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Exergy-based Analysis of Diesel Engine when fuelled with Fossil Diesel and Palm Methyl Ester (PME)

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Abstract. Biomass-based energy sources as an alternative to conventional fossil fuel have gained public attention due to the increasing rate of environmental pollutions and depletion of fossil energy source. For diesel engines, comparisons on fuel sustainability and First Law of Thermodynamics are common to inspect biodiesel's potential in replacing conventional diesel fuel. However, the present work focuses on the energetic and exergetic comparisons of a light-duty diesel engine fuelled with fossil diesel and neat Palm Methyl Ester (PME). This study also covers emission characteristics and exergy destruction rate under varying engine operating parameters and fuel types. It was revealed that the best engine thermal efficiency when fuelled with fossil diesel and PME are 22.1% (2750 rpm, 1950W) and 24.3% (3000 rpm, 2400W), respectively. Additionally, the exergy efficiencies of the diesel engine at the same operating conditions appear to be approximately 2% lower than their First Law counterparts. This can be attributed to the generation of the entropy in reactions which destroyed the fuels' potential. The availability destroyed rates were observed to have significant impacts on the exergy efficiencies of the diesel engine. Thus, heat transfer and exhaust exergy rates were investigated since they are the main factors for this outcome. In general, the use of PME fuel will be more beneficial in terms of exergy destruction, engine's thermal and exergy efficiencies due to its higher oxygen content which improves the fuel combustion process.

1. Introduction

The increasing environmental pollution rates and depletion of fossil fuels have triggered public awareness on the issues of environmental conservation and sustainable energy source. For the case of diesel engines, attention has been shifted towards the use of biodiesel as an alternative to conventional fossil diesel, since biodiesel is renewable, biodegradable, oxygenated and has similar properties to that of fossil diesel [1]. Much research has been done to compare the emission characteristics differences between these two fuels. The research done by Kathirvelu et al. has shown that CO emission levels produced by standard diesel fuel is the highest as compared to that of Jatropha oil methyl ester (JOME), Fish oil methyl ester (FOME) and their blends across all load conditions [2]. A comparison between the NOx emission level produced from a direct injection (DI) diesel engine fuelled with tallow methyl ester biodiesel, diesel fuel and their blends has been done by Öner and Altun [3]. It was shown that the NOx level for pure biodiesel and all blends are on average of at least 11.5% lower than that of fossil diesel. Besides emission-based analysis, considerations for engine performances are equally important.



Although the First Law of Thermodynamics efficiency is widely used, it does not provide a clear breakdown of energy allocation when compared with exergy analysis. The additional irreversibility terms in the exergy balance equation provide better insights into the methods to improve energy systems. Caliskan et al. researched on the exergy efficiency of a diesel engine running at 1400 rpm fuelled with high-oleic methyl ester as the dead state varies [4]. It was stated that the efficiency values decrease as the dead state temperature increases. Azoumah et al. investigated the performance of a direct injection compression ignition engine running with diesel and vegetable oil [5]. Recently, energy-exergy analysis for biodiesel made from waste cooking oil has been extensively studied by Madheshiya and Vedrtam [6], where energetic and exergetic performance parameters shared similar trends, however biodiesel showed an increased brake specific fuel consumption and reduced exhaust gas emission, due to the nature of higher oxygenated content in biodiesel.

This study aims to find the optimum load conditions that could improve engine efficiency, through utilising exergy and exhaust analyses, in the context of renewable and non-renewable fuels. For this study, the energetic and exergetic comparisons of fossil diesel and palm methyl ester (PME) are done through comprehensive First and Second Laws of Thermodynamics analyses in a control volume, and estimations of thermodynamic heat transfer in a DI diesel engine.

2. Methodology

2.1. Experimental setup

The experimental work was performed on a 4-stroke, naturally aspirated light-duty diesel engine (Yanmar L70). Figure 1 shows a simplified schematic diagram of the test engine setup. The engine's specifications are listed in Table 1.

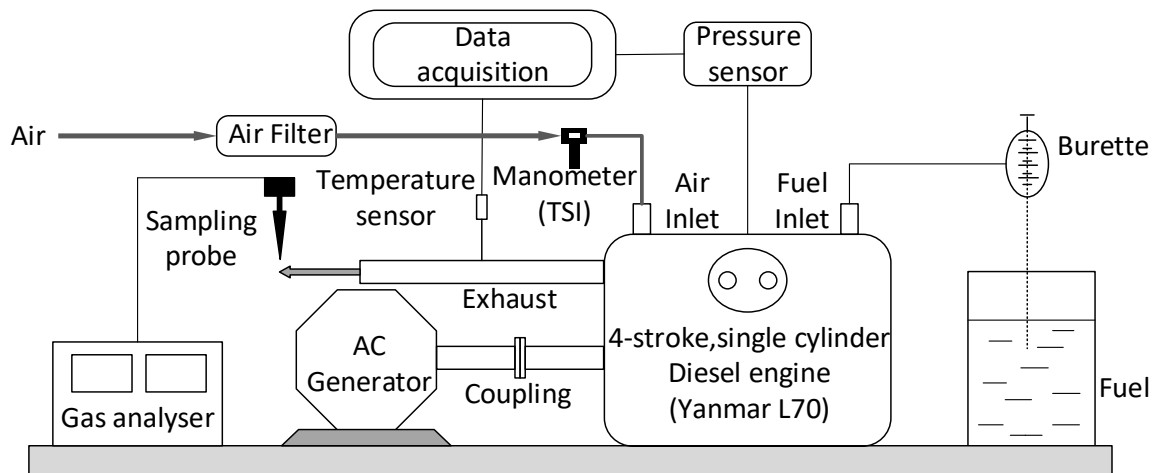


Figure 1. Schematic of the diesel engine test rig.

Table 1. Yanmar L70 specifications.

Model	Yanmar L70
Type	4-stroke, vertical cylinder
Bore × Stroke	ø78 × 67 mm
Displacement	0.32 L
Compression ratio	19.5
Maximum rated output	4.5 kW @ 3000 rpm
Continuous rated power	4.1 kW @ 3000 rpm

2.2. Test fuel

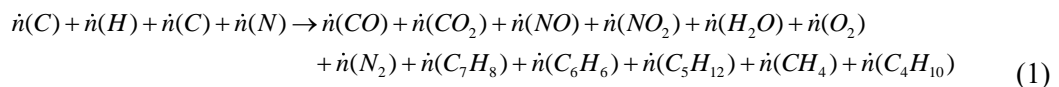
The types of fuel used in this study were palm methyl esters (PME) and fossil diesel. The PME fuel was sourced from *Carotino Sdn. Bhd. (Malaysia)*, whereas the diesel fuel was obtained from a local *Petronas* kiosk. Table 2 shows the properties of PME fuel and conventional diesel fuels.

Table 2. Properties of test fuels.

Categories	Biodiesel standards EN 14214	Diesel standards EN 590	Palm Methyl Esters (PME)	Diesel
C/H/O/N (wt%)				
C	-	-	75.9	86.7
H	-	-	12.2	14.1
O	-	-	11.9	0.0
N	-	-	0.0	<1.0
Boiling range (°C)	-	360	>215	190-360
Cetane number	≥51	≥51	63	52
Density at 15°C (kg/m ³)	860-900	820-845	880	850
Flash point (°C)	>101	>55	174	60-72
Lower heating value (kJ/kg)	-	-	36,770	43,090
Viscosity at 40°C (mm ² /s)	3.5-5.0	2.0-4.5	4.5	2.6

2.3. Theoretical

The stoichiometric balance as shown below was used in calculating mass flow rate, molar and mass ratio of each exhaust component.



where \dot{n} represents the mole flow rate of the element or molecule. The steady-state flow assumption was used in this research [7]. The Steady Flow Energy Equation that was used is shown as below:

$$\dot{E}_{fuel} + \dot{m}_{in\ air} [\sum y_{i\ air} \times (h_{in\ air} - h_{0i})] + \dot{m}_{in\ fuel} [Cp_{fuel} \times (T_{in} - T_0)] = \dot{Q}_{lost} + \dot{W} + \dot{E}_{un} + \dot{m}_{out} [\sum y_{i\ exh} \times (h_{out\ i} - h_{0i})] \quad (2)$$

where \dot{E}_{fuel} = energy flow rate of fuel, \dot{W} = power generated, \dot{Q}_{lost} = heat transfer rate, \dot{E}_{un} = unaccounted power loss and y_i = mass ratio of compound.

The heat transfer rate was determined by [8]:

$$\dot{Q}_{lost} = \text{Heat Release Rate} - \frac{\sum \left[\frac{\gamma}{\gamma-1} \times pdV + \frac{1}{\gamma-1} \times VdP \right]}{2} \times \frac{rpm}{60} \quad (3)$$

The exergy balance equation is stated as [9]:

$$\dot{e}_{fuel} + \dot{e}_{air}^{im} + \dot{e}_{fuel}^{im} = \dot{Q}_{lost} \times \left(1 - \frac{T_0}{T_{env}} \right) + \dot{W} + \dot{e}_{des} + \dot{e}_{exh} + \dot{E}_{un} \quad (4)$$

where \dot{e}_{fuel} is the inlet exergy rate of fuel while \dot{e}_{air}^{im} and \dot{e}_{fuel}^{im} are the thermomechanical exergy rates of inlet air and fuel, respectively. Energy rate of exhaust emission is defined as \dot{e}_{exh} , while \dot{e}_{des} represents exergy destruction rate which is determined by the following equation [10]:

$$\dot{e}_{des} = T_0 \times \left(\dot{S}_{outlet} - \dot{S}_{inlet} + \frac{\dot{Q}_{lost}}{T_{in}} \right) \quad (5)$$

3. Results and discussion

3.1. Cumulative heat release rate

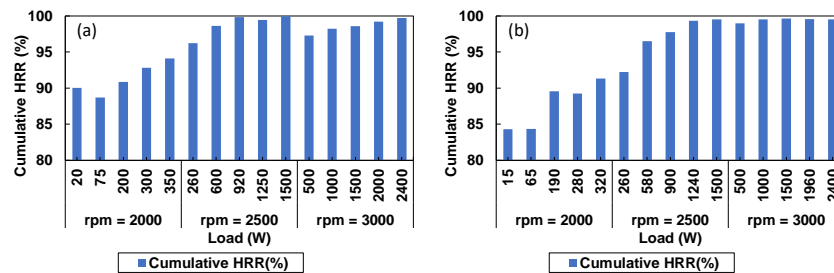


Figure 2. Cumulative heat release rate for (a) fossil diesel and (b) PME fuel at varying engine speeds and loads.

The cumulative heat release rate percentage (CHRR) in figure 2 for both fuels clearly show a general increasing trend as the engine load and speed values rise. However, there is a slight difference between the increasing gradients for fossil diesel and PME fuel. It is apparent that the CHRR values for PME fuel experience bigger changes than that of fossil diesel as the engine operating conditions increase. From the plot, PME and fossil diesel have minimum CHRR percentages of approximately 84.0% and 89.0%, respectively at low speed of 2000 rpm. This is because at lower rpm and load values, the higher PME viscosity and density as compared to that of diesel fuel cause poorer atomisation [7]. Nonetheless, as load and engine speed increases, injection pressure will rise to an extent where the inferior PME properties will no longer affect the fuel atomisation. Thus, the gap between CHRR values for fossil diesel and PME fuel were brought closer at higher engine operating conditions, where both fuels can reach to a maximum CHRR percentage of around 99.8%. Besides, the drastic CHRR increment for PME fuel is also due to the high oxygen content within the fuel composition that promotes fuel combustion and mass fraction burned.

3.2. First law efficiency

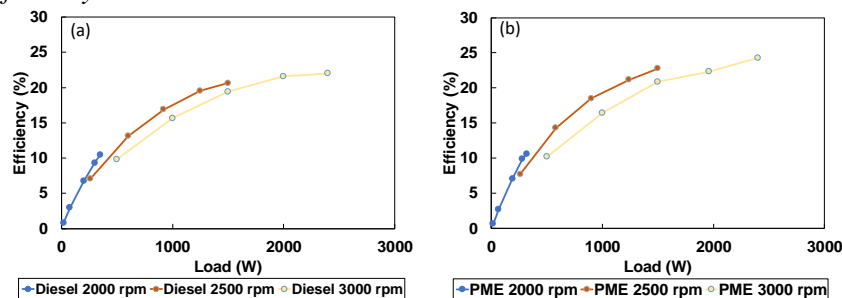


Figure 3. First Law of Thermodynamics efficiency plots for (a) fossil diesel and (b) PME at varying engine speeds and loads.

Figure 3 shows that generally an increase in load reduces the brake specific fuel consumption for the engine even though the fuel consumption rises. On the other hand, increasing speed will reduce the engine's capability to produce work. The thermal efficiencies for both PME and fossil diesel at 2500 rpm, 1500 W appeared to be approximately 1.0% lower than that at 3000 rpm, 1500 W. The reduction in available combustion time and increasing frictional losses play a crucial role in this decreasing trend. Engine fuelled with PME fuel has better efficiency at higher engine speeds and loads, where the value can reach up to 24.0% as compared to that when fuelled with fossil diesel, which has a maximum of 22.0%. This is mainly due to the oxygenated content in PME fuel which boosts reaction rate through the provision of oxidiser at the end stage of combustion. However, fossil diesel performs better at lower engine speed and load conditions primarily due to its lower viscosity and density [7].

3.3. Exergy destruction

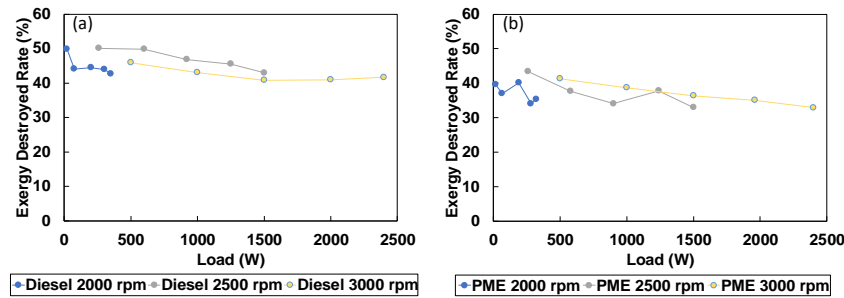


Figure 4. Percentage exergy destroyed rate of (a) Diesel and (b) PME at varying engine speeds and loads.

The rate of total exergy destruction is shown in figure 4. The exergy destroyed rate does not vary much with speed. However, it has a decreasing trend as loading value increases. The total irreversibility in a diesel engine constitutes mostly of combustion irreversibility [11]. As the loading rises, the in-cylinder combustion temperature and pressure rise as well, resulting in lower combustion irreversibility. However, the higher combustion temperature will also promote heat transfer rate and exergy loss rate. This explains the fluctuating values, indicating that there is a competition between these two factors in determining the total irreversibility percentages. At the lowest engine operating condition, the irreversibility values for fossil diesel and PME are around 50.0% and 40.0%, respectively. However, there is a 7-8% reduction in irreversibility for both PME and fossil diesel as the engine speed and load increase from minimum to maximum. Overall, the average exergy destruction rate percentage for PME fuel (37.8%) is lower than that of fossil diesel (44.4%). This is mainly due to oxygenated fuel having lesser mixing and reaction irreversibility [12].

3.4. Second law efficiency

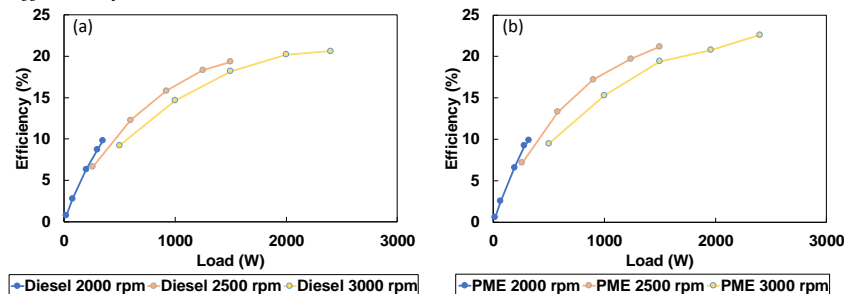


Figure 5. Second Law efficiency plots for (a) Diesel and (b) PME at varying engine speeds and loads.

Figure 5 show that the Second Law efficiency follows the same pattern as that for the First Law efficiency. However, the values are always lower than their First Law counterparts because the fuel's inlet exergy rate is around 7% greater than its energy rate. When the engine is running under constant load, exergy efficiency is found to decrease with increasing engine speed. The exergy efficiencies for both PME fuel and fossil diesel at 2500 rpm, 1500 W are approximately 1.0% lower than that at 3000 rpm, 1500 W. This is because higher engine speed results with more power losses, reduction of combustion duration and insufficient air intake for fuel combustion. On average, the engine's exergy efficiency when fuelled with PME fuel is 0.66% better than that when fuelled with fossil diesel. It can be inferred that using oxygenated fuel will contribute to a more complete fuel combustion hence, maximising the work extraction from fuel. It is also expected that the total exergy destroyed rate will have a significant impact on the fuel efficiency. The highest exergy efficiency for both fuels are 20.7% and 22.6% for diesel and PME fuel, respectively. It is also observed that the lowest overall exergy destruction percentage for fossil diesel (40.0%) and PME fuel (32.9%) lie at the same operating parameters as well.

4. Conclusion

From the results, it can be concluded that PME fuel has a better combustion efficiency at higher engine speed and load values as compared to fossil diesel due to the fuel-bound oxygenated content which promotes fuel combustion. The average thermal efficiency for PME fuel is greater than that of fossil diesel by approximately 0.8%, where PME fuel mostly dominates at higher speed and load values. The exergy destruction rate for both fuels have similar trends as the heat transferred rates. PME fuel has a lower average irreversibility rate percentage than that of diesel fuel by approximately 6.75 % due to higher oxygen contents that can reduce mixing and reaction irreversibility. Exergy efficiencies for both fuels follow the same trend as First Law efficiencies but are on average 2% lower due to higher fuel exergy rate compared to their energy rate counterparts. Overall, the engine has better energetic and exergetic performances when fuelled with oxygenated PME fuel as compared to that of fossil diesel.

Acknowledgments

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