Experimental studies of single cylinder engine run on diesel-biodiesel-butanol blends

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**Abstract.** Biodiesel and butanol are excellent additive fuels, especially for diesel fuel. Many studies in literature reported that the biodiesel-butanol with various ratios is applied to diesel engines. In this experiment, diesel engines operated using biodiesel-butanol blend in low proportions 5%-5%, 5%-10%, 10%-5%, 10-10%, 15-5% and 15-10% mixed with pure diesel, and the blend is characterized. This blend of fuels can be represented as B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5 and B15B10 with a numeric number in the fuel blends. This fuel blend is used as test fuel which is operated on a single cylinder diesel engine, four steps, direct injection (DI) at a constant speed of 1200 rpm and engine load of 25% and 50%. The combustion characteristics, performance and engine emissions are analyzed and evaluated by comparing each load and the speed of the engine being operated. Furthermore, fuel additives with pure diesel are needed to check emissions from the engine when the engine is run with a blend of diesel-biodiesel-butanol fuel. Among the six fuel blends samples examined in this experiment, better performance was shown in the B5B10 blend and produced fewer emissions. The results of the whole experiment are presented in full in this paper.

1. Introduction

Alternative fuels from biofuels used for internal combustion engines (IC) have gained momentum in the past few decades to reduce greenhouse gas (GHC) emissions, overcome dependence on fossil fuels and be environmentally friendly. Biofuel is a better choice in the future to meet global demand as transportation fuel as reported by the International Energy Agency (IEA). The low toxicity from the production of vegetable ingredients has released sulphur in biofuels. At present, biodiesel and alcohol are two biofuels that have the potential to be focused as alternative fuels to replace fossil oil [1]. In 2016 global biofuel production increased 2.6% compared to 2015 with only 0.4% of products. Liquid biofuel is very suitable for transportation because it is a very important strategy in reducing air populations, increasing fuel security and supporting rural development. The first generation of biofuels produced from sugar cane corn, etc. is a conventional biofuel commonly referred to as ethanol. Globally, the number of biofuel production reaches more than 100 billion litters each year [2, 3]. Global supply of biofuels for about 70% is produced from Brazil and America in 2015, with each consisting of sugar cane and corn [4, 5]. The use of conventional biofuels has attracted the interest of several researchers in focusing on making biofuels the next generation.

Biodiesel fuel is soluble, sulphur free and bio-degradable into any diesel fuel with any ratio and has an oxygen content of up to 10-15%. Biodiesel has a heating value and an energy content of about 12%
lower than diesel fuel. So it is very suitable for use as a blend of diesel fuel. A biodiesel blend of 20% compared to 80% of diesel fuel (B20) produces comparable engine performance and results in lower emissions of conventional diesel [6, 7]. The combustion process in a diesel engine can be changed in the presence of the properties of fuels such as viscosity, cetane number, density and flame temperature. The time of combustion and fuel injection can be caused by increasing density in biodiesel. Increased NOx emissions are generated from high unsaturated molecules and reduce fuel consumption [8, 9]. The problem with regulating injection time is the reason for increasing NOx emissions. Ignition and spray patterns in the combustion chamber can be affected by changes in fuel and rapid NOx formation [10]. Meanwhile, shorter ignition delays and longer burning duration, most of which are indicated by the use of biodiesel. The percentage of fuel blend that increases can reduce NOx emissions. Meanwhile, biodiesel fuel can reduce particulate matter (PM) compared to diesel fuel when operated in diesel engines. The main concern in using biodiesel fuel for diesel engines is to control NOx emissions. Control of NOx emissions on the engine triggered by biodiesel fuel has been carried out with various methods by making several modifications to the engine [11–14]. Blends fuels emulsified with biodiesel and added nanoparticles with higher latent heat evaporation, use of alcohol-biodiesel blends, etc. An example of fuel modification is adopted in controlling NOx emissions from biodiesel fuel for diesel engines [15]. Some of them are steps for exhaust gas recirculation (EGR), water injection, chemical absorption and running dual fuel modes in an effort to reduce NOx emissions from diesel engines using biodiesel fuel from modified engines.

Biodiesel fuel produced from vegetable oil raw materials is not recommended by the Indian government, because it stabilizes food security. Therefore, the focus is on the use of oil from raw materials only in recent years. Some vegetable oils for producing biodiesel such as Karanja oil, castor oil, Neem oil, Mahua oil, cottonseed oil, castor oil and rubber seed oil are currently very important to use in India [16–20]. Among all the vegetable raw materials, Karanja oil is one of the potential raw materials for producing biodiesel fuel because of its adequate availability of oil content to produce biodiesel [21]. Many studies have been done by several researchers relating to KME as an alternative fuel that is applied to IC machines. Examination of the effects of Karanja’s biodiesel fuel blend to measure performance, combustion characteristics and emissions of single-cylinder diesel engines with different engine loads for constant speed has been investigated by [22]. The results of their investigation reported that the thermal efficiency of the brakes increased from the consumption of KOME mixed fuel compared to when the engine was operated using pure diesel fuel. However, the engine performance is better when using a 20% KOME blend and reduces emissions compared to diesel fuel. While different studies can be reported that NOx emissions are recorded to increase when the engine is operated using Karanja biodiesel fuel rather than diesel [23].

The effects of biodiesel-n-butanol mixed fuels with performance parameters and emissions from diesel engines have been investigated [24]. Experiments carried out to investigate the performance and emission of the engine are mixed-biodiesel-butanol fuel with varying ratio (B95Bu5, B90Bu10 and B80Bu20). Based on the results of testing they did increase NOx emissions rather than diesel. However, CO emissions were found to decrease for low concentrations of butanol fuel (5% and 10%). While NOx emissions were found to decrease when using butanol fuel with a concentration of 20%. However, it is inversely proportional to the blend of 20% butanol showing an increase in CO and UHC emissions from other blends. The increasing mix of biodiesel-butanol and biodiesel fuels can increase fuel consumption. In different studies as conducted by [24], the concentration of n-butanol blend of 5%, 10% and 20% with Jatropha biodiesel jatropha based on different volumes such as (95JME 5B, 90JME 10B, and 80JME 20B) operated in parallel single cylinder DI diesel engine. Where JME stands for Jatropha methyl ester and butanol abbreviated B. Engine performance can be reported to increase with decreasing viscosity and more oxygen contained in fuel. Meanwhile, engine emissions significantly decreased, but did not occur at UHC emissions when the engine was operated using a blend of n-butanol and JME rather than neat JME. This experiment shows that UHC emissions increase from the results of diesel operations. However, NOx, CO and smoke emissions were recorded to decline. The biodiesel-butanol fuel blend can reduce fuel consumption compared to pure diesel.
In this study experiment, 5%, 10% and 15% biodiesel-butanol fuels were mixed with pure diesel fuel with volumes specified as B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5 and B15Bu10. The study uses a one-cylinder, four-step engine, constant-speed direct injection (DI) tested with different volume fuel blends to measure combustion parameters, performance, and emissions evaluated, analysed and compared to the operation of both engine load tested. CO and NOx engine emissions as measured parameters, compared to diesel fuel operations and presented in this work.

2. Experiment setup
This experiment was operated using a single cylinder diesel engine, four steps, direct injection (DI) at a constant speed of 1200 rpm. The machine diagram specifications and schematic are shown in figure 1 and table 1. The machines are combined into eddy current dynamometers to provide brake loads. Fuel injection into the engine uses an injection system. Measurement of fuel consumption through the help of a controlled burette to connect to the engine fuel pump. At certain loads and speeds, specific fuel consumption is calculated. The optical axis encoder position serves to give a signal at the centre of the upper die (TDC). TDC position signals and pressure signals are recorded from an analogue-to-digital converter (A/D) that has been connected to the computer. In general, conventional diesel root materials are operated on CI machines. Performance parameters such as Cylinder pressure (CP), Heat Release Read (HRR) and Pressure Rise Rate (PRR) on each load are stored in an Excel sheet. Carbon monoxide (CO) emissions, nitric oxide (NOx) emissions at each load were measured using the A KANE exhaust gas analyser. Each is measured to obtain combustion parameters, cylinder pressure and crank angle and then stored into DAQ. Sample collection was taken as many as 50 cycles continuously. The average value of crank angle pressure, peak pressure, heat release rate and maximum pressure increase rate are calculated using software.

Figure 1. Schematic diagram of single cylinder diesel engine.

The first law for such a system can be written as shown by equation (1).

$$dQ_{hr} = dU + dW + dQ_{ht}$$  \hspace{1cm} (1)

where, $dQ_{hr}$ is the instantaneous heat release modeled as heat transfer to the working fluid, $dU$ is the change in internal energy, $dW$ is the work done, $dQ_{ht}$ is the heat transmitted away from the working fluid to the combustion chamber walls. The change of internal energy can be written as equation (2).

$$dU = \left(\frac{C_v}{R}\right) \times (PdV + Vdp)$$  \hspace{1cm} (2)
Table 1. Detail of engine specifications.

| Description              | Specification                              |
|--------------------------|--------------------------------------------|
| Engine model             | YANMAR TF120M                              |
| Engine type              | Horizontal single-cylinder 4-stroke diesel engine |
| Fuel injection type      | Direct injection                           |
| Bore × Stroke (mm)       | 92 × 96                                    |
| Displacement (L)         | 0.638                                      |
| Injection timing         | 17° BTDC                                   |
| Injection pressure (kg/cm²) | 200                                        |
| Compression ratio        | 17:7                                       |
| Continuous output (HP)   | 7.82 kW at 2400 rpm                       |
| Rated output (HP)        | 8.94 kW at 2400 rpm                       |
| Cooling system           | Water cooled (radiator type)               |

Parameter \( R \) in equation (2) represent the gas constant, \( C_v \) is the specific heat at constant volume, \( dW \) is work done by the working fluid which equals to \( PdV \). Parameters \( T, P \) and \( V \) represent temperature, pressure and volume, respectively. The heat transfer rate to the wall can be written equation (3).

\[
\frac{dQ_{ht}}{dt} = hA_s(T_g - T_w)
\]  

The contents in the cylinder can be assumed by modeling as an ideal gas and the cylinder contents have a uniform temperature during the combustion process [25]. The above equation is the first thermodynamic law which can be written as equation (4).

\[
dQ_{ht} = \frac{y}{y-1}P \frac{dv}{dq} + V \frac{1}{y-1} \frac{dp}{d\theta} hA_s(T_g - T_w) \frac{dt}{d\theta}
\]  

where \( \theta \) the crank angle in degrees, \( h \) is the coefficient of heat transfer, the specific heat ratio of fuel and air is assumed to be \( y \), wall temperature as \( T_w \), while the gas temperature is \( T_g \), where the area in \( m^2 \) is through the displacement of gas heat to the combustion chamber wall. The value for pressure is obtained from the cylinder pressure at the appropriate crank angle as shown by equation (5).

\[
dQ_{ht} = \frac{y}{y-1}P \frac{dv}{d\theta} + V \frac{1}{y-1} \frac{dp}{d\theta}
\]  

The heat release rate can be calculated using this relationship. All quantities on the right side are known or can be easily derived after the history of the time the pressure is recorded.

3. Results and discussion

3.1. Cylinder pressure

Figure 2 and figure 3 illustrate the variation in peak cylinder pressure with engine load of 25% and 50% for all fuel samples tested in this study. The air-fuel blend preparation, the delay period and the amount of heat released during combustion largely determine the pressure of the peak cylinder on the CI engine. From the figure it can be observed that, when the engine load increases, the peak pressure also increases for all fuel samples tested. Higher cylinder temperatures and increased amounts of fuel have caused this increasing trend to occur at higher loads. The highest cylinder pressure of 65.5 bar was found for pure diesel fuel at a load of 50%. While the overall fuel blend tested shows cylinder peak pressure reported to be lower than pure diesel fuel at a load of 50%, due to the low heat released. The peak cylinder pressure increases when butanol is added up to 10% compared to biodiesel for overall engine operation. Increased ignition delay and more available oxygen in mixed fuels have resulted in higher amounts of heat in the combustion phase. Furthermore, the percentage of butanol increased in the biodiesel blend with peak cylinder pressure can be reduced. This is because in the combustion phase more amount of heat is released from mixing the fuel. At a load of 50%, the lowest
5

peak cylinder pressure of 56.4 bar is recorded for the B10Bu5 blend. This trend can be caused by combustion that occurs far from TDC due to ignition delays in the fuel blend. The peak cylinder pressure value shows a very small difference. Similar results for n-butanol fuel mixtures in different studies have also been observed by [26].

![Figure 2. Cylinder pressure for different fuel at engine load 25%.](image2)

![Figure 3. Cylinder pressure for different fuel at engine load 50%.](image3)

3.2. Heat release rate

The variation of heat release rate with crank angle using biodiesel-butanol and diesel mixed fuel at a load of 25% and 50% for each sample tested is illustrated in figure 4 and figure 5. The maximum heat release rate is highly dependent on the delay period with the amount of fuel taken from the combustion section of the previous fuel blend and the air-fuel blend formation [27]. The maximum speed of the biodiesel-butanol blend is lower than pure diesel. This is due to a relatively shorter delay period, lower heating values and increased viscosity of the fuel blend into diesel. The rate of heat release, energy content and latent heat of evaporation are more defined by the blend of biodiesel-butanol-diesel fuel than pure diesel. The maximum value of the heat release rate using mixed fuels and diesel at a load of 50% is 54.1 J/°CA and 56.5 J/°CA, respectively. Whereas the lowest heat release rate was found in the B10Bu5 blend among the entire fuel blend tested, with increasing latent heat of evaporation causing a decrease in this blend.

![Figure 4. HRR for different fuel at engine load 25%.](image4)

![Figure 5. HRR for different fuel at engine load 50%.](image5)
3.3. NOx emission

The variations in NO emissions can be illustrated in figures 6 and figure 7 of both 25% and 50% loads using a blend of B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5 and B15Bu10 fuels. It can be observed that NO emissions are reduced for a load of 25% compared to a load of 50% for all samples tested. The operation of pure diesel fuel shows NOx emissions are higher than the fuel blend tested in this study, the results show that the heat released in the combustion phase is higher.

NOx emissions are lower when the load is 25% for all fuel blends tested compared to when the engine load reaches 50%. However, this result is lower than the engine operated with pure diesel fuel. Adding small amounts of butanol can reduce ignition delays, causing less amount of injected fuel [28]. Moreover, increasing latent heat from evaporation of butanol-biodiesel has reduced the temperature inside the cylinder and reduced NOx emissions when using the overall blend of fuel tested. For B10Bu5 NO emissions are recorded lower among all fuels tested mainly for diesel.

![Figure 6. NOx emission compare exhaust temperature at load 25% for different fuel.](image)

![Figure 7. NOx emission compare exhaust temperature at load 50% for different fuel.](image)

3.4. Carbon monoxide (CO) emissions

Figure 8 and figure 9 illustrate trends in CO emissions against combustion temperatures with different engine loads. In general, CO emissions from diesel engines are lower at 25% engine load compared to 50%. Oxygen content, temperature in the cylinder, fuel spray, oxidation rate and formation of ignition centers change because of the effects of oxygenated additives and alcohol [29]. Supply of oxygen can produce inadequate CO emissions in the engine combustion process. This is also due to the formation of the duration of combustion and air-fuel from the fuel blend. The low combustion duration and high oxygen molecules from the B5Bu5 blend can reduce CO emissions compared to pure diesel fuel. As a result, the overall engine operation tested for CO emissions was found to be reduced. However, CO emissions from both engine loads triggered by biodiesel-butanol and diesel fuel blends have a marginal difference.
4. Conclusion

This research, combustion characteristics, engine performance and emission were investigated when the engine was operated using a blend of biodiesel-butanol with pure diesel fuel. This experiment was carried out on a single-cylinder diesel engine to measure performance parameters, combustion and emission from the engine. These blends fuels are as many as six samples banned B5Bu5, B5Bu10, B10Bu5, B10Bu10, B15Bu5 and B15Bu10 tested in the engine at constant speed with engine loads of 25% and 50%. Based on the results of the entire sample tested, the blend of biodiesel-butanol fuel with NOx and CO diesel emissions decreases at low engine loads. Furthermore, some findings that are important from the investigation are explained as follows:

i) The ignition delay of the B10Bu5 blend for a 50% load was found to be shorter around 2 °CA, compared to diesel fuel, while the addition of higher butanol ignition delay periods increased up to 4 °CA when the engine load was 50%.

ii) The increasing the load of the test engine, can increase the duration of combustion. The duration of combustion decreases due to an increase in the percentage of butanol in mixed fuels.

iii) The biodiesel-butanol fuel blends with biodiesel generally reduces NOx emissions in the engine. However, an increase in the B10Bu5 blend occurred compared to pure diesel. This increase is due to the high oxygen content, higher evaporation heat and decreased heat content in the engine.

iv) The butanol fuel blend which increases with a high oxygen supply the average value of CO emissions is found to decrease. However, when the butanol blend decreases with increasing biodiesel it has increased CO emissions.

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