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Comparison of Thermal Energy Lost through Exhaust Gases at Various Engine Speeds and Torque Loads for Diesel and Biodiesel Fuels

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Abstract: *This paper compares amount of thermal energy lost through exhaust gases when an engine was operated on diesel and biodiesel. The study used a 4.7 hp (3.5 kW) single cylinder, four-stroke, multi-fuel engine which was operated on diesel and biodiesel fuels. Experiments were conducted for the two fuels at engine speeds of 1000, 1250 and 1500 rpm in accordance with the manufacturer's recommendations. The engine was tested for torque loads of 6 to 22 Nm at intervals of 4 Nm for speeds and fuels studied. The instrumentation of the engine was mainly equipped with data acquisition system and software for analysis. Exhaust gas mass flow rate and temperature measurements were used to determine lost thermal energy. Lost heat energy depended on the temperature of the waste heat gases and mass flow rate of exhaust gas. The energy lost in exhaust gases increased substantially with increased exhaust gas temperature. The results showed that more energy was lost through exhaust when the engine used biodiesel as compared to when it was fueled on diesel. Maximum heat loss through exhaust was 18.7% of fuel energy when the engine used biodiesel at a speed of 1500 rpm and a torque load of 14 Nm.*
Keywords: *Engine Speed, Enthalpy, Exhaust Gases, Thermal Energy, Torque Load*

I. Introduction

Exhaust gases immediately leaving the engine can have high temperatures. Consequently, these gases have high heat content, carried away as exhaust emission. In general, diesel engines have an efficiency of about 35% and thus the rest of the input energy is wasted. Despite recent improvements of diesel engine efficiency, a considerable amount of energy is still expelled to the ambient with the exhaust gas. The mass flow rate of exhaust gas is a function of the engine size and speed, hence the larger the engine size and the higher the speed, the more the exhaust gas heat. Compared to the composition of air, the diesel exhaust gas contains increased concentrations of water vapour and carbon dioxide. These are the main combustion products. The concentrations of both water vapour and carbon dioxide can vary from a few percent, up to about 12% in diesel exhaust. These combustion products displace oxygen, the concentration of which can vary from a few percent, up to about 17% (compared to 21% in ambient air). The main component of diesel exhaust, just as is the case with ambient air, is nitrogen [1]. By comparison, the concentrations of diesel exhaust pollutants are very small and for the purpose of calculating the physical properties of diesel exhaust gas, they can be neglected. Moreover, studies on total energy distribution from an internal combustion engine has shown that out of the possible 100% fuel energy content in an engine, 35% is useful as brake power, 30% is lost in the cooling system, 5% is lost through radiation and approximately 30% is lost through the engine exhaust [2]. As an approximation, the properties of air can be used for diesel exhaust gas calculations. The error associated with neglecting the combustion products is usually no more than about 2%. In a more rigorous approach, corrections must be taken to account for the actual exhaust gas composition (increased water vapour and carbo dioxide, decreased oxygen). An additional difficulty with this approach is the necessity to account for the variable exhaust gas composition, which changes with the engine load factor and the air-to-fuel ratio [3]. Physical properties of mixtures of gases, and methods to calculate them from the properties of components can be found in the literature [4]. In addition to the physical properties, knowledge of certain other exhaust gas parameters is important. These include exhaust gas temperature which is of special importance for the design of catalytic after treatment devices, as catalyst performance is a function of temperature and exhaust gas flow rate. Another important parameter is the maximum pressure drop through the exhaust system, caused by the hydraulic resistance of exhaust system components. This parameter, commonly referred to as the "engine backpressure" requires that the engine perform additional pumping work, and has other impacts on engine operation. In the light of the above discussion based on introduction, it is hoped that this paper on lost thermal energy will make some contribution to existing knowledge in the wide and ever changing field of engineering. In addressing the knowledge gap, the paper seeks to propose a study on efforts to design more energy efficient engines with better heat transfer and lower exhaust temperatures. In addition, if some of this waste heat could be recovered, a considerable amount of primary fuel could be saved.

II. Materials and Methods

The experimental set-up consisted of a single cylinder, four-stroke, multi-fuel engine connected to an eddy current dynamometer for loading at various engine speeds for diesel and biodiesel fuels. Experiments were conducted for the two fuels at engine speeds of 1000, 1250 and 1500 rpm in accordance with the manufacturer's recommendations. The engine was tested for torque loads of 6 to 22 Nm at intervals of 4 Nm for the speeds and fuels studied. The dynamometer was bidirectional. The shaft mounted finger type rotor ran in a dry gap. A closed circuit type cooling system permitted for a sump. Dynamometer load measurement was from a strain gauge load cell and speed measurement was from a shaft mounted three hundred sixty pulses per revolution rotary encoder. To control the speed, a set speed was given to the controller. If the measured speed of the shaft was less than that of the set speed, the load was decreased. If the measured speed of the shaft was greater than that of the set speed, then the load was increased. Since the engine had sufficient torque to attain the set speed, this maintained a constant speed. To control the load, a set load was given to the controller. If the measured load on the dynamometer was greater than that of the set load, the load was decreased. If the measured load on the dynamometer was less than that of the set load, then the load was increased. Since the engine had sufficient torque to attain the set load, this maintained a constant load while the speed varied.

2.1 Heat Lost through Exhaust

The setup enabled the measurement and collection of the following data: fuel consumption (kg/hr); air consumption (kg/hr); exhaust gas inlet temperature (°C); and ambient temperature (°C). The instrumentation of the engine was mainly equipped with a data acquisition system and ICE Software. Data was collected using LabView 9.0. LabView based software (Enginesoft) was used for engine performance analysis and evaluation. Data was displayed on a windows based personal computer screen in real time basis and the results were also recorded in Excel file format. From the data collected, recorded values of air and fuel consumption; and exhaust gas to calorimeter inlet temperature were used in calculations. The specific heat capacity of exhaust gas was used as 1.006 kJ/kg·K. The ambient temperature was recorded as 24 °C. The quantity of heat lost in the exhaust gas was determined as given in (1)

$$\dot{Q}_L = \left(\dot{m}_a + \dot{m}_f\right) \times C_p \times \left(T_i - T_{amb}\right) \tag{1}$$

Where:

$\dot{Q}_L$ = energy lost in exhaust gas (kJ/h)

$\dot{m}_a$ = air consumption (kg/h)

$\dot{m}_f$ = fuel consumption (kg/h)

C_p = specific heat of exhaust gas (kJ/kg·K)

T_i = exhaust gas to calorimeter inlet temperature (°C)

T_{amb} = ambient temperature (°C)

III. Results and Discussion

3.1 Thermal Energy Lost through Exhaust at 1000 rpm

The results for heat lost through exhaust when the engine was operated on diesel fuel at a speed of 1000 rpm show that heat lost through exhaust was 0.9% higher than when the engine used biodiesel at a torque load of 6 Nm. Heat lost through exhaust corresponding to 1000 rpm and 6 Nm was 2% of the fuel energy for diesel fuel and 1.6% of the fuel energy for biodiesel fuel. When the torque load was increased to 10 Nm, heat lost through exhaust for diesel fuel was 8.9% lower than biodiesel fuel. Importantly, heat lost through exhaust at a torque load of 10 Nm was 2.5% of the fuel energy for diesel fuel and 2.6% of the fuel energy for biodiesel. While maintaining the engine speed at 1000 rpm and increasing the torque load at an interval of 4 Nm to 14 Nm, heat lost through exhaust corresponding to this load for diesel fuel was 24% lower than biodiesel fuel. Heat lost though exhaust at 1000 rpm and 14 Nm was 5.2% of the fuel energy for diesel fuel and 5.6% of the fuel energy for biodiesel. Similarly, at a torque load of 18 Nm, heat lost through exhaust for diesel fuel was 14.6% lower than biodiesel fuel. Loading the engine at 18 Nm resulted in heat lost though exhaust as 7.1% of the fuel energy for diesel and 7.7% of the fuel energy for biodiesel. However, at a torque load of 22 Nm, heat lost through exhaust result was 3% lower when the engine was operated on diesel in comparison to biodiesel. Finally, heat lost through exhaust at a torque load of 22 Nm was 7% of the fuel energy for diesel and 7.3% of the fuel energy for biodiesel fuel. The regression analysis gave the coefficient of determination (R^2) as 0.9634 and 0.941

corresponding to diesel and biodiesel as illustrated in Fig. 1. Table 1 shows heat lost through exhaust at a speed of 1000 rpm for diesel and biodiesel fuels.

Table 1: Heat lost through exhaust at 1000 rpm

Fuel	Heat Lost through Exhaust (kJ/h)				
Diesel	989.8614	1409.5496	2390.5778	3668.3981	3957.1291
Biodiesel	981.0659	1535.2942	2965.4695	4204.5903	4076.2986

3.2 Thermal Energy Lost through Exhaust at 1250 rpm

Increasing the engine speed to 1250 rpm gave the results of heat lost through exhaust as 8.7% lower when diesel fuel was used as compared to biodiesel at a torque load of 6 Nm. Heat lost through exhaust corresponding to 1250 rpm and 6 Nm was 2.3% of the fuel energy for diesel fuel and 2.6% of the fuel energy for biodiesel fuel. Moreover, heat lost through exhaust for diesel fuel was 13.1% lower than biodiesel at a torque load of 10 Nm. Importantly, heat lost through exhaust at a torque load of 10 Nm was 2.7% of the fuel energy for diesel fuel and 3.2% of the fuel energy for biodiesel. Similarly, at the engine speed of 1250 rpm and a torque load of 14 Nm, heat lost through exhaust for diesel fuel was 42.2% lower than biodiesel. Heat lost though exhaust at 1250 rpm and 14 Nm was 3.3% of the fuel energy for diesel fuel and 4.9% of the fuel energy for biodiesel. However, when the torque load was increased to 18 Nm, heat lost through exhaust was 33.7% lower and at 22 Nm, heat lost through exhaust was 19% lower when the engine used diesel in comparison to biodiesel. Loading the engine at 18 Nm resulted in heat lost though exhaust as 5.5% of the fuel energy for diesel and 6.9% of the fuel energy for biodiesel. Finally, heat lost through exhaust at a torque load of 22 Nm was 6.2% of the fuel energy for diesel and 7.7% of the fuel energy for biodiesel fuel.

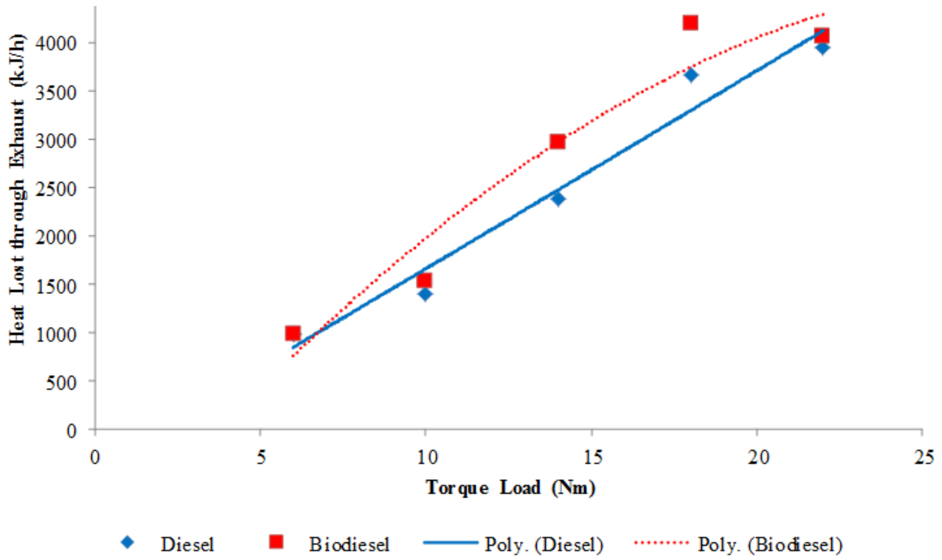

Figure 1: Lost energy against torque load at 1000 rpm

The results as analyzed at 5% level of significance show that both the engine load and speed had a significant effect on the lost energy when the engine was operated on diesel. The calculated F-value for the load of 47.1302 was greater than the corresponding critical F-value of 3.84. Similarly, the calculated F-value for the speed of 52.4387 was greater than the corresponding critical value of 4.46. The regression analysis gave the coefficient of determination (R^2) as 0.993 and 0.9678 corresponding to diesel and biodiesel as illustrated in Fig. 2. Table 2 shows the results of heat lost through exhaust at a speed of 1250 rpm for the two fuels. Studies have shown that the energy lost in exhaust gases increases substantially with increased exhaust gas temperature [5, 6].

Table 2: Calculated heat lost through exhaust at 1250 rpm

Fuel	Heat Lost through Exhaust (kJ/h)				
Diesel	1931.0414	2061.5348	2617.9890	3782.0884	4819.2337
Biodiesel	2098.7024	2330.8797	3721.5741	5056.1765	5734.7508

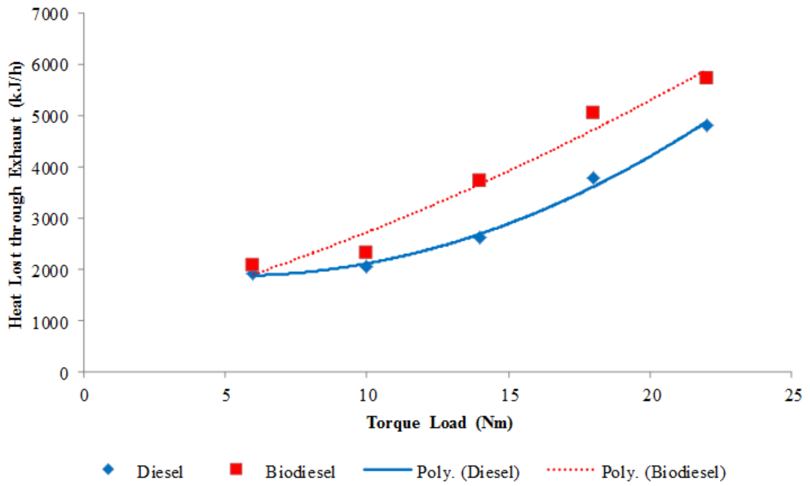

Figure 2: Lost energy against torque load at 1250 rpm

3.3 Thermal Energy Lost through Exhaust at 1500 rpm

Comparatively, when the engine was operated at a speed of 1500 rpm with a torque load of 6 Nm, heat lost through exhaust for diesel fuel was 20.1% lower than biodiesel. Heat lost through exhaust corresponding to 1500 rpm and 6 Nm was 4.4% of the fuel energy for diesel fuel and 18.2% of the fuel energy for biodiesel fuel. Subsequently, at a torque load of 10 Nm, heat lost through exhaust for diesel fuel was 22.8% lower than biodiesel. Importantly, heat lost through exhaust at a torque load of 10 Nm was 5.3% of the fuel energy for diesel fuel and 16.6% of the fuel energy for biodiesel. Similarly, at a torque load of 14 Nm, heat lost through exhaust was 21.7% lower when the engine used diesel as compared to biodiesel. Heat lost though exhaust at 1500 rpm and 14 Nm was 6.7% of the fuel energy for diesel fuel and 18.7% of the fuel energy for biodiesel. Loading the engine at 18 Nm showed that heat lost through exhaust for diesel fuel was 21.5% lower than biodiesel. Heat lost through exhaust in relation to 1500 rpm and 18 Nm was 7.2% of the fuel energy for diesel fuel and 16.8% of the fuel energy for biodiesel fuel. Finally, at a torque load of 22 Nm, heat lost through exhaust was 22.9% lower when the engine used diesel in comparison to biodiesel. Relatively, heat lost through exhaust at a torque load of 22 Nm was 7.4% of the fuel energy for diesel fuel and 12.6% of the fuel energy for biodiesel. The results as analyzed at 5% level of significance show that both the engine load and speed had a significant effect on the lost energy when the engine was operated on biodiesel. The calculated F-value for the load of 45.8267 was greater than the corresponding critical F-value of 3.84. Similarly, the calculated F-value for the speed of 62.6307 was greater than the corresponding critical value of 4.46. The regression analysis gave the coefficient of determination (R^2) as 0.9409 and 0.9533 corresponding to diesel and biodiesel as illustrated in Fig. 3. Table 3 presents the calculated results of heat lost through exhaust at an engine speed of 1500 rpm.

Table 3: Lost heat through exhaust at 1500 rpm

Fuel	Heat Lost through Exhaust (kJ/h)				
Diesel	2859.3147	3384.1830	4654.8988	4899.9731	4794.8023
Biodiesel	3434.2268	4154.6987	5663.3434	5955.2175	5891.7099

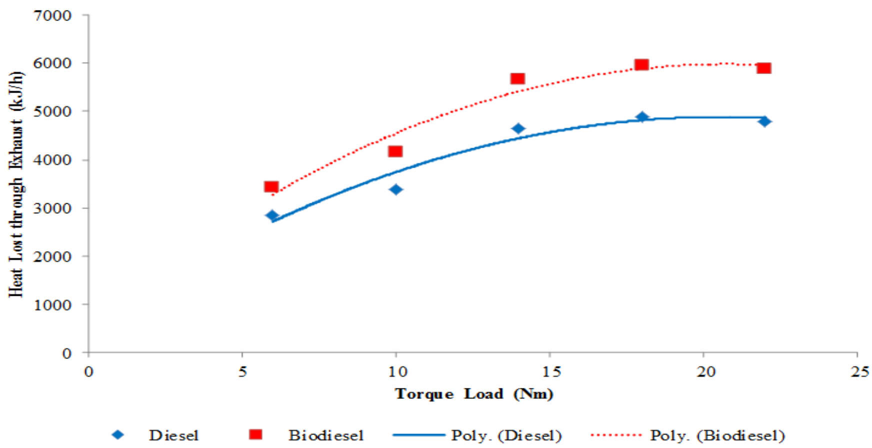

Figure 3: Lost energy against torque load at 1500 rpm

IV. Conclusion

Based on this research, the peak thermal energy lost through the exhaust was 7.4% of the fuel energy when the engine was operated on diesel. When the engine used biodiesel the peak thermal energy lost through the exhaust was 18.7% of the fuel energy. The peak heat loss through the exhaust was 18.1% lower when the engine was fueled on diesel than when biodiesel was used. The lost energy increased with increased exhaust gas temperature at higher engine speeds and loads.

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