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Energy Balance for a Diesel Engine Operates on a Pure Biodiesel, Diesel Fuel and Biodiesel-Diesel Blends

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Abstract: In general, small part of fuel chemical energy transforms to effective power in diesel engines and other parts are going as energy losses, there for many researchers, as well as engine designers, are searching to increase this part by using various methods. In this study, the effect of pure biodiesel and biodiesel-diesel fuel blends on engine energy balance, compared with diesel fuel, has been performed. For this purpose, diesel engine coupled with a dynamometer, as well as, the thermocouples (to measure the temperatures in different locations) and the flow meter (to measure the water flow rate) have been used. In addition, biodiesel mixed with diesel fuel to obtain various proportions of the fuel blends. The engine heat losses through: Cooling water system, exhaust gases and by radiation have been calculated, on the base of experimental results. The results show that an increase of the biodiesel in the fuel blends lead to increase of heat losses. Moreover, the energy distribution from the fuel used for the experiments show a decrease in useful work, increase of heat lost with cooling water, heat lost with exhaust gases and by radiation by about of (average values) 7, 3.8, 4.8 and 4.5% respectively when compared with diesel fuel. The energy distributions were as 26, 27, 22 and 0.46% for useful work, heat losses with cooling water, with exhaust gases and by radiation, respectively.

Keywords: Biodiesel, Energy Balance, Heat Losses, Diesel Engine, Fuel Blends

Introduction

The depletion of petroleum reserves in the world, increased demand for energy and environmental concerns around the world, pay researchers to look for alternative sources of fuel, which depends on petroleum such as gasoline and diesel fuel. Recently, biodiesel is considered as the best alternative to diesel fuel, since it can be used in any diesel engine without any technical problems. With the increased use of bio-diesel fuel all over the world, many studies have been conducted on the performance of diesel engines using pure biodiesel or blended with diesel fuel. Most of these studies reported that engine effective power and brake thermal efficiency are lower and brake specific fuel consumption is higher for used frying oil methyl ester and its blends than diesel fuel, especially with increase of biodiesel in the blends (Canakci *et al*., 2009; Rao *et al*., 2008; Utlu and Kocak, 2008; Murillo *et al*., 2007; Sudhir *et al*., 2007; Dorado *et al*., 2003; Canakci and Van Gerpen, 2003; Prabhu *et al*., 2013). However, some studies reported that biodiesel could cause a slightly higher engine effective power than diesel fuel (Deepanraj *et al*., 2011; Usta *et al*., 2005; Najafi *et al*., 2007). These discrepancies can be related to the fact that, the biodiesel has different physical and chemical properties, which depends on the feedstock used to produce it, from those of diesel fuel, which cause changes in engine performance.

Recently, to improve the engine performance parameters (i.e., Decrease the brake specific fuel consumption and increase effective power) much attention has focused on reducing the heat losses during different operation conditions of the engine. Ramadhas *et al*. (2006) studied the energy balance for a diesel engine running on biodiesel and diesel fuel and found that the engine heat losses, when using biodiesel, is higher compared with diesel fuel. Buyukkaya (2010) experimentally investigated the using of pure biodiesel and biodiesel-diesel blends in a diesel engine. He found that the peak pressure, peak heat release rate and ignition delay decreases by about of 5, 14 and 32% respectively, at 2000 rpm and engine full load.

Zhu *et al*. (2011) studied the effects of ethanol-biodiesel blends on a DI diesel engine performance. They found that, at low and medium engine loads, the maximum cylinder pressure from fuel blends was nearly similar to that of Euro V diesel fuel. While, at high engine loads the heat release rate is higher. Canakci and Hosoz (2006), conducted an experimental study on a four-cylinder, turbo-charged diesel engine to determine the performance parameters and the heat transfer rates during operation using diesel fuel, soybean oil methyl ester, yellow grease methyl ester and 20% blends of two biodiesels and diesel fuel. They found that, when the engine operates on both biodiesel fuels, the heat losses, apart from exhaust loss, were higher than No.2 diesel fuel, due to the better combustion of the biodiesel. Ali *et al*. (1996) studied the influence of different fuels prepared from mixing tallowate and soyate methyl esters and ethanol with diesel fuel on heat release curves for Cummins diesel engine. They found that, the decrease of the diesel fuel amount in the fuel blends, leads to the decrease of the charge temperature. Benjumea *et al*. (2009) performed an experimental study on a diesel engine for heat balance using biodiesel derived from neat palm oil. The results show that the engine heat losses when using biodiesel as a fuel were higher than diesel fuel. From the provided literature review, it can be seen that some experimental and theoretical heat balance studies for diesel engines operated on a biodiesel derived from different feedstock's have been performed. Nevertheless, there is a lack of studies on Waste Frying Oil (WFO) biodiesel's performance. Accordingly, the aim of this study was to evaluate the engine heat balance experimentally when operates on pure biodiesel, biodiesel-diesel fuel, blends and diesel fuel as a base fuel for comparison. Moreover, to study how the diesel and biodiesel fuels transferred its energy throughout the engine to draw conclusions on engine performance characteristics of one fuel source compared to the other.

Materials and Methods

The equipment's used for transesterification were: A 500 mL cylindrical graduated glass vessel, digital thermometer with accuracy of ±1%, a magnetic hotplate stirrer provided with a temperature and stirring speed controllers (Stuart Scientific, UK) and Sartorius electronic balance scale-2355 (readability of 0.1% g). The operation variables employed were methanol/WFO Molar Ratio (MR) 5:1 and NaOH concentration 0.70 wt.% of WFO. While, WFO volume (200 mL), reaction time (60 min), reaction temperature (50°C) and a stirring speed (200 rpm) had fixed as a common parameters in all experiments.

Transesterification Process

Since the WFO, used in this study, has a low acid value (0.95 mg KOH/g), the transesterification process was applied without a titration. The process was conducted by using a two-step method, as well as, different combinations of methanol/WFO MR and NaOH concentration for each step. Therefore, 5:1 MR and 0.7% NaOH by weight of WFO (represented by 43 mL methanol and 1.3 g NaOH), respectively were used for a two-step method. The transesterification procedures were as follows: The vessel was preheated to 70°C, to eliminate moisture and then 200 mL of WFO was added. The MR and the NaOH concentration were divided, by percent's, into different groups for the first and second steps, as shown in Table 1.

In the first step, for instance, trial 5 (70, 30%), the methanol amount of 30 mL was added to 0.91 g of NaOH and stirred until the NaOH was completely dissolved. At the same time, as the oil stirred on a hot plate stirrer and heated to a temperature of 58°C (after pouring the NaOH and methanol solution to the WFO, the temperature of the reactants dropped to 50°C) the solution of NaOH and methanol was poured to the vessel, considering this instant as a time zero for reaction. This mixture was stirred for 30 min. at 50°C and then poured into a separating funnel. After an hour, the separation process happened (i.e., appear two layers, the upper contains the main product-biodiesel and the lower-glycerol) and the glycerol was removed from the bottom of the funnel. After that, the product was washed by distilling the residual methanol and water at 110°C. In the second step, 13 mL methanol and 0.39 g of NaOH was prepared and stirred until the NaOH dissolved. This was then added to preheated yield product obtained from the first step and was again stirred for 30 min. Then, the mixture was put in a separating funnel throughout the night. After separation of the two layers, the biodiesel was purified by distilling the residual methanol and water at 110°C.

The remaining catalyst was removed by incessant washing with warm distilled water (50°C) to becomes clear. Finally, the water present was removed by heating at 110°C and final product, WFO methyl ester light yellow liquid (biodiesel) (Fig. 1).

The chemical and physical properties of diesel fuel and WFO methyl ester (biodiesel) were determined according to the ASTM D6751-12 standard. These properties include density and viscosity. In addition, typical formula, lower heating value, stoichiometric AFR and the Cetane number were determined based on the fatty acid compositions. Table 2 shows the properties of the tested fuels used in this study.

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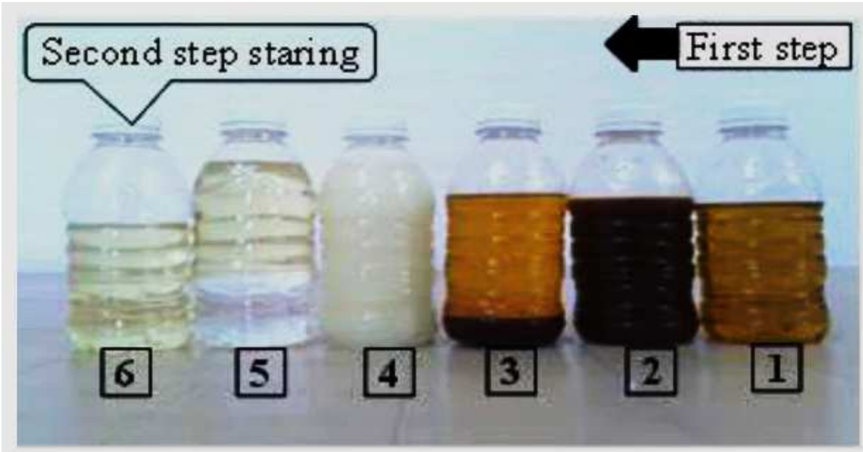

Fig. 1. Biodiesel production steps: (1) WFO; (2) settling after transesterification process; (3) two layers (FAME-upper layer and Glycerin-lower layer); (4) water-FAME emulsion; (5) separation process; (6) FAME

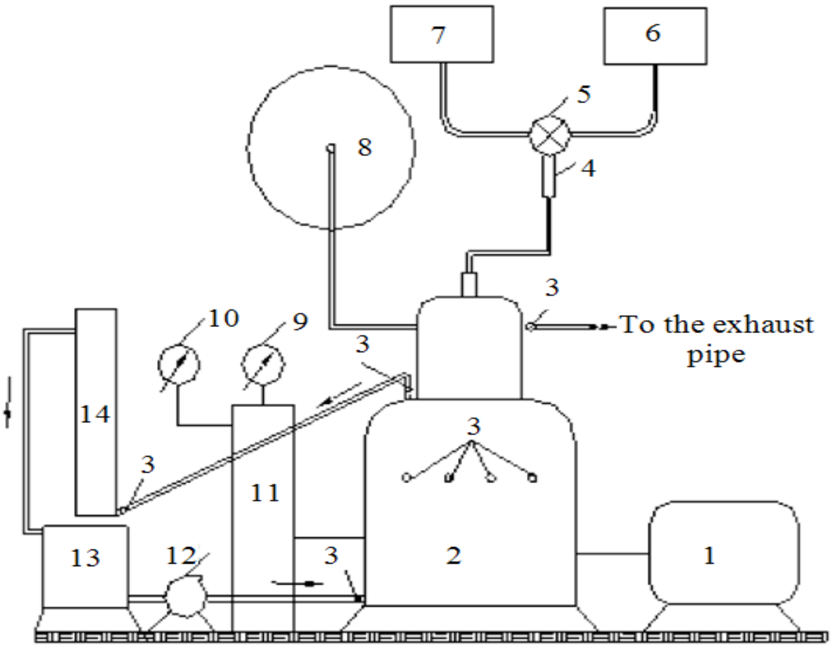

Fig. 2. The schematic of experimental set-up. 1-Electrical motor, 2-Diesel engine, 3-Thermocouples, 4-graduated glass pipe for fuel measurements, 5-three way valve, 6-base fuel tank, 7-tested fuel tank, 8-air tank, 9-engine load indicator, 10-engine speed indicator, 11-engine coupling unit, 12-water pump, 13-water tank, 14-rotameter

Table 1. Experimental schedule for conducting a two-step method

	First-step (Second-step)				
Trial	Distributions, (%)	Methanol/WFO molar ratio	Methanol, mL/200 mL WFO	NaOH, wt. (%)	NaOH, g/200 mL WFO
1	50 (50)	2.50:1 (2.5:1)	21.28 (21.28)	0.350 (0.350)	0.65 (0.65)
2	55 (45)	2.75:1 (2.25:1)	23.41 (19.16)	0.385 (0.315)	0.71 (0.58)
3	60 (40)	3:1 (2:1)	25.54 (17.03)	0.420 (0.280)	0.78 (0.52)
4	65 (35)	3.25:1 (1.75:1)	27.67 (14.90)	0.455 (0.245)	0.84 (0.45)
5	70 (30)	3.50:1 (1.50:1)	29.80 (12.77)	0.490 (0.210)	0.91 (0.39)
6	75 (25)	3.75:1 (1.25:1)	31.93 (10.64)	0.525 (0.175)	0.9 7(0.32)

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Table 2. Chemical and physical properties of the tested fuels

Fuel property	Tested fuels: Diesel	Biodiesel	B5	B10	B15	B20
Typical formula	$C_{12.35}H_{21.76}$	$C_{18.73}H_{36.75}O_{1.96}$	-	-	-	-
Elemental composition, wt. (%)						
C	87.120	76.8200	86.610	86.090	85.580	85.060
H	12.880	12.3100	12.850	12.820	12.790	12.770
O	0.000	10.7600	0.540	1.080	1.610	2.150
Density 20°C (kg/m^3)	846.600	886.8000	848.610	850.620	852.300	854.640
Kinematics viscosity @ 40°C (mm^2/s)	3.290	4.6800	3.360	3.430	3.500	3.570
Cetane number	47.000	48.3200	47.070	47.130	47.210	47.260
Lower heating value (MJ/kg)	42.820	37.6400	42.550	42.279	42.011	41.745
Stoichiometric AFR, wt./wt.	14.440	12.6900	14.350	14.260	14.170	14.080

Tested Enginei

Experiments were conducted on a single cylinder, four-stroke, water-cooled, direct injection diesel engine at various operating conditions. The engine used developing 6 kW at 1500 rpm. The schematic of the experimental set-up is shown in Fig. 2. The fuels used are: Pure diesel fuel (B0), pure biodiesel (B100) and blends of biodiesel and diesel, which are 95% B0 and 5% biodiesel (B5), 90% B0 and 10% (B10), 85% B0 and 15% (B15), 80% B0 and 20% (B20), in the volume bases. The fuel consumption time was measured by using a digital stopwatch. The air consumotion of the engine was measured by an inclined U tube manometer mounted on the air storage tank which mainains a constan flow through the orifice meter. Cromel-Alumel (type K) thermocouples in combination with a digital temperature gage were used for measuring the cylinder block surface temperature.

The engine was run at several speeds and at 50% of full load for all tests. The measured parameters are the following: Manometer head, volume of fuel flow, inlet and outlet cooling water temperature, volume of water flow, room and exhaust temperatures, the cylinder block temperature and engine braking force and the air and fuel mass flow rates, engine effective power or useful work, input heat, heat losses with water, with exhaust gases and by radiation were calculated.

Energy Balance Analysis

Energy balance of a fuel for a diesel engine shows that, about one-third is lost by the transfer of heat from the engine, another third is lost by the portable heat with exhaust gases and only one-third is available as shaft work, Sharma and Jindal (1989). Consequently, decrease these losses and knowing the mechanism of heat losses plays a significant role to enhance the engine thermal efficiency.

In general, the governing equation for an engine energy balance takes the following form:

$$Q_{in} = Q_{out} \tag{1}$$

where, Q_{in} and Q_{out} are the total input and output energy to and from the engine in kW, respectively. The input energy describes the fuel chemical energy that results from the fuel combustion inside the engine cylinder, (Q_f) while the output energy consist of: engine effective power (B_p), the heat lost with the cooling water (Q_c) exhaust gasses (Q_{exh}), by radiation (Q_r) and other losses that account lubricating oil, mechanical heat losses and other total losses (Q_a), all in kW. By using these energy elements, the engine energy balance can be expressed as follows:

$$Q_f = Q_p + Q_c + Q_{exh} + Q_r + Q_a \tag{2}$$

The above-mentioned terms of Equation 2 (except other losses, which were not studied in this study) in addition to other engine performance parameters were determined by the following equations:

$$Q_f = \dot{m}_f \times LHV \tag{3}$$

$$B_p = T_b \times N / 9549 \tag{4}$$

$$Q_w = \dot{m}_w \times C_{pw} \times \left(T_{ouw} - T_{inw}\right) \tag{5}$$

$$Q_{exh} - \dot{m}_{exh} \times C_{pexh} \times (T_{exh} - T_a) \tag{6}$$

$$\dot{m}_f = \left(V_f / t\right) \times \rho_f \tag{7}$$

$$\dot{m}_a = C_d \times A_o \left(2\rho_a \times \Delta p\right)^{1/2} \tag{8}$$

$$Q_r = \sigma \times A_s [T_{sur}^4 - T_s^4] \tag{9}$$

Therefore, the contribution of each energy part (existing in Equation 2) in the engine energy balance can be calculated in percentage form, relative to the total input energy and, Equation 2 becomes:

$$\eta_f = \eta_{th} + \eta_c + \eta_{exh} + \eta_r \quad (10)$$

$$\eta_i = (Q_i \,/\, Q_f) \times 100\% \quad (11)$$

where, $\dot{m}_{exh}$ [kg/sec] is the exhaust gases mass flow rate [equal the sum of mass flow rates of air $(\dot{m}_a)$ and fuel $(\dot{m}_f)$, LHV is the fuel lower heating value [kJ/kg], N is engine speed [rpm], T_b is the brake torque [N m], C_{pexh}, C_{pw} are the specific heat capacity of the exhaust gases and cooling water under constant pressure [kJ/kg°C], respectively, T_{exh}, T_a, T_{inw}, T_{outw} are the exhaust gases, ambient air, cooling water inlet, cooling water outlet temperatures [°C], respectively, $\dot{m}_w$ is the mass flow rate of cooling water entering in the engine [kg/sec], V_f is the consumed volume of fuel [cm^3], is the time of a consumed fuel [sec.], ρ_f, ρ_a are the fuel and air densities [kg/m^3], respectively, C_d is the discharge coefficient, Δp is the pressure difference [N/m^2], A_0 is the orifice aria [m^2], σ is the Stefan-Boltzmann constant [5.67*10^{-8} W/m^2.K^4], T_{sur}, T_s are the engine cylinder block surface and surrounding temperatures [K], respectively and $A_s$is the engine surface area [A_s = 0.075 m^2].

Results and Discussion

Methyl esters of WFO and their blends with diesel fuel were used as a fuel for compression ignition engine without any engine modifications. Accordingly, the engine energy balance is presented and discussed below.

The properties of biodiesel from WFO and diesel-biodiesel blends in comparison with those of diesel are shown in Table 1. The energy content of diesel fuel and WFO methyl ester are 42.82 and 37.64 MJ/kg, respectively. As can be seen from Table 2, as the biodiesel percentage in the fuel blends increases a decrease in energy content is observed. Factors that influence the energy content of biodiesel include the oxygen content and carbon to hydrogen ratio. Biodiesel contains 12% oxygen, while diesel fuel contains zero percent. In addition, the carbon to hydrogen ratio of the biodiesel and their blends with diesel are lower than that of diesel. Therefore, lower energy content was obtained.

Figure 3 shows the relation between the engine speed and the input energy. From the Fig. 1 can be obserfed that as the engine speed increases the input energy increases for all tested fuels, due to the increase of the consumed fuel. In addition, the input energy of the fuels is close to each other's.

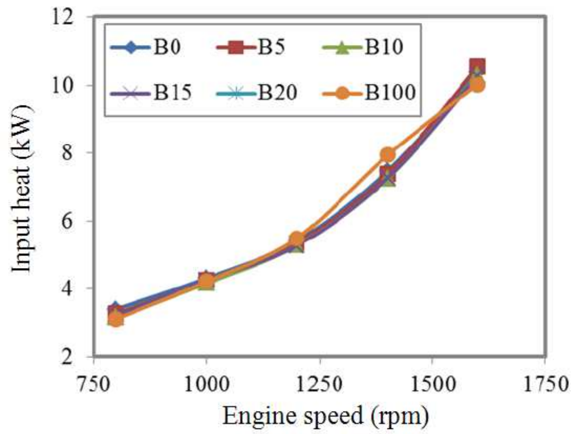

Fig. 3. The input energy of the tested fuels

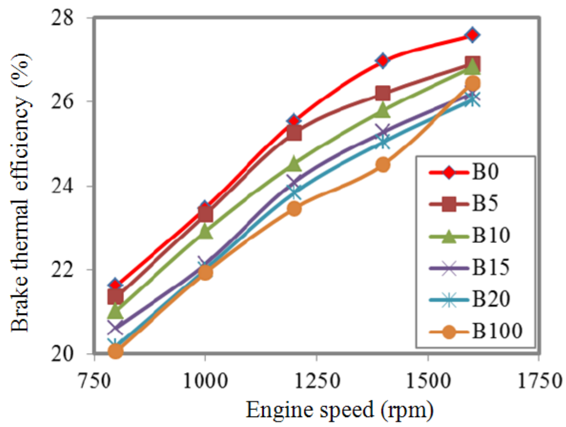

Fig. 4. The brake thermal efficiency

This can be related to the increase of the fuel mass flow rate of the biodiesel and biodiesel-diesel blends compared with diesel fuel.

The effect of the tested fuels on the effective power, presented by the Brake Thermal Efficiency (BTE) with different engine speeds is shown in Fig. 4. It can be seen from the figure that, the BTE increases with the increase of the engine speed for all tested fuels, due to the increase of engine load. Additionally, as the figure shows, the BTE decreases with the increase of biodiesel percentage in the fuel blends for all speeds. This can be attributed to the increase of the fuel mass flow rate due to its higher density and viscosity as compared with diesel fuel (Table 2).

Figure 5-7 shows the heat losses through the exhaust gases, cooling water and by radiation, respectively, as a function of the engine speed for different fuels.

The heat loses through the exhaust gases as a function of the engine speed is presented in Fig. 5. From the figure it can be seen that, an increase in the engine speed accompanied by the increase of the heat loses (presented by the heat flow rate) for all fuels. The same behaviors were obtained for heat lost through the cooling water. However, as shown in Fig. 6, the maximum heat carried away by cooling water occurs at engine speed of 1400 rpm for all fuels. This can be attributed to the incomplete combustion of the air-fuel mixture in the cylinder engine, which reduce the combustion gases temperature and consequently decrease the heat transferred from these gases to the cooling water.

The heat lost by radiation is very small comparing with other losses as shown in Fig. 7. However, it is higher than that of diesel.

Comparing with diesel fuel, the heat losses when using B100, B5, B10, B15 and B20% were higher than that of diesel fuel, due to the increase in temperature of combustion resulted from their oxygen contents, which enhances the combustion process (Fig. 5-7).

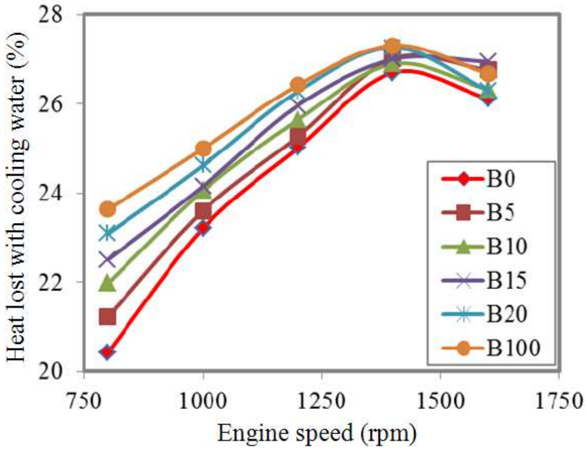

Fig. 6. The heat lost with the cooling water

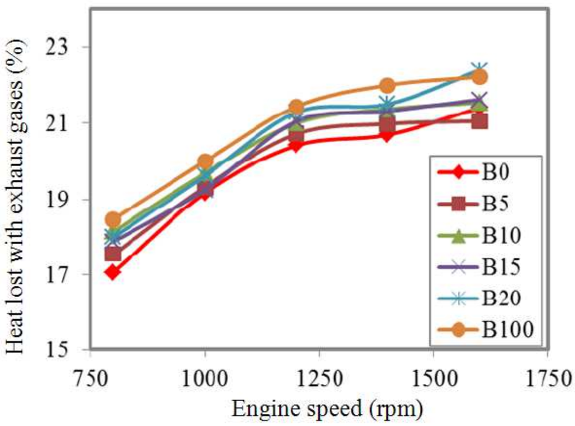

Fig. 5. The heat lost with the exhaust gases

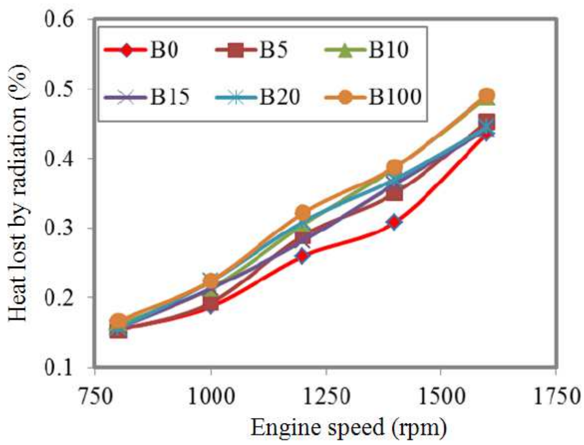

Fig. 7. The heat lost by radiation

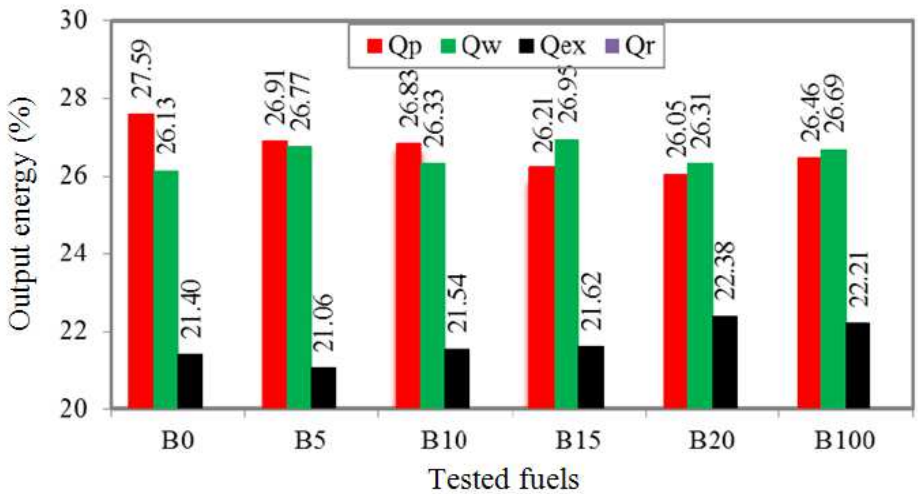

Fig. 8. The energy balance at engine speed of 1600 rpm

The engine energy balance at engine speed of 1600 rpm was presented in Fig. 8. The figure shows that the amount of effective power for diesel was 27.59% while it was 26.91, 26.83, 26.21, 26.05 and 26.46% for B5, B10, B15, B20 and B100% biodiesel-diesel blends and pure biodiesel, respectively. As the mount of biodiesel in the fuel blends increased, there was a slightly decrease of the engine effective power compared with diesel fuel. This happened due to the lower energy content of biodiesel. In addition, the heat losses through the cooling water, exhaust gases and by radiation are higher than that diesel fuel by about of 4.8, 3.8 and 4.5% respectively. These findings conforms with the results obtained by Ramadhas *et al*. (2006), Canakci and Hosoz (2006) and Benjumea *et al*. (2009).

Conclusion

An experimental study was performed on a diesel engine operating on pure biodiesel and its blends with diesel fuel as well as on diesel fuel in order to conduct the engine heat balance. Based on the experimental results of this study, the following conclusions can be drawn.

The energy distribution, obtained by the use of biodiesel and their blends with diesel fuel, shows a slight difference in the effective power, heat losses with cooling water, with exhaust gases and by radiation when compared to diesel. The heat losses increases as the percentage of the biodiesel in the fuel blends increases, due to the increase in temperature of combustion. The heat lost through cooling water increases until as the engine speed reaches 1400 rpm and then decreases due to the decrease of the combustion gases temperature, which decrease the heat transferred from these gases to the cooling water. The heat lost by radiation is very small for all tested fuels. The energy distributions were as: 26, 27, 22 and 0.46% for effective power, heat losses with cooling water, with exhaust gases and by radiation, respectively.

Future works: Utilisation artificial neural network in order to predic in the energy distribution of the diesel engine using biodiesel fuel.

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Author’s Contributions

Al-Hasan, M.I.: Contribute to conception and design, acquisition of data analysis and interpertation of data. Give final approval of the submitted version and revised version.

A.S. Al-Ghamdi: Contribute in drafting the article and reviewing it critically for significant intellectual content. Give final approval of the submitted version and revised version.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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