction, lubrication and other mechanical activities (Q_{unacc}) by the engine occur at 62.5% engine load with B10 having the highest value of 46.97% followed by B20 with 41.85%. Considering the low value of BTE of the engine running on biodiesel fuel blends, there is need to modify the engine design in order to improve the BTE of the engine.

Keywords: Compression Ignition Engine, Fossil Diesel, Biodiesel, Brake Thermal Efficiency

1.0 Introduction

The fuel energy supplied to an internal combustion engine is converted to mechanical and heat energy. Out of this energy supplied to the engine, only about 25-35% of it is utilized as mechanical work, and about 75-65% of this total energy supplied is lost in form of heat to the environment, thereby contributing to the temperature buildup of the environment [1], with the heat lost through the exhaust gases constituting about 30% of the total heat lost from the engine [2]. Therefore it is of great importance to look at how a diesel engine running on *Khaya senegalensis* fuel blends is utilizing the heat supplied to it in form of fuel energy by experimentally evaluating the engine performance parameters such as the brake thermal efficiency and the various forms of heat losses from the engine.

The brake thermal efficiency of combustion engine is defined as the brake horse power output divided by the rate of heat released from the fuel burning process and it account for all losses that occur in the engine [3]. It can be expressed as;

$$BTE = \frac{\text{actual power output}}{\text{rate of heat input}} = \frac{P_B 3600}{\dot{m}_f C_V} \quad (1)$$

Where,

C_V = calorific value of the fuel (kJ/kg)

\dot{m}_f = fuel flow rate (kg/hr)

P_B = Brake power of the engine (kW)

[4] experimentally investigated the performance of a stroke, single cylinder, direct injection, naturally aspirated, single cylinder, diesel engine at a rated speed of 1500rpm running on different blends of biodiesel fuel and obtained a maximum thermal efficiency for the various fuels tested as 28% for B10, and 25% for diesel fuel.

[3] compared the brake thermal efficiency of diesel engine running with two different biodiesel fuel and a diesel fuel, and reported that the two biodiesel fuels have higher brake thermal efficiency than diesel fuel due to the presence of oxygen molecule in the biodiesel fuel which improves their burning characteristics, and also due to lower cetane index of diesel fuel when compared to biodiesel. [5], reported that biodiesel fuel B100 has maximum value of brake thermal efficiency of 32.4% whereas D100 has the least value of brake thermal efficiency of 29.98%, they argued that net biodiesel fuel B100 has the maximum value of brake thermal efficiency because of the high oxygen content and high cetane number of biodiesel fuel when compared to fossil diesel. [6], reported that at full load the brake thermal efficiency of rice bran biodiesel fuel R75 is 0.93% higher than that of diesel fuel due to constant volume combustion and larger increases in mass of fuel injected into the cylinder leading to better combustion at full load.

[7] analyzed the heat balance of an internal combustion engine running on diesel fuel, palm oil biodiesel and its blends (B5, B10, and B20) using the first law of thermodynamics by analyzing all the energy inflow and out flow from the engine and reported that the heat loss from cooling water and the heat loss from the lubricating oil increased, whereas the engine brake power, exhaust gas heat loss and the unaccounted heat loss decreased with increase in biodiesel concentration in the blends. [2] reported an increase in total heat loss as the percentage of biodiesel concentration in the fuel blend increases due to increase in the combustion temperature of the engine, with radiation heat loss from the engine contributing a very small percentage (<1%) of the total heat lost for all the fuels tested. The heat balance equation for a diesel engine as given in literature [2, 7] is:

$$Q_f = P_B + Q_w + Q_{exh} + Q_{rad} + Q_{unacc} \quad (2)$$

Where,

Q_f = Chemical energy from fuel combustion (kW)

Q_w = Heat lost with cooling water (kW)

Q_{exh} = Heat lost by the engine through exhaust gas (kW)

Q_{rad} = Heat loss by radiation from the engine surface (kW)

Q_{unacc} = Unaccounted heat loss due to lubricating oil heat absorbed, friction and other mechanical activities (kW)

The chemical energy from fuel combustion in the engine, which is also the heat input to the engine is determined from equation (3).

$$Q_f = \dot{m}_f C_V \quad (3)$$

The mas flow rate of the fuel is expressed as [2];

$$\dot{m}_f = C_d A_o (2\rho_a * \Delta P)^{\frac{1}{2}} \quad (4)$$

Air mass flow rate (\dot{m}_a) and the fuel mass flow rate (\dot{m}_f) are normally measured and their ratio is used in defining engine's operating conditions, and it is defined as;

$$\text{Air/fuel ratio (A/F)} = \frac{\dot{m}_a}{\dot{m}_f} \quad (5)$$

$\dot{m}_a =$ mass flow rate of air through an orifice kg/hr

The value of A/F ratio for engines running on diesel fuel is between 18 and 70 [8].

The power delivered by the engine and measured by the dynamometer is the product of the torque and angular speed. This power is called the brake power (P_b), and is the useable power delivered by the engine to the load.

$$P_B = \frac{2\pi NT}{60,000} \quad (6)$$

$N =$ rotational speed of the engine (rpm)

$T =$ torque produced by engine (Nm)

Torque produced by an engine is a measure of the ability of the engine to do work and is normally measured with a dynamometer [8] with the engine clamped to the test bed and the shaft to the dynamometer rotor. The torque is expressed as;

$$T = \frac{FL}{1000} \quad (7)$$

$F =$ force acting on spring balance (N)

$L =$ torque arm length (mm)

The heat lost by the engine to the circulating cooling water (Q_w) in the engine is obtained from equation (8) as;

$$Q_w = \dot{m}_w C_{pw} (T_{outw} - T_{inw}) \quad (8)$$

$\dot{m}_w =$ mass flow rate of water used in cooling the engine (kg/hr)

$C_{pw} =$ specific heat capacity of water (kJ/kgK)

$T_{outw}, T_{inw} =$ Inlet and out let temperature of water used in cooling the engine (K)

The heat lost from the engine through the exhaust gases (Q_{exh}) is given by Equation (9)

$$Q_{exh} = \dot{m}_{ech} C_{pexh} (T_{exh} - T_a) \quad (9)$$

$\dot{m}_{exh} =$ mass flow rate of exhaust gas from the engine (kg/hr)

$C_{pexh} =$ specific heat capacity of exhaust gas (kJ/kgK)

$T_{exh} =$ temperature of exhaust gas (K)

$T_a =$ ambient temperature of air (K)

Heat loss by radiation from the engine surface area (Q_{rad}) is given by Equation (10)

$$Q_{rad} = \sigma A_s (T_{sur}^4 - T_a^4) \quad (10)$$

$T_{sur} =$ surface temperature of engine block (K)

$T_a =$ ambient temperature of air (K)

$A_s =$ surface area of engine block m^2

$\sigma =$ stefan – boltzmann constant (kW/m^2K^4)

The contribution of each energy part in equation (2) is then calculated in percentage form related to the total energy input (Q_f) [2] as shown in equations (11) and (13).

$$\eta_f = \eta_b + \eta_w + \eta_{exh} + \eta_{rad} + \eta_{unacc} = \sum n_i \quad (11)$$

with,

$$\eta_i = \frac{Q_i}{Q_f} \times 100 \quad (12)$$

$Q_i =$ component i of the heat loss from the engine.

2.0 Materials and Methods

2.1 Blending of the Biodiesel Fuel

Khaya senegalensis biodiesel fuel was mixed with fossil diesel using volume proportion in a container and properly mixed by shaking the container thoroughly, for example B10, was mixed by adding 10% by volume of biodiesel fuel to 90% by volume of fossil diesel and thoroughly shaken. Similar procedure was used for the other fuel blends.

2.2 Experimental Procedure

The diesel engine that was used in this study is a single cylinder four stroke diesel engine as shown in Figure 1, detailed specification of the engine are shown in Table 1. A hydraulic dynamometer was coupled to the engine for torque measurement.

A five gas automotive exhaust gas analyzer (model: NHA-506 EN) was used to measure the emission level of oxides of nitrogen (NO_x), hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO₂) and oxygen (O₂), from the engine by inserting the analyzer probe into the exhaust pipe of the engine.

The torque acting on the engine was measured using torque meter located on the control panel of the engine test bed. The speed of the engine was measured using a digital contact tachometer (model: DAM110A) while the surface temperature of the block engine and the exhaust gas temperature were measured using multipoint digital thermometer.

The performance of the engine was evaluated by running the engine with *Khaya senegalensis* biodiesel at different engine load levels (25%, 37.5%, 50%, 62.5%, 75% and 100% of the total engine load capacity of 4000g) at constant speed of 1500 rpm. The time taken by the engine to consume 8ml of the fuel was recorded, the torque produced by the engine, exhaust temperature, engine block surface temperature, barometric pressure and the ambient temperatures were also observed and recorded. The experiment was repeated with various percentage of biodiesel blend B10, B20, B30, B40 and B50. For each of the fuel samples tested, the experiment was repeated three times and the average of the three readings was recorded. The emission levels of oxides of nitrogen (NO_x), hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO₂) and oxygen (O₂) were also recorded as displayed by the exhaust gas analyzer.

Other engine performance parameters such as brake power, brake thermal efficiency, heat input to the engine, percentage heat loss by the engine through the exhaust gas, percentage heat loss by the block engine through radiation, air mass flow rate, flue gas flow rate and air/fuel ratio were calculated from the values of the measured parameters.

Table 1: Specification of the Diesel Engine used for the Study

Parameter	Specification
Model	TD111 (PETTER AA1)
Swept volume	219 cm ³
Bore	70 mm
Stroke	57 mm
Maximum speed	3600 rpm
Compression ratio	17
Maximum torque	12 Nm
Engine power range	2.5-7.5 kW
Method of cooling	Air cooled



Figure 1: Diesel Engine Test Bed

3.0 Results and Discussion

The results for the engine performance evaluation are presented in figures 2 to 7.

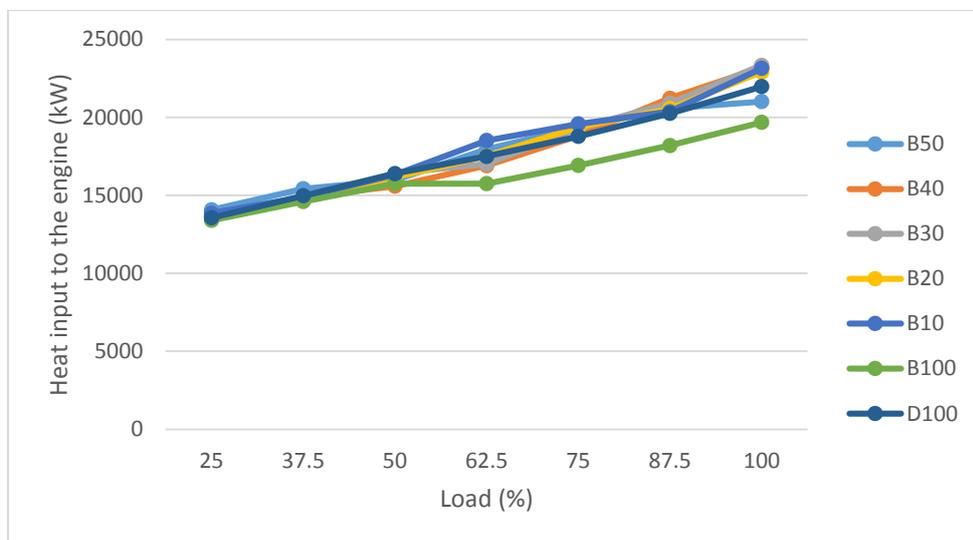


Figure 2: Variation of heat input to the engine (kW) with load (%) on the diesel engine run on the different fuel samples

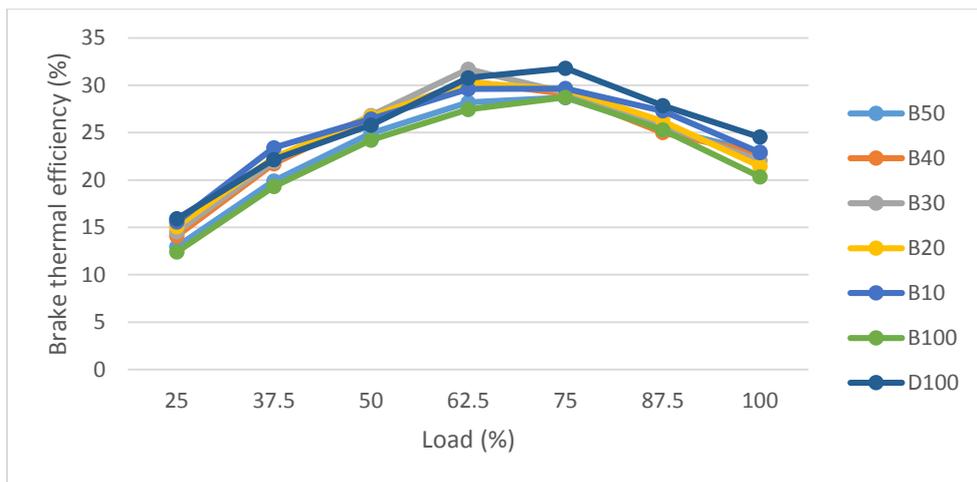


Figure 3: Variation of brake thermal efficiency (%) with load (%) on the diesel engine run on the different fuel samples

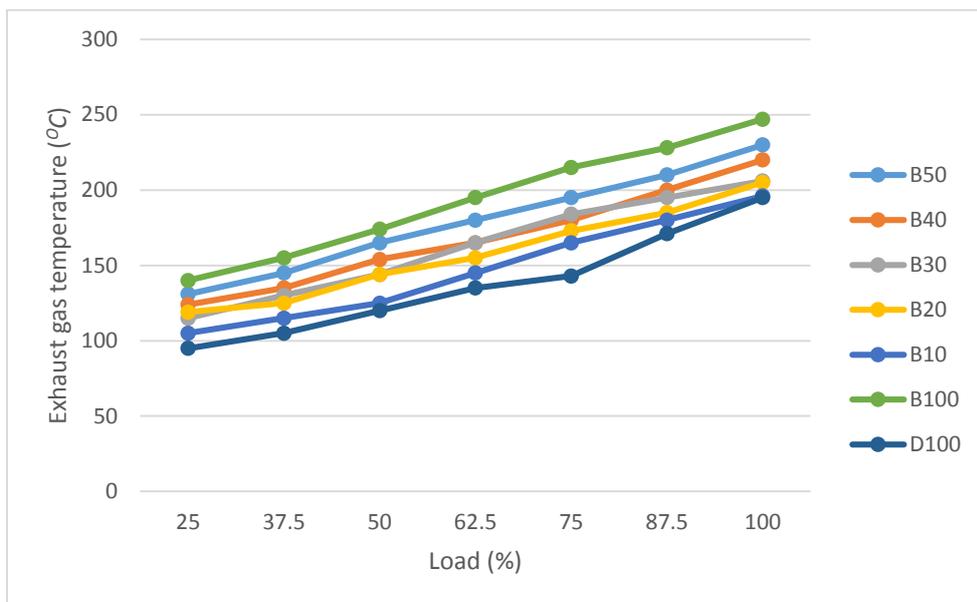


Figure 4: Variation of exhaust gas temperature (°C) with load (%) on the diesel engine run on the different fuel samples

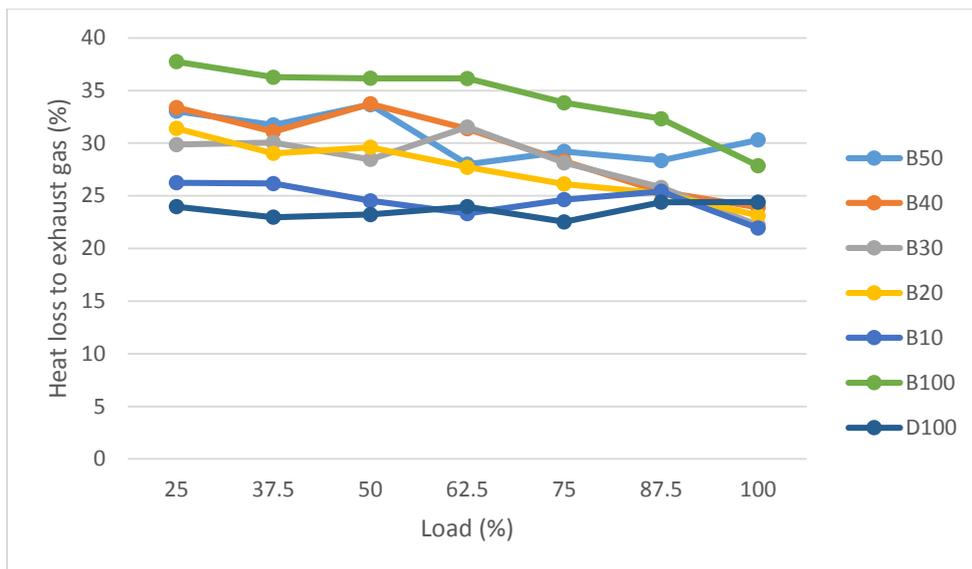


Figure 5: Variation of heat loss to exhaust gas (%) with load (%) on the diesel engine run on the different fuel samples

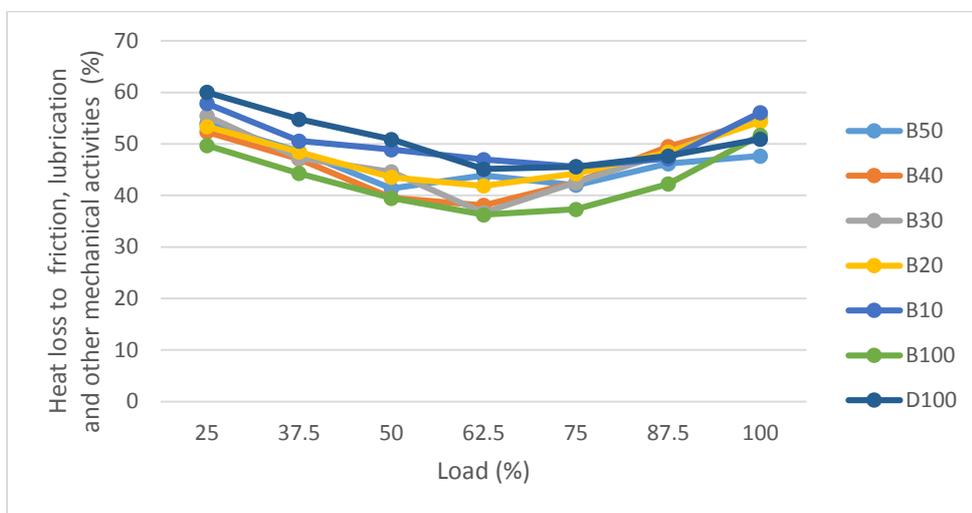


Figure 6: Variation of heat lost to friction, lubrication, and other mechanical activities, (%) with load (%) on the diesel engine run on the different fuel samples

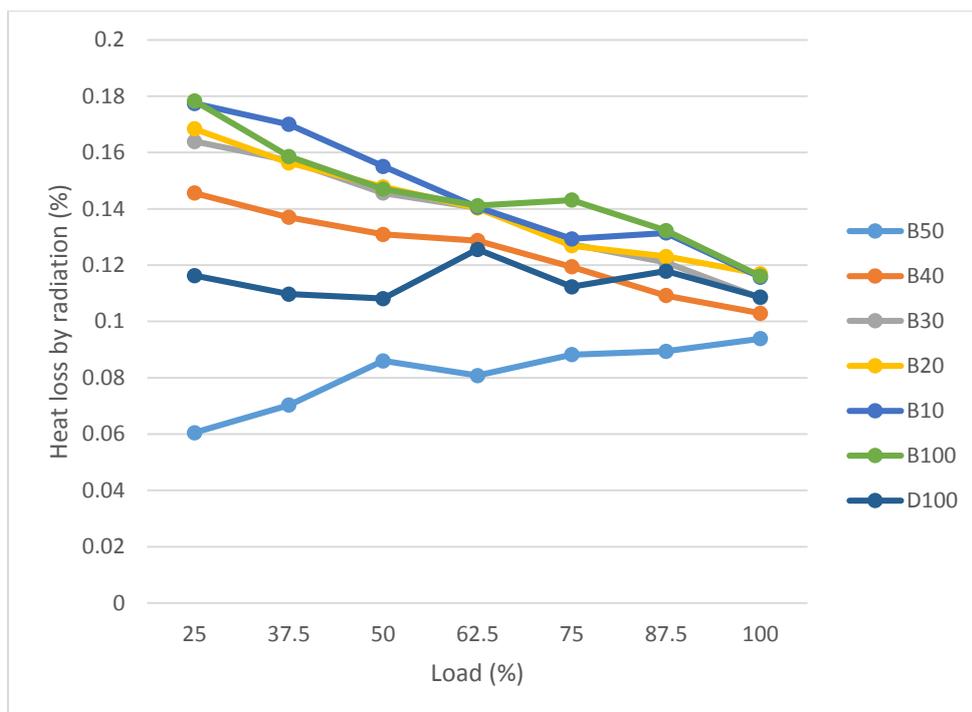


Figure 7: Variation of heat lost by the surface of the block engine by radiation (%) with load (%) on the diesel engine run on the different fuel samples

3.1 Brake thermal efficiency (BTE)

The brake thermal efficiency was found to increase with an increase in load on the engine and reached a maximum value at 75% engine load and then decreased as shown in Figure 2. The reason for the increase in the BTE with increase in load on the engine might be as a result of reduction in heat lost and increase in brake power developed as a result of an increase in load on the engine [4, 9]. [10] attributed this to improved combustion quality of the fuel with an increase in load on the engine.

The maximum value of BTE was obtained at 75% engine load, with *Khaya senegalensis* biodiesel (B100) fuel having the least value of brake thermal efficiency of 28.72%, while fossil diesel (D100) has the highest value of brake thermal efficiency of 31.8%, which is about 9.7% higher than that of *Khaya senegalensis* biodiesel fuel. Also, the brake thermal efficiency of *Khaya senegalensis* biodiesel fuel blends B10, B20, B30, B40 and B50 were respectively 6.8%, 7.1%, 8.1%, 6.7% and 9.7% lower than that of fossil diesel. The reason for lower brake thermal efficiency of *Khaya senegalensis* biodiesel fuel and its blends compared with diesel fuel might be due to lower viscosity, lower calorific value and lower volatility of the biodiesel fuel and its blends, resulting into poor atomization and vaporization of the biodiesel fuel blends, and hence, low thermal efficiency [11].

3.2 Heat input to the engine

The heat supplied to the engine was found to increase with an increase in load on the engine as shown in Figure 3, due to the fact that as the load on the engine increases, more fuel is required to be burnt in the combustion chamber of the engine, and hence, more input energy is required since heat input to the engine is the product of fuel mass flow rate and the calorific value of the fuel [7].

3.3 Exhaust gas temperature

As can be seen from Figure 4, the exhaust gas temperature increases with increase in load on the engine for all fuel tested. This might be due to the need for more amount of fuel needed in the engine to make up extra power required to take up additional loading [12] or due to higher amount of fuel injected into the cylinder at higher loading [13].

Also the exhaust gas temperature increases with increasing concentration of biodiesel in the blend. At 100% engine load *Khaya senegalensis* biodiesel (B100) fuel has the highest value of exhaust gas temperature of 250°C while fossil diesel (D100) has the least value of exhaust gas temperature of 195°C which is about 28.2% lower than that of *Khaya senegalensis* biodiesel fuel. Also the exhaust gas temperature of *Khaya senegalensis* biodiesel fuel blends B10, B20, B30, B40 and B50 are respectively 0.5%, 5.1%, and 5.6%, 12.8% and 17.9% higher than that of fossil diesel. The reason for the higher exhaust gas temperature of *Khaya senegalensis* biodiesel and its blends in comparison with diesel fuel might be due to the increasing heat losses of *Khaya senegalensis* biodiesel fuel and its higher blends as can be seen from their lower value of brake thermal efficiency [12]. [14] argued that for blends with lower concentration of biodiesel, their lower value of exhaust gas temperature might be due to effective combustion taking place that result in reduction of energy loss in the exhaust gas.

3.4 Heat loss in exhaust gas

The effect of load on the heat loss to exhaust gas as a percentage of heat input to the engine for all the fuel samples tested in diesel engine is shown in Figure 5. The heat loss to exhaust gas was found to decrease with an increase in load on the engine for all the fuel samples tested.

3.5 Heat loss to lubrication, friction, and other mechanical activities (unaccounted heat loss)

Figure 6 shows the graph of unaccounted heat loss from the engine. It decreased with an increase in load on the engine and reached its minimum value at 62.5% engine load and then increased with an increase in load on the engine. The reason for the decrease in the unaccounted heat loss by the engine with increase in load at lower engine loading might be due to complete combustion taking place in the combustion chamber, resulting into an increase in brake thermal efficiency of the engine with an increase in load on the engine as can be seen from Figure 3. Also, at higher loading of the engine, the reason for the increase in unaccounted heat loss from the engine with an increase in load on the engine might be caused by poor combustion taking place in the combustion chamber, resulting in decreased brake thermal efficiency of the engine at higher loads.

3.6 Heat lost by the surface of the engine block by radiation

The variation of the heat loss by the surface of the block engine to its surrounding by radiation is shown in Figure 7. For all the fuel samples tested with the exception of biodiesel blend B50, the heat loss by radiation decreased with an increase in load on the engine.

4.0 Conclusion

1. The maximum value of BTE was obtained at 75% engine load, with *Khaya senegalensis* biodiesel (B100) fuel having the least value of brake thermal efficiency of 28.72%, while fossil diesel (D100) has the highest value of brake thermal efficiency of 31.8% and *Khaya senegalensis* biodiesel fuel blend (B10) has 29.65% followed by B20 with 29.53%. The heat supplied by the fuel (Q_f) to the engine increases with an increase in load on the engine for all the fuel samples tested. The maximum value of heat supplied

by the fuel to the engine occur at 100% engine load with Khaya senegalensis biodiesel fuel blend (B30) having the highest value of 23.34MW followed by B20 with 23.20MW.

2. The heat lost to exhaust gas by the engine and the heat lost by radiation from the surface of the engine decrease with an increase in load on the engine, while the unaccounted heat lost (heat lost to lubrication, friction, and other mechanical activities) decreases with an increase in load on the engine and then increases after reaching its minimum value. The heat lost through the exhaust gas is at its lowest value at 100% engine load with B10 having the lowest value of 21.94% followed by B30 with 22.21% and the lowest value of heat loss to friction, lubrication and other mechanical activities (Q_{unacc}) by the engine occur at 62.5% engine load with B10 having the highest value of 46.97% followed by B20 with 41.85%.
3. Considering the low value of BTE of the engine running on biodiesel fuel and the high value of heat lost from the engine, there is need to modify the engine design in order to improve the BTE of the engine.

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