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Energy and Exergy Analysis of a CI engine fuelled with biodiesel fuel from palm kernel oil and its blends with petroleum diesel

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***Abstract*— Exergy analysis method has been widely used in the design, simulation and performance assessment of various types of engines for identifying losses and efficiencies. In this study, the first and second Laws of thermodynamics are employed to analyze the quantity and quality of energy in a single -cylinder, direct injection diesel engine using petroleum diesel fuel and biodiesel fuel from palm kernel. The experimental data were collected using steady-state tests which enable accurate measurements of air, fuel, and all the relevant temperatures. Balances of energy and exergy rates for the engine were determined and then various performance parameters and energy and exergy efficiencies were calculated for each fuel operation and compared with each other. The results of tested biodiesel from palm kernel showed similar energetic and exergetic efficiencies as petroleum diesel fuel although exergy efficiency of petroleum diesel was higher than that of palm kernel oil biodiesel and its blends. Therefore, as biodiesels derived from Palm Kernel oil (Pkl 100) have comparable performances to diesel fuel, it was concluded that they can be used as substitutes for petroleum diesel without much power loss.*

***Keywords*— Diesel engine, energy analysis, exergy analysis, Palm kernel biodiesel.**

I. INTRODUCTION

The basic human needs met through transportation, agriculture and industrial activities hinge on the role played by the petroleum fuels. The increasing energy demand, increasing harmful emissions and depletion of fossil fuel resources inevitably necessitate the optimum utilization of exhaustible fossil fuel and non-renewable energy resources. Hence, researchers are looking for alternative fuels and biodiesel is one of the best available sources to fulfill the energy demand of the world (Mukul *et al.,* 2009). The concept of using vegetable oil as fuel dates back to 1895 to the work of Rudolf Diesel. Although vegetable oils hold promise as alternative fuels (Murungesan *et al.,* 2009), using raw oils in diesel engines can lead to engine-related problems such as injector coking and piston ring sticking. Biodiesel is a sulfur-free, non-toxic, biodegradable, and oxygenated alternative diesel fuel with a higher cetane number and lubricity (Sekmen *et al.,* 2007). Many researchers (Sahoo et al.,2009 and Zheng *et al.*,2008) have studied biodiesel fuels and their blends with petroleum diesel fuel as an alternative energy source in the compression ignition engine. The performance, emissions and combustion characteristics of the engine have been analyzed. The results show that for biodiesel fuels, brake specific fuel consumption (Bsfc) increases since these fuels have lower heating values. Based on these studies, biodiesel can be used as a substitute for diesel in diesel engine. Some studies show that almost 1/3 of the energy of a fossil fuel is destroyed during the combustion process in power generation. This has caused a renewed interest in exergy analyses since effective management and optimization of thermal systems is emerging as a major modern technical problem (Graves *et al*., 2004). An exergy-based performance analysis is the performance analysis of a system based on the second law of thermodynamics that overcomes the limit of an energy-based analysis (Rakopoulos *et al*.,2006). In this type of analysis of a thermodynamic system, second law equations are presented and discussed thoroughly (Moran *et al.*, 2000) and are used to analyze the operation of power plants (Rosen *et al*., 2003). Series of papers have been published on second law or exergy analysis applied to internal combustion engines in the last few decades. A review study was published by (Caton 2000) and was extended by Rakopoulos *et al* .(2005). It can be seen from these review papers that numerous studies have been performed on the application of exergy analysis of SI engines (Bourhis *el at.*, 2009) and compression ignition engines using hydrocarbon fuels and/or alternative fuels (Caliskan *et al.,* 2009). Various investigators have conducted some studies on exergy

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analysis of ICEs at fixed dead state temperatures (Kanoglu *et al*., 2005) using same characteristic engines using different fuels. Kanoglu *et al.* (2008) and Caliskan *et al*.(2009) conducted experiment on the effects on exergy efficiencies of different dead state temperatures using alternative fuels in a four stroke, four-cylinder, turbocharged diesel engine. The results obtained showed that exergetic efficiency increased as dead state temperature decreased. The combustion process is the most important stage during IC engine operation and modeling of combustion in a realistic way is very important for exergetic computations. In furtherance of research in this area, this work is geared towards the use of exergy analysis to evaluate the performance of an internal combustion (IC) engine fuelled with biodiesels derived from Nigerian palm kernel oil and its blends with petroleum diesel.

II. THEORETICAL ANALYSIS

Relations presented in equation 1-17 are taken mostly from Caliskan *et al*. (2010). For a thermodynamic system, mass and energy balances for a control volume expressed as follows:

2.1 Energy Analysis:

Energy analyses are conducted by balancing mass and energy flows of the control volume.

The mass and energy balances for a control volume can be expressed by equations (Caliskan *et al*., 2008)

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (1)$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_{out}\, h_{out} - \sum \dot{m}_{in}\, h_{in} \qquad (2)$$

Equation (1) and (2) are mass and energy balance for a control volume of a general thermodynamic open system respectively where the subscripts *in* and *out* represent inlet and exit (output) states respectively while $\dot{Q}$ denotes heat rate, $\dot{W}$ work rate, $\dot{m}$ mass flow rate and h specific enthalpy. These balances describe what is happening in a system an instantaneous time between two instants of time.

Energy input rate ($\dot{E}_{fuel}$) is found using the lower heating values (H_U) and the mass flow rate ($\dot{m}_{fuel}$) defined in relation as:

$$\dot{E}_{fuel} = \dot{m}_{fuel}\, H_U \qquad (3)$$

Net work ($\dot{w}$) is calculated with experimental data using the equation

$$\dot{W} = \omega T \qquad (4)$$

Where ω is the angular velocity in (rad/s) and T is the torgue (*NM*)

Heat losses ($\dot{Q}_{loss}$) are evaluated as differences between the energy input rate and net work as follows:

$$\dot{Q}_{loss} = \dot{E}_{fuel} - \dot{W} \qquad (5)$$

The thermal efficiency is defined as the ratio of the network to the fuel energy input rate as follows:

$$\eta = \frac{\dot{W}}{\dot{E}_{fuel}} \qquad (6)$$

2.2 Exergy Analysis:

Exergy balance of a control volume is written as follows

$$\dot{Ex}_{heat} + \dot{Ex}_{w} = \sum \dot{m}_{in}\, \varepsilon_{in} - \sum \dot{m}_{out}\, \varepsilon_{out} - \dot{Ex}_{dest} \quad ,$$

(Kanoglu *et al*., 2009)

Where, $\dot{Ex}_{heat}$ is the exergy transfer rate associated with the heat transfer at temperature T , $\dot{Ex}_{w}$ is exergy work rate, $\dot{m}$ is mass flow rate, ε is specific flow exergy and $\dot{Ex}_{dest}$ is exergy destruction (irreversibility) rate.

Input exergy rate (fuel exergy rate**,** $\dot{Ex}_{fuel}$) include the chemical exergy rate or specific exergy of the fuel (ε_{fuel}) and the mass flow rate described by the relation

$$\dot{Ex}_{in} = \dot{m}_{fuel}\varepsilon_{fuel} \qquad (7)$$

$$\text{But, } \varepsilon_{fuel} = H_U \varphi \qquad (8)$$

Where, φ is the chemical exergy factor and hence defined as follows:

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}\left(1 - 2.0628\frac{h}{c}\right) \qquad (9)$$

Where, $\frac{h}{c}$, $\frac{o}{c}$ and α are hydrogen / carbon, oxygen/ carbon and hydrogen carbon ratio respectively.

Table.1: Some Properties of the fuels used in the test

Property	**Diesel 100**	**PKL100**
Typical formula*	$C_{18.27}H_{34.04}$	$C_{18.24}H_{34.01}O_2$
Heating value, (MJ/Kg)[a]	0.07874	0.07874
Sulphur content(wt/wt)[a]	0.1287	0.0307
Cetane number [b]	47.98	52.51
Viscosity@40°c[b]	4.57	7.31
FLASH POINT °C[b]	63	122
ANILINE POINT°F[b]	136.76	101.3

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**Source: Centre for Advanced Nanotechnology programme Akure. (NASENI)*
[a] Source: Lighthouse petroleum engineering co.LTD, warri, Detal State, Nigeria.
[b] Source: Warri refinery and petrochemicals company, a subsidiary of Nigerian National Petroleum Corporation, Quality Control Department.

Net Exergy work rate is equal to the Net Energy work rate.

$$\dot{Ex}_w = \dot{W} = \omega T \quad (10)$$

Heat transfer Exergy rate ($\dot{Ex}_{heat}$) is defined by

$$\dot{Ex}_{heat} = \sum\left(1 - \frac{T_o}{T_{cw}}\right)\dot{Q} \quad (11)$$

But the quantity $\frac{T_o}{T_{cw}} = 0$ since the engine is air cooled.
Therefore , the relation becomes

$$\dot{Ex}_{heat} = \dot{Q} \quad (12)$$

But,

$$\dot{Q} = \dot{m}_{fuel}\, H_U - \left(\dot{Ex}_w + m_{out}\Delta h_{out}\right)$$

Where, $\Delta h = h - h_{0,}$ *whlie* h *and* h_0 *is enthalpies of exhaust gases at measured exhaust temperature*

m_{out} *is the total mass of exhaust gas species.*

Exhaust exergy (output exergy, $\dot{Ex}_{ex}$) contains thermomechanical and chemical exergies

$$\dot{Ex}_{ex} = \sum \dot{m}_i(\varepsilon_{tm} + \varepsilon_{chem})_i \quad (13)$$

Where, $\dot{m}_i$ is the mass rate of the combustion products, ε_{tm} and ε_{chem} are specific thermo-mechanical and chemical exegies of the exhaust gases respectively.

While,

$$\varepsilon_{tm} = (h - h_0) - T_0(S - S_O) \quad (14)$$

h and S are specific enthalpy and entropy respectively easily found using the exhaust temperatures of the fuels. and subscript "o" denotes the dead reference state.
The chemical exergy of the exhaust gases was found using relation.

$$\varepsilon_{chem} = \bar{R}T_0 In\frac{y}{y^e} \quad (15)$$

$\bar{R}$ is the general gas constant, T_0 is the environmental temperature, y is the mole fraction of the component given under the definition of the environment as measured y^e is the mole fractions of the exhaust gases and were calculated by balancing real combustion reactions of the fuels by means of emission measurement.

Exergetic efficiency (Ψ) is defined as ratio of net exergy work rate and the Input (fuel) exergy rate.

$$\Psi = \frac{\dot{Ex}_w}{\dot{Ex}_{in}}$$

III. MATERIALS AND METHODS

The Test-bed Techquipment TD 114 with the engine specification given as shown in Table 1 was used for the engine test experiment. The system has two major units; the engine and instrumentation units.

Table.1: Engine Specification

S/N	Description	Specification
1.	Engine Manufacturer/Model	Techquipment TD 114
2.	Type	Single Cylinder, Air Cooled, Naturally Aspirated 4-Stroke Diesel Engine
3.	Bore/Stroke	70mm/57mm
4.	Compression Ratio	17:1
5.	Maximum Torque	8.2 Nm at 2700 rpm
6.	Maximum Brake Power	2.6 kW at 3600 rpm
7.	Fuel Injection Timing	24 to 33^o BTDC
8.	Fuel Injection Pressure	180psi

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Plate.1: Engine set-up for the experiments

The engine unit consists of the following parts: Base plate, stearing handle, ignition switch, dynamometer, carburetor with speed adjustment screw, magneto ignition system with spark plug, throttle and control lever, exhaust muffler, air inlet, power shaft, torque arm and spring balance.

3.2.1 Description of the engine:

The engine is bolted to base plate. The engine is started by switching on the ignition switch and pulling the handle of the engine. The carburetor of the engine mixes the air and fuel and supplies the combustion chamber where the magneto ignition system with spark plug initiates the combustion processes. The inflow of fuel is controlled by the throttle through the cable and control lever. The power generated from the combustion reaction is transmitted through the power shaft by a means of flexible coupling to the dynamometer. The engine drives the dynamometer paddles inside the dynamometer casing. The casing is partially filled with water. Water enters through the fine control valves and leaves through gate valves(coarse control). There is a vent and outlet to the drain. The paddle has vanes to accelerate the water in the dynamometer which pushes against vanes in the casing. The result is a shearing of the water, causing resistance to the rotation of the engine and a force turning the dynamometer casing on its trunnions (supporting bearings). This force (torque) is measured by the spring balance connected by the torque arm. The load on the engine is dependent on the amount of the water in the dynamometer casing which is controlled by the two valves. The tachometer is driven by an extension of the dynamometer shaft. The tachometer is a magnetic device for measuring the speed of the engine. The instrumentation units are equipped with the necessary indicators of measurable variables.

3.2.3.1 Precautions:

The following precautions were taken before and during the course of the experiment;

i. Sufficient diesel samples that will enable the test sequence to be completed were ensured (i.e 2 liters of each of the sample)
ii. It was ensured that there was a supply of clean water to the Dynamometer
iii. There were no obstructions for air entering the orifice.
iv. It was ensured that the dynamometer arm was horizontal.
v. Initial readings on the instrumentation unit were set and noted.
vi. After each experiment the engine was flushed with the next sample to be used.
vii. for statistical reason each experiment was repeated three times.

3.2.3.3 Engine Adjustment for the experiment:

i. The experiment was conducted by adjusting the engine to the predetermined speed of 3200 rpm. The engine,

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at the set speed, was run with four variable loads of 25%, 50%, 75% and 100%. At each loading, the speed was maintained constant by re-adjusting the throttle. After allowing the engine to run smoothly, measurements were taken accordingly.

ii. The experiment was conducted for the two different fuel samples (i.e PKL 100 and Diesel 100). Engine performance parameters measured were torque, break power(BP), break specific fuel consumption, break thermal efficiency, engine exhaust temperature and exhaust emissions such as carbon monoxide (CO), unburnt hydrocarbon (HC), nitrogen oxides (NO_X) and smoke opacity.

IV. RESULTS AND DISCUSSION

4.1 Fuel Energy rate:

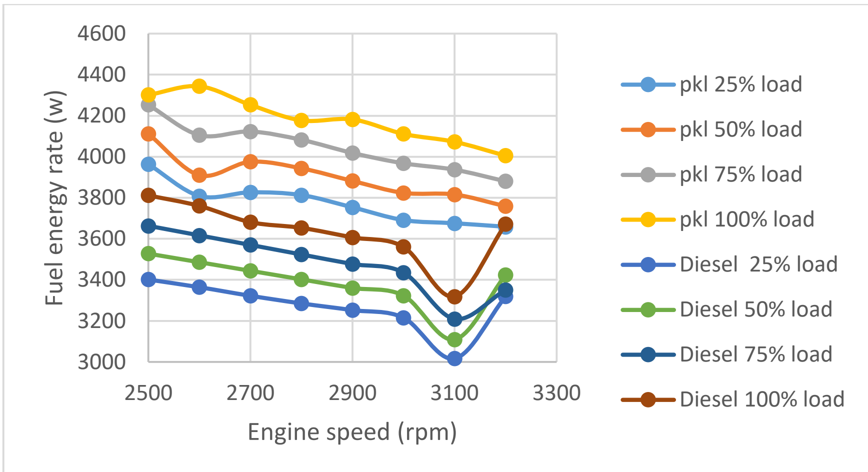

Fig.1: Fuel Energy rate versus engine speed for fuel sample PKL 100 and Diesel 100 .

Fig. 1 shows the effect of speed and load on the fuel energy rate. The graph for both Pkl 100 and Diesel 100 follows the same trend for all the engine loads. The trend shows that, as the engine load increases the fuel energy rate increases. This so because as the load increases, more fuel is combusted to provide the energy required to maintain the desired speed levels (Cem, 2010). Also, with Diesel 100, as the engine speed increases, fuel energy rate reduces to minimum at 3100rpm, and increases at 3200rpm to maximum whereas Pkl100 reduces almost linearly at all the operational speeds. The maximum values (3812.3 watt) for Diesel 100 was at (2500 rpm, 100% load) and 4344.06 watt for Pkl 100 at (2600rpm, 100% load) .which shows that Pkl100 has the highest fuel energy rate compared to Diesel 100. This is due to the lower heating value of Pkl100 as compared to Diesel 100, more of Pkl 100 is required to compensate it's lower heating value for the same engine operation.

4.2 Heat energy rate:

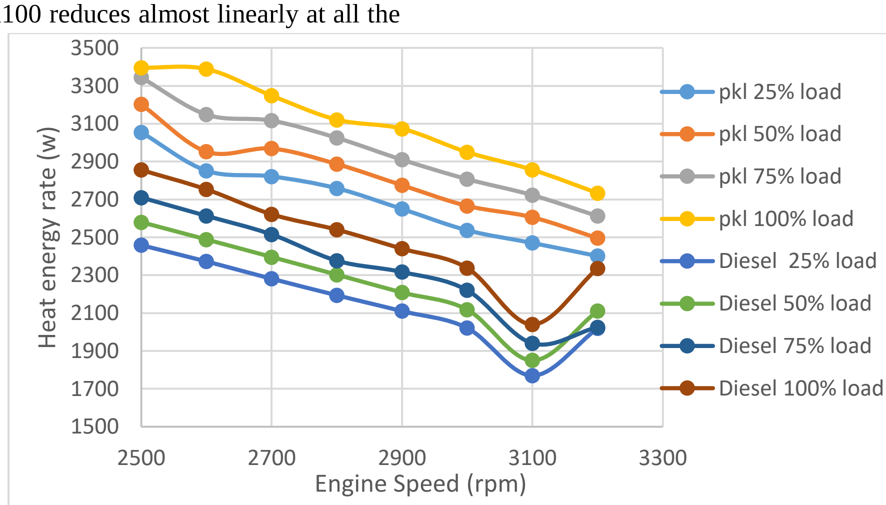

Fig.2: Energy Heat loss rate with Engine speed for fuel sample PKL 100 and Diesel 100.

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Fig. 2 shows the effect of engine speed and load on the heat energy loss. The graph follows similar trend with all the load variation. The trend for energy heat loss shows that, as the engine load increases the energy heat loss increases. Also, as the engine speed increases, heat energy loss rate for diesel 100 reduces to minimum at 3100rpm, and increases at 3200rpm to maximum whereas Pkl100 reduces almost linearly at all the operational speeds.

The maximum values (2855.9watt) for Diesel 100 was at (2500 rpm, 100% load) and 3388.42 watt for Pkl 100 was at (2600rpm, 100% load) .which shows that Pkl100 has the highest heat energy loss rate compared to Diesel 100. Heat transfer is a significant performance loss and affects engine operation loss of available energy, its magnitude is much from the burned gas (Heywood 1988). Heat energy loss is mostly due to friction developed as a result of high viscosity and flash point associated with Pkl 100 (biodiesels); also radiation operation of auxiliary components and heat transfer across the cylinder thermal boundary layer in most cases are causes of heat energy losses (Bilal *et al.*, 2007

4.3 Fuel exergy rate:

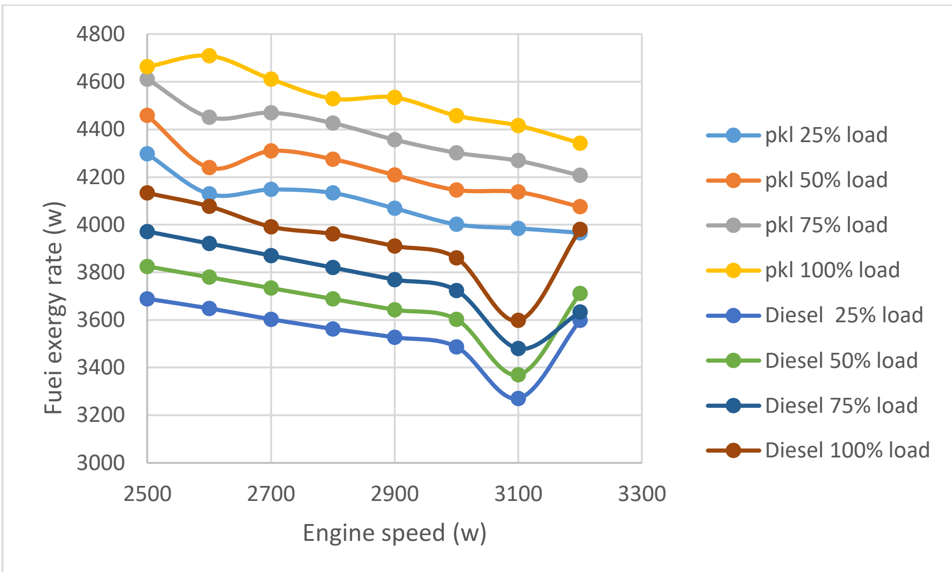

Fig.3: Fuel Exergy rate versus engine speed for fuel sample PKL 100 and Diesel 100.

Figs. 3 shows that as the engine load increases the fuel exergy rate increases. This so because as the load increases, more fuel is combusted to provide the energy required to maintain the desired speed levels (Cem, 2010). Also, with Diesel 100, as the engine speed increases, fuel energy rate reduces to minimum at 3100rpm, and increases at 3200rpm to maximum whereas Pkl100 reduces almost linearly at all the operational speeds.

The maximum values (4133 watt) for Diesel 100 was at (2500 rpm, 100% load) and 4709.52 watt for Pkl 100 was at (2600rpm, 100% load) .which shows that Pkl100 has the highest fuel exergy rate compared to Diesel 100. This is because Diesel 100 has high value of the lower heating value as compared to Pkl 100. The low calorific value of pkl 100 is always compensated with increase in fuel exergy rates for the same engine operation as compared with diesel (Yilbasi *et al.*, 2007).

4.4 Effective power rate:

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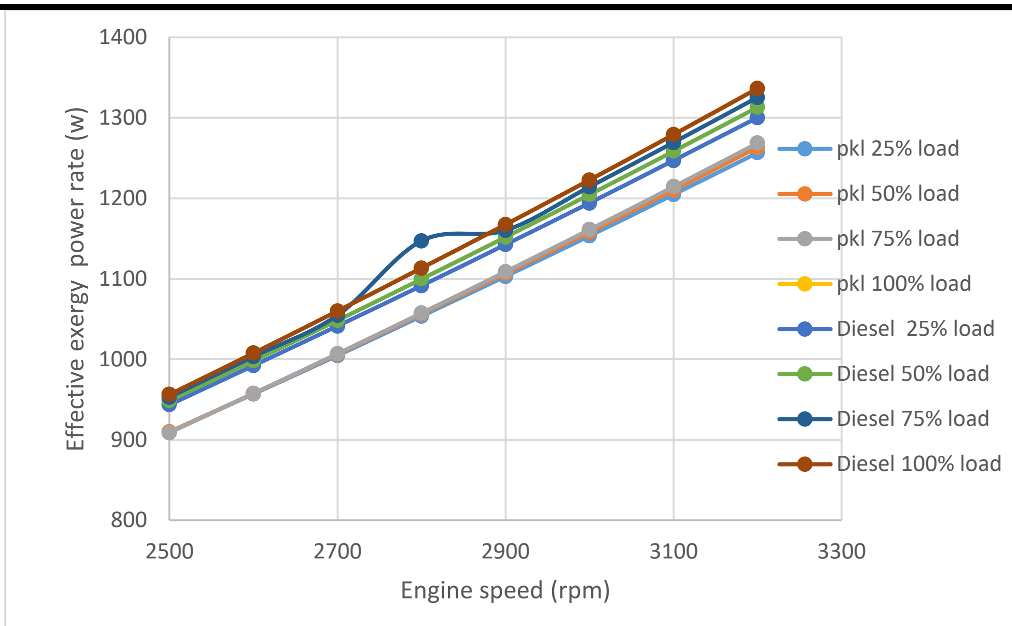

Fig.4: Effective power exergy rate versus engine speed for fuel sample PKL 100 and Diesel 100.

From fig.4 effective exergy power rate is directly proportional to engine speed and inversely proportional to the engine load. This is due to the fact that increasing engine load reduces the developed engine torque but the torque increases with increase in the engine speed (Gumus *et al*., 2012). It can be observed that the trend of this parameter as a function of speed for pkl 100 is almost found to be similar to the diesel fuels. Diesel 100 has the highest effective exergy power rate of 1336.4watt, and Pkl 100 has 1268.66watt , this may be due to the fact that diesel fuel has higher heating value than Pkl100.

4.5 Heat exergy rate

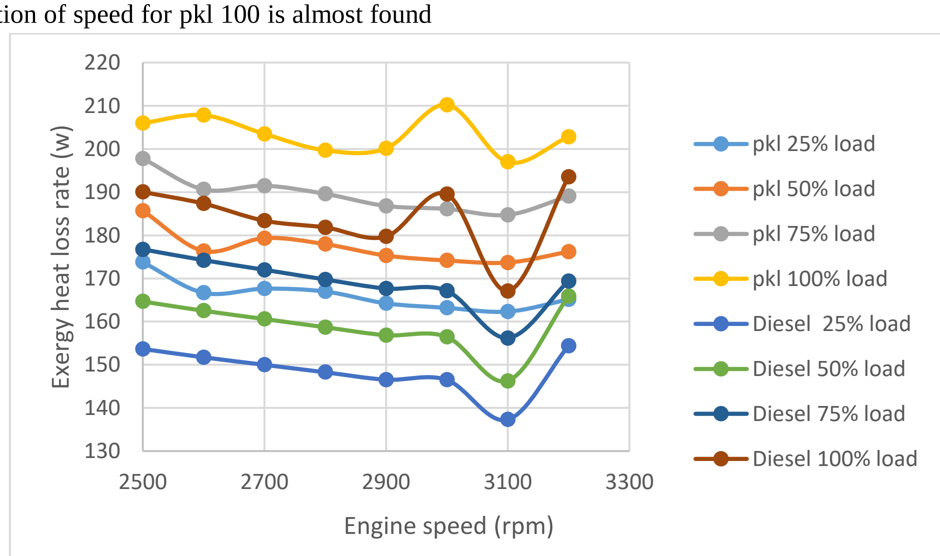

Fig.5: Exergy Heat loss rate versus engine speed for fuel sample PKL 100 and Diesel 100.

Fig.5 shows the trend for exergy heat loss, as the engine load increases the exergy heat loss increases also, and as the engine speed increases the exergy heat loss for Diesel 100 reduces to minimum at 3100rpm, and increases at 3200rpm to maximum. Pkl100 reduces from 2500rpm to 2600rpm and increases almost linearly through 3200rpm. The maximum exergy heat losses (192. 8 watt) for diesel 100 was at 3200 rpm and 100% load and (210.27 watt) for Pkl 100 was at (3000rpm, 100% load). Exergy Heat loss is due to forced convectional heat transfer across the cylinder thermal boundary layer influenced by flame geometry and charge motion/turbulence level (Bilal *et al.*, 2007).

4.6 Exhaust exergy rate:

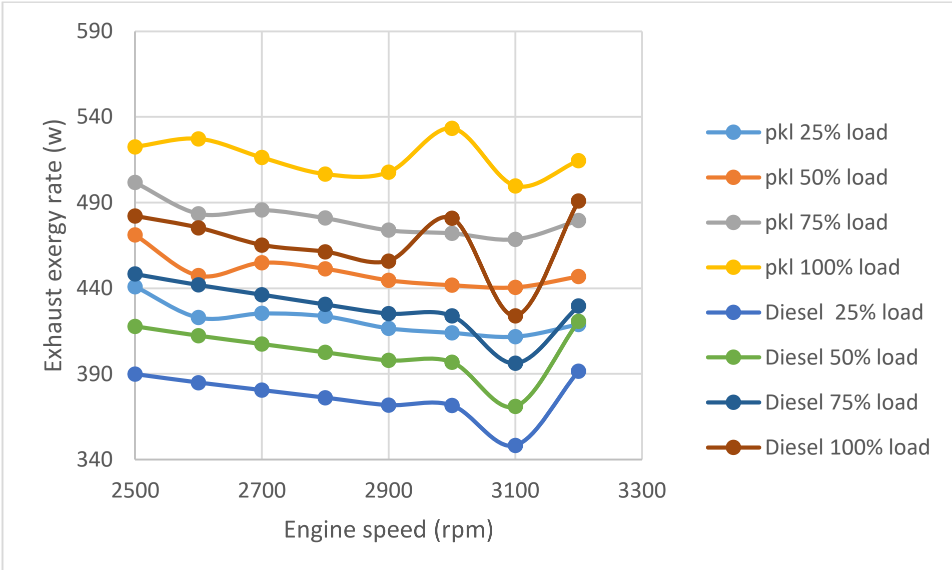

Fig.6: Exhaust Exergy rate with Engine speed for fuel sample PKL 100 and Diesel 100.

The trend for Exhaust exergy (Figs. 6) shows that, as the engine load increases the exhaust exergy increases. Also, as the engine speed increases the exergy heat loss for Diesel 100 reduces to minimum at 3100rpm, and increases at 3200rpm to maximum. Pkl100 reduces from 2500rpm to 2600rpm and increases almost linearly through 3200rpm. The maximum exergy heat losses (490.964 watt) for diesel 100 was at 3200 rpm and 100% load and (533.377 watt) for Pkl 100 was at (3000rpm, 100% load). Because of the higher exhaust temperatures the exergy loss accompanying the exhaust gas is higher in pkl 100 fuel. Consequently, for the same power output, operation with pkl 100 yields higher rate of heat transfer from the engine. It is also important to note that load has significant bearing on the exhaust gas temperature. As the load increases, exhaust gas temperature for both the Pkl100 and diesel100 fuel increases. But in the case of Pkl 100 fuel, exhaust gas temperature is higher at the lower loads than that of diesel fuel signifying better combustion of diesel fuel at the lower loads then the Pkl100, and hence it causes lower specific fuel consumption for the diesel fuels (Sumitaat *et al.* 2011).

4.7 Exergy Destruction rate:

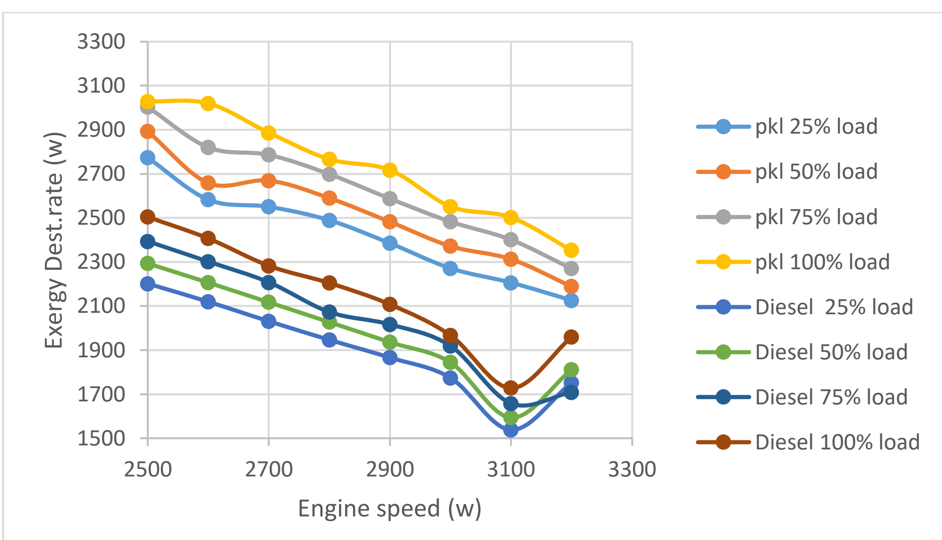

Fig.7: Exergy Destruction rate versus engine speed for fuel sample PKL 100 and Diesel 100.

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Fig. 7 shows the effect of engine speed and load on exergy destruction rates. The trend for exergy destruction rates shows that, as the engine load increases the exergy destruction rate increases and as the engine speed increases, the rate of exergy destruction for Pkl 100 reduces to minimum at 2600rpm and increases to 2700rpm and slightly reduces through 3200rpm whereas with diesel 100 as the engine speed increases the exergy destruction rate reduces to minimum at 3100rpm and increases at 3200rpm to maximum. The maximum value was 2504.4w for diesel 100 at (2500 rpm, 100% load) and for Pkl 100 was 3028.52watt at (3200 rpm, 100% load). This means that the destruction rate is more with fuel sample Pkl 100 and less with Diesel 100. The combustion process in an engine is complex, and is a major source for the destruction of a significant portion of the availability (Kopac *et al*., 2005). The high viscosity of Pkl 100 as compared to that of Diesel leads to unfavorable pumping, inefficient mixing of fuel with air which contributes to incomplete combustion. Also, the high flash point results in increased carbon deposit formation; these problems lead to increased combustion temperatures, hence the increase in the rate of exergy destroyed in the engine.

4.8 Thermal efficiency:

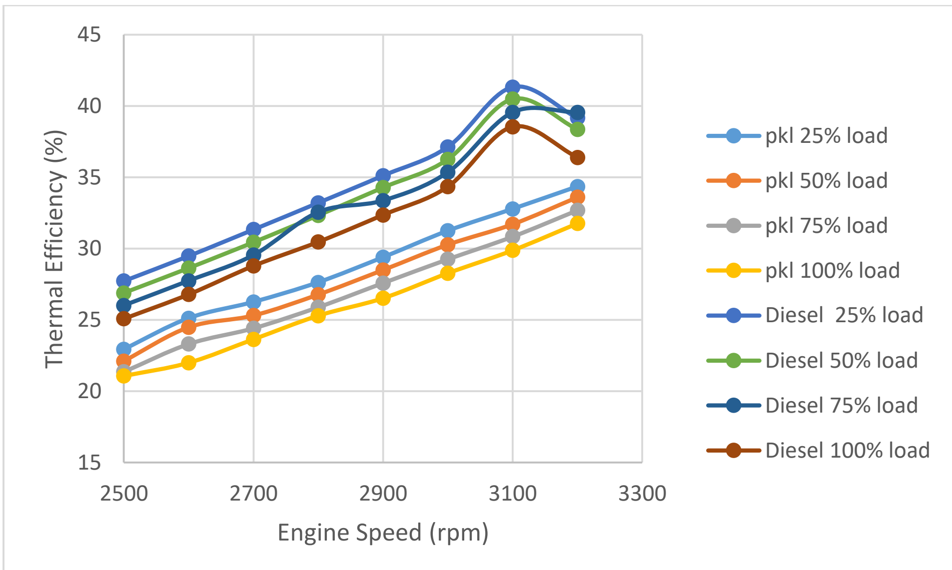

Fig.8: Energy (thermal). Efficiency versus engine speed for fuel sample PKL 100 and Diesel 100.

Fig. 8 shows the effect of engine speed on Energy (thermal) efficiency. The thermal efficiency reduces as the engine load increases while it increases as the engine speed increases. The thermal efficiency for fuel sample Pkl 100 increases almost linearly at all operational speeds. For diesel 100, as the engine speed increases the thermal efficiency increases to maximum at 3100rpm. The maximum thermal efficiency for fuel sample Pkl 100 was 34.35% at (3200rpm, 25% load) and for Diesel 100 was 41.33% at (3100rpm, 25% load). The increase in thermal efficiency means that a larger portion of combustion heat has been converted into work. The low efficiency of Pkl 100 as compared to Diesel 100 may be due its low volatility, slightly higher viscosity and higher density which affects mixture formation of the fuel and thus leads to slow combustion.

4.9 Exergy Efficiency:

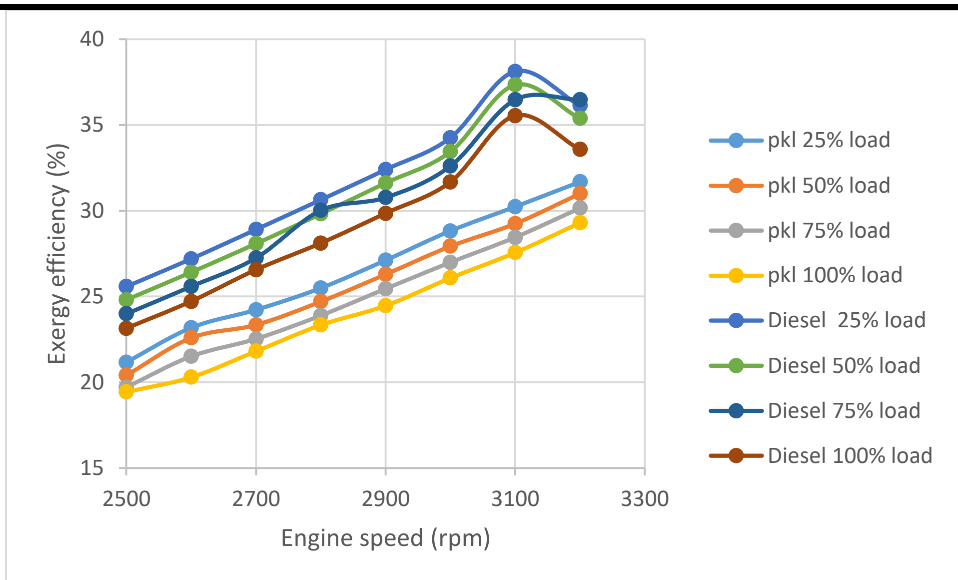

Fig.9: Exergetic Efficiency versus engine speed for fuel sample PKL 100 and Diesel 100.

The effect of engine speed on exergy efficiency is shown in fig. 9. Exergy efficiency relationship with engine load is inverse but direct with engine speed to a maximum value and decreases with further increase in speed. As the engine speed increases the exergy efficiency of fuel sample Pkl 100 increases almost linearly at all operational speeds. But for diesel 100, as the engine speed increases the exergy efficiency increases to maximum at 3100rpm. The trend also revealed that the maximum exergy efficiency for fuel sample Pkl 100 was 31.68% at (3200rpm, 25% load) and for Diesel 100 was 38.12% at (3100rpm, 25% load). The exergy efficiency is to large extent a function of combustion processes. The interaction of the fuels and the engine across the various phases of combustion processes accounts for the overall exergy efficiency (Cem, 2010).

Because biodiesel fuels have different properties than petroleum diesel, such as higher viscosity, higher cetane number, higher specific gravity and lower heating value, when used in unmodified diesel engines, these fuel properties may affect the engine performance and emissions considering that the engines were originally optimized with petroleum diesel (Graboski and McCormick, 1998).

V. CONCLUSIONS

Based on the experiment carried out the following conclusions are reached.

i. Both thermal and exergy efficiencies reduce with increasing load and increase with increasing speed. Exergy efficiency maximum values range from 28.18% to 38.12%; diesel 100 is the most efficient and fuel sample B60 is the least efficient.
ii. Comparatively, petroleum diesel (Diesel 100) is more efficient than the biodiesels derived from palm kernel oil (PKL100). However, biodiesels derived from Palm Kernel oil (Pkl 100) have comparable performances to diesel fuel and can be used as substitutes for the petroleum diesel.

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