

Performance study of using preheated biodiesel in a diesel engine

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ABSTRACT – The use of biodiesel in blended mode is holding a more significant potential in making diesel engines environment-friendly. Published work specifies an optimum blend of biodiesel with diesel oil as B20. Further, the literature indicates that preheating biodiesel in the temperature range between 60°C to 120°C helps to increase the blend percentage up to 50%. In this experiment an effort has been made to use 100% Waste cooking oil methyl ester (WCME) biodiesel by employing two stage heating in the temperature range from 100°C to 250°C. In the first stage the heater is immersed in fuel tank that heats biodiesel up to 70°C that lowers the viscosity and eases pumping. In the second stage, an electric preheater is installed along the high-pressure fuel line for achieving higher temperatures. The performance and emission results are encouraging and indicates that Brake Specific Fuel Consumption decreases by 5.4%, Brake Thermal Efficiency increases by 6.15%, Carbon Monoxide (CO) and unburnt hydrocarbon (HC) emissions fall by 38% and 25.5%, respectively. NO_x has increased marginally by 4-6%.

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INTRODUCTION

Biodiesel is a diesel fuel derived from plants or animals consisting of long-chain fatty acid esters. It is typically made by chemically reacting liquids such as animal fat, soya bean oil, or other vegetable oils with alcohol, producing methyl, ethyl, or propyl esters. Biodiesel is a domestically produced, clean-burning, renewable substitute for petroleum diesel. Using biodiesel as a vehicle fuel increases self-reliance of energy needs, reduces air pollution, and improves rural economy by creating employment. *Jatropha curcas*, Soya bean, Switchgrass, *Pongamia oiltree*, Cassava, *Ricinus common sunflower*, *Safflower* are some of the plants from which biodiesel can be produced.

Biodiesel is considered to be a potential alternative fuel source for diesel engines due to its equivalent diesel fuel characteristics. But it has higher viscosity and density, making it difficult to be used directly in diesel engines [1]. Hence blends of biodiesel with neat diesel in different percentages have been attempted. However, research has concluded that the B20 (blend of 20% biodiesel and 80% diesel) combination resulted in improved performance and reduced emissions [2]. Therefore, sustained efforts have been made to increase the blend percentage beyond the B20 limit by employing fuel preheating methods. Heating can be done either using waste heat from exhaust gas or an electric heater.

RELATED WORK

In a review paper, Mohod R et al. [3] highlighted the effectiveness of preheating biodiesel fuel in improving diesel engine performance. Fuel was preheated to temperatures at 60°C, 90°C, 120°C, and 150°C and blend percentage also increased from 20% to 40%. A recuperative type heat exchanger was used for preheating the fuel blend that employs exhaust gas. It was found that preheating the fuel to 120°C resulted in lowering the kinematic viscosity from 35.9 to 5.82 centistokes, and the performance parameters measured were comparable to that of neat diesel. In addition to this, the carbon monoxide (CO) and smoke lowered by 24% to 39% and 10% to 24%, respectively. But Nitrogen Oxides (NO_x) increased by 23% to 25% as the preheating temperature rose. But HC emissions are not reported by the Author.

In a study by S. Kodate et al. [4], Karanja oil methyl ester (KOME) was tested in a diesel engine at preheating temperatures of 95°C for various loading conditions and different blends percentages (B0, B30, B50, and B100). The study infers that preheated blends performed better at elevated temperatures with improved atomization, vaporization of the air-fuel mixture, resulting in better performance and reduced emissions. In comparison to unheated fuel, for 100% biodiesel (B100) at full load, brake thermal efficiency increased by 9.1%, BSFC reduced by 6.5%, CO and HC emissions decreased by 8.1% and 10.6%, respectively. Preheating of fuel was done by wrapping the heating cords around the fuel pipeline and controlled by a rheostat and a temperature regulator. At 95°C kinematic viscosity of KOME oil reduced by 73% and was lesser than the viscosity of neat diesel at ambient temperature. Also, the presence of oxygen in biodiesel is more than diesel and tends to form bubbles beyond certain temperature limits. Hence temperature of preheating was limited to 95°C.

Lea-Langton et al. [5] studied the effect of preheating temperature on combustion and emissions with 100% using Rapeseed oil (RSO) for diesel engines. The fuel was heated to temperatures in the range of 80°C-120°C using an electrically heated fuel transfer line before the fuel injectors. Fuel temperature was measured on the outer surface of the pipeline since direct measurement was not possible due to safety concerns. The temperature difference between the pipe

surface and the fuel inside the pipeline was less than 5°C based on heat transfer calculation for stainless steel pipe. The temperature rise of fuel is affected by fuel residence time in the fuel pipeline and fuel flow rate. The power consumed for heating was as low as 330 W for a 23kW rated diesel engine, quickly recovering from exhaust gas heat. Test results show that HC and CO emissions decreased while NO_x emission was less significant with preheating.

Khond [6] used waste heat of the exhaust gases to preheat Karanja oil up to a temperature of 80°C with the help of a shell and tube heat exchanger. This method decreased kinematic viscosity, which was on par with pure diesel at 80°C. Results of the performance test were compared with neat diesel. Brake thermal efficiency (BTE) increased for preheated Karanja oil, but Brake Specific Fuel Consumption (BSFC) also increased. This effect was mainly due to the lower calorific value of the oil. In a similar work, Raw Rapeseed oil [7] (RRO) was used in the blended form (B20 and B50) with diesel fuel using preheating up to 100°C. B50 with preheating showed lower BSFC (9.64%), lower CO (25.86%), and lower smoke density (26.3%), increased NO_x (15%) compared to the unheated B50 blend. The same approach (use of exhaust gas waste heat) was followed by Agarwal et al. [8], where the Jatropha oil was heated till 90°C, at which kinematic viscosity was within ASTM limits (around six centistokes). Again, performance and emission results were better for heated jatropha fuel than unheated ones, and its properties were close to neat diesel.

Pugazhvadivu et al. [9] used waste frying oil (WFO) at two different preheated temperatures (75°C and 135°C) as an alternative fuel to diesel engines. Heating was done using an electric coil wound around a high-pressure fuel line. The temperature of 135°C was decided based on the kinematic viscosity test at which it was equal to that of pure diesel fuel. Results show that for WFO at 135°C, BSFC reduced by 1.9%, BTE increased by 4.2%, exhaust gas temperature increased, NO_x increased by 25%, smoke decreased by 24%, and CO also reduced.

Lemongrass biodiesel (B20) was used as an alternative fuel by Kotaiah et al. [10] with preheating at 60°C, and performance and emission test results were compared with unheated fuel and diesel. For preheated B20 fuel, BTE increased by 4%, BSFC decreased by 20%, and emissions like CO, HC, and smoke decreased. But NO_x showed an increase of 17% after preheating, indicating an improved combustion process.

Ramakrishnan et al. [11] have developed a waste gas heat exchanger that is installed between the fuel tank and fuel filter for preheating Neem oil methyl ester (B1) fuel and pumpkin seed oil methyl ester (B2) at various temperatures like 60°C, 70°C, and 80°C. Results of the experiment report that for B1 fuel, the increase in BTE is by 2%, decrease in BSFC by 9.34%, CO and HC lowered by 35.3% and 59%, respectively. Furthermore, due to increased atomization and excess oxygen than diesel oil, the smoke is reduced by 50% and NO_x increased by 26%.

Biodiesel extracted from Palm oil with different blend ratios such as B20, B40, B60, B80, and B100 was used by Ingle et al. [12] in a diesel engine, with injection temperatures of fuel at 50°C, 55°C, and 60°C. A preheater setup was housed in the fuel tank. He found that B20 at 60°C showed performance and emission characteristics comparable with neat diesel. Hoang et al. [13] used preheated pure coconut oil (PCO) and compared its performance with Jatropha oil methyl ester (JOME) and diesel oil (DO). Best results were obtained for PCO preheated at 100°C. Vedharaj et al. [14] used Cashew nut shell liquid (CNSL) directly in a diesel engine with preheating instead of using CNSL methyl ester (CNSLME) in blend with diesel. A separate heater, installed upstream of the fuel pump, was used to heat fuel. Since CNSL is biodiesel with a lower viscosity than vegetable oil and an oxygenated fuel, preheating beyond 80°C was prone to bubble formation. Hence, the temperature was limited to 80°C. Performance measures have indicated an increase of BTE by 20%, reducing CO and HC emissions by 52% and 66%, respectively, at full load conditions. Further, it is found that preheating CNSLME has lowered the fuel cost rate per hour due to improved combustion and performance.

Hoang et al. [15] designed a heat exchanger for recovering exhaust gas waste heat for preheating straight coconut oil (SCO) and achieved temperature up to 105°C using tubular type design. Both experimental and simulation tests were conducted, and about 52% of heat energy from exhaust gas was recovered to preheat the fuel. In a similar work, Mourad et al. [16] designed and developed a heat exchanger to preheat sunflower oil (B100) up to 70°C and compared the performance with neat diesel at room temperature. Results suggest that BSFC decreased by 8%, BTE increased by 1.3%, CO and HC decreased by 12.95% and 12.85%, respectively, at a load of 75%.

Anis et al. [17] have investigated the effect of preheating on the spray characteristics and performance of the injection fuel pump. Waste cooking oil was used as biodiesel, and blends were used as B0 (100% diesel), B20 (20% biodiesel and 80% diesel), B30, B50, and B100 (100% biodiesel) for investigation purposes. The preheating temperature ranged from 30°C to 70°C. Results indicate that higher blends require a higher preheating temperature to achieve better atomization. Because, at 70°C, B30 fuel showed the increased spray cone angle and spray area.

Rao et al. [18] discussed the characteristics of diesel engines using preheated WCME. The temperature of preheating was limited to 50°C. Compared to unheated WCME, preheating helps increase BTE by 3.8%, decrease BSFC, and reduce CO and HC emissions by 15.6% and 13.5%, respectively, but NO_x emission increases by 12.3%. Nanthgopal et al. [19] also studied using 30% EGR in diesel engines using 100% WCME.

The above literature review suggests that various researchers attempted preheating biodiesel in the temperature range from 60°C to 120°C. Method of heating has been either extracting heat from the exhaust gases or electric preheater setup. Results have shown a marked improvement in performance such as higher BTE, Lower BSFC, and reduction in emissions with a minor NO_x penalty, with a possibility to increase the blend percentage beyond 20 percent (B50 to B100). Interestingly, there is no literature available related to heating the fuel beyond 120°C. According to Jinping [20], injecting fuel at a very high temperature into a combustion chamber where the ambient pressure is less than the saturation pressure of fuel leads to a flash boiling phenomenon. In this experimental work an attempt has been made to preheat 100% biodiesel to a very high-temperature range from 100°C to 220°C by using two stage heating. The first stage of heating is done by using an immersed coil heater in the fuel tank to a temperature of upto 70°C. Further, fuel is heated using an

electric preheater located very close to the injector on the high-pressure fuel line. Details of the experimental setup, test procedures, and results are discussed in the following sections.

EXPERIMENTAL DETAILS

A four-stroke single-cylinder, a water-cooled diesel engine is used for conducting experimental investigations. The specifications of the engine are provided below.

Table 1. Test rig specification

Parameters	Details
No. of cylinder	1
No. of stroke	4
Fuel	Diesel
Rated power	3.7 kw@1500 rpm
Bore diameter	80mm
Stroke length	110mm
Compression ratio	16.5:1
Brake drum diameter	275mm
Rope diameter	19mm
Coefficient of discharge (C_d) of orifice	0.65
Orifice diameter	19mm

The standard fuel injection timing of the engine is 23 degrees before the top dead center (BTDC). Figure 1 shows the detailed test setup. Biodiesel is supplied from a stainless-steel container maintained at a constant temperature (T1) manually at 70°C using a primary heater, and a thermometer is used for measuring the temperature. Heating biodiesel at this temperature lowers the viscosity and helps smooth fuel flow through the fuel filters and the pump. A secondary heater is provided on the high-pressure fuel line between the fuel pump and nozzle (heater capacity is 750W). Fuel is maintained at a constant temperature using a regulator setup that is controlled manually. The temperature can be varied from 100°C to 250°C. Two thermocouples are employed in measuring the temperature, one on the electric heating system (T2) and the other on the fuel line (T3). This arrangement ensures proper temperature control of the fuel supplied to the engine. Fuel consumption is calculated using a burette and stopwatch. Airflow is measured using an orifice and a U-tube manometer. The engine loading is done using a rope brake-type mechanical dynamometer, as shown in Figure 2. Exhaust emissions like CO, HC, NOx, and Carbon dioxide (CO₂) are measured using AVL make Exhaust Gas analyzer.

The experiments have been carried out in the following steps: load is applied in steps of 0kg, 4kg, 8 kg, and 12 kg, which corresponds to 0%, 33%, 67%, and 100% of full load. Initially, the engine is run on neat diesel without preheating the fuel, and the set of results obtained are taken as reference. Further, the engine is run using pure Biodiesel (B100) at preheating temperatures of 100°C, 175°C, and 250°C, respectively. Results of engine performance and emissions, using neat diesel without preheating (referred to as 'Normal diesel') are compared with that of B100 at preheated temperatures such as 100°C, 175°C, and 250°C (referred as B@100, B@175, and B@250 respectively). Experiments are conducted at 66% and 100% of full load and discussed in the following section. Since B100 fuel has higher viscosity at temperatures below 80°C, the performance of this fuel is measured at temperatures 100°C and above.

Engines are generally used in 66% and 100% of full load. Comparing the engine's performance in this range while using standard diesel and preheated biodiesel will have practical implications. Therefore, the data obtained for biodiesel at different temperatures of preheated biodiesel supplied vis-a-vis standard diesel are considered for discussion and presented in the following section.

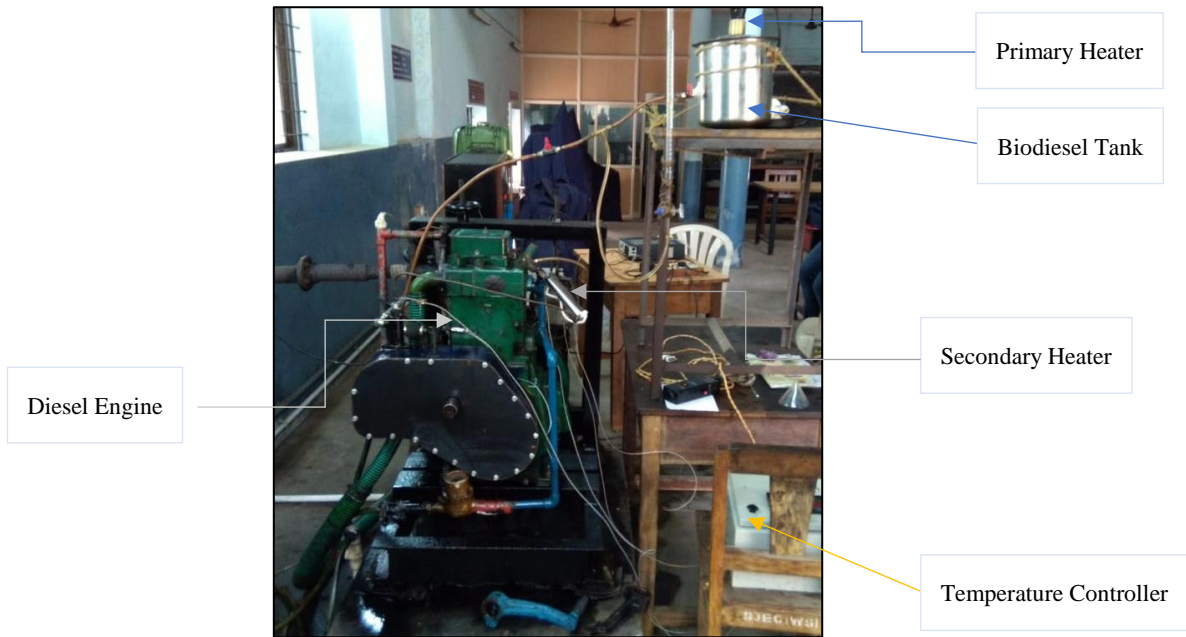


Figure 1. Diesel engine test rig

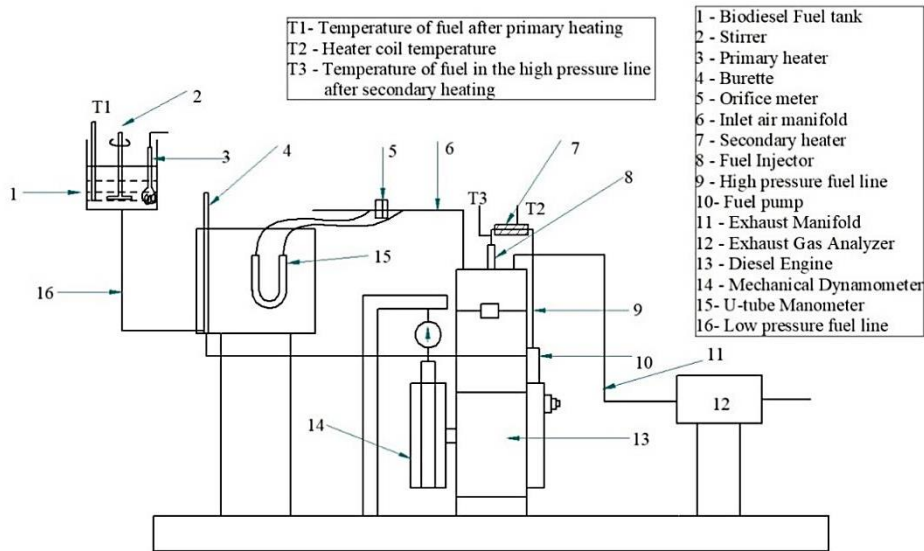


Figure 2. Schematic diagram of test rig showing heating arrangements

In the present work, biodiesel obtained from Waste Cooking-oil Methyl Ester (WCME) is used to study a diesel engine's performance and emission under various preheating temperatures. Following are some physical and chemical properties of pure WCME Bio-Diesel (B100) [21].

Table 2. Properties of Bio-diesel and Diesel

Properties	WCME (B100)	Normal Diesel
Density at 15.56°C kg/m ³	892.6	840
Flash point °C	176	52-96
Calorific value kJ/kg	39835	43500
Kinematic Viscosity at 30 °C (Centistokes)	4 -4.5	2.5-3.2
Specific heat of fuel (kJ/kg °C)	2.13	1.93

An electric heater is used for preheating biodiesel, and the required capacity is found as follows:

The heat supply rate needed to heat the fuel from room temperature (approximately 30°C) to the maximum temperature of preheating, which is about 300°C, is given by,

$$Q = m C_p \Delta T \quad (1)$$

Where,

m = mass flow rate of fuel in the given engine at full load condition = 2.94×10^{-4} kg/sec.

C_p = specific heat of fuel = 2.13 kJ/kg °C

ΔT = maximum temperature rise required in heater coil = $300 - 30 = 270^\circ\text{C}$

Therefore, $Q = 169.33$ W

The calculation above shows that the heat required to preheat the fuel is about 170W. But considering heat losses, a 750W capacity electric band heater is used. Electric power regulators are used for controlling fuel temperature. A thermocouple is used for measuring the fuel temperature. The location of the preheater and the thermocouples is shown in Figure 2.

RESULTS AND DISCUSSIONS

Performance Results

Figure 3, 4, and 5 show the graphical plots of Brake Power (BP), BSFC (Brake Specific Fuel Consumption), and BTE (Brake Thermal Efficiency), respectively measured at 67% and 100% of full load for standard diesel without preheating and 100% biodiesel at different preheated temperatures. Figure 3 shows that BP appears to be nearly constant for standard diesel and biodiesel at both the loads at all the temperatures considered. Thus, even though B100 has a lower heating value than diesel, the brake power produced at the given loads and temperatures has remained unaffected. It proves that preheating fuel leads to better atomization (may be partial gasification) and improves combustion; therefore, the performance parameters of preheated biodiesel are on par with the standard diesel. Kodate et al. [4] and Sumedh et al. [12] also highlighted the contribution of the preheating the biodiesel towards improved atomization and combustion phenomenon.

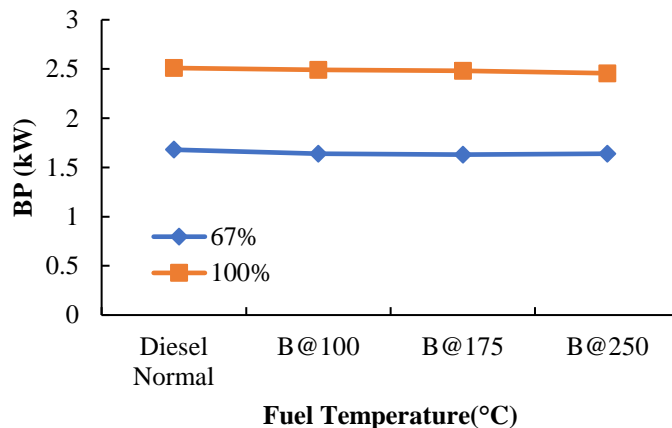


Figure 3. BP against fuel temperature at 67% and 100% of full load

Figure 4 illustrates the brake-specific fuel consumption (BSFC) at different loads. It is seen that BSFC is higher for Biodiesel than for normal diesel. Similarly, BTE is found to be lesser for Biodiesel than for normal diesel (refer Figure 5). This behavior is quite evident because of the lower heat value of biodiesel, resulting in a lower heat release rate and higher fuel consumption. But it is very significant to note the effect of preheating on biodiesel. Comparing the performance at 67% load, BSFC decreases by 5.4%, and BTE increases by 6.15% at fuel temperature of 250°C than at 100°C . This result proves that preheating helps lower the viscosity and improves fuel atomization, resulting in better combustion. But at 100% load, BSFC remains almost constant, and BTE increases marginally at 100°C and at 175°C . But at 250°C , BSFC increases marginally by 6%, and BTE reduces by 2.9% due to the effect of the flash boiling phenomenon [20]. This is because the fuel spray length decreases at a higher fuel temperature and load, which affects formation of air-fuel mixture and significantly shorter ignition delay leads to slightly higher fuel consumption. Therefore at full load, heating the fuel temperature up to 175°C is found to be beneficial at which the maximum thermal efficiency achieved is 17.70%.

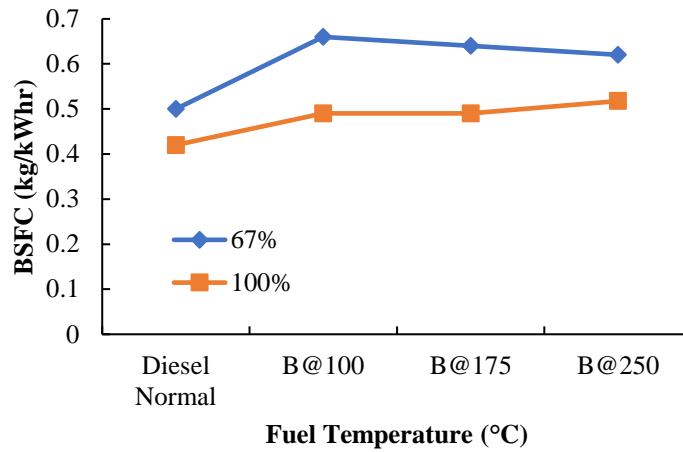


Figure 4. BSFC against Fuel temperature at 67% and 100% of full load

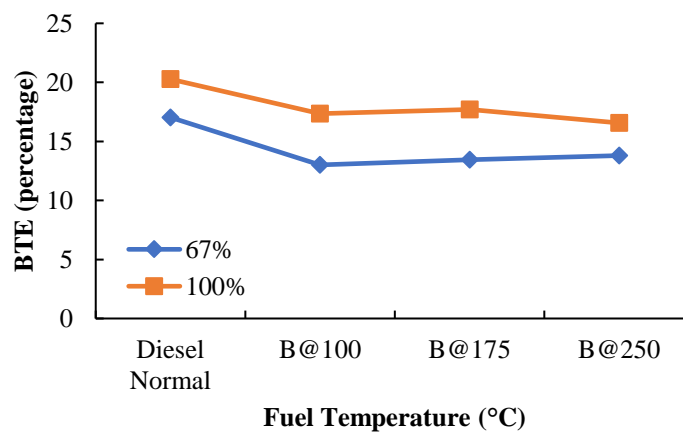


Figure 5. BTE against Fuel temperature at 67% and 100% of full load

Emission Results

Since preheating leads to fine atomization and better mixing of air and fuel, both CO and HC emissions are expected to reduce. Also NO_x emissions are tend to increase due to higher in-cylinder temperature caused by improved combustion. Emission results justifies these hypothesis. Figure 6 compares CO emission of regular diesel and B100 fuels at different preheat temperatures and loads. Carbon monoxide emission indicates lesser availability of oxygen for complete combustion and vice-versa. Compared to standard diesel, at 67% load, CO emissions decrease by 38% at 250°C. It implies that preheating reduces viscosity and increases atomization, leading to better air-fuel mixing, ensuring complete combustion. Additionally, biodiesel is more oxygenated than diesel which also helps reduce CO emission. But at 100% load, the CO emissions of biodiesel are reduced by 12.5% at 100°C, equivalent to the CO emissions at higher temperatures. The reason for this result may be due to two aspects: 1st- the presence of a rich mixture of fuel and air at higher loads that have led to improper combustion [2] and 2nd- flash boiling effect[20] as discussed earlier.

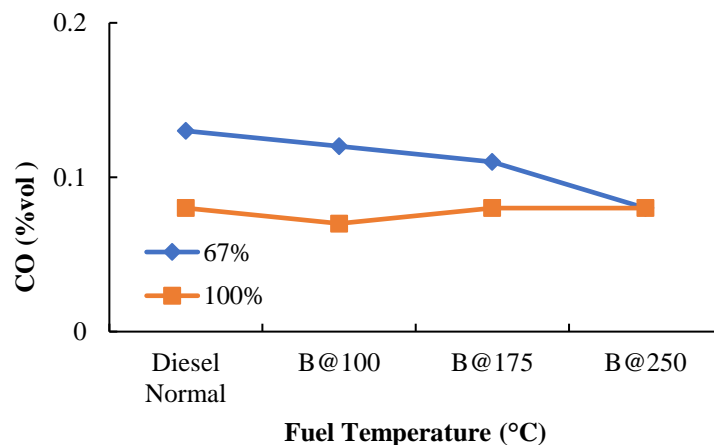


Figure 6. CO against fuel temperature at 67% and 100% of full load

Results of HC emission are presented in Figure 7. HC emissions are formed due to incomplete combustion of fuel. Compared to standard diesel, biodiesel combustion emits higher amounts of HC at lower temperatures but decreases as temperature of fuel increases. For example, biodiesel preheated to 100°C and 175°C, HC emission is slightly more than that for standard diesel, but at 250°C, it reduces by 25.5% and 10.9% for 67% and 100% load, respectively. This result is chiefly due to improved atomization and formation of homogeneous mixture at higher temperatures of preheated fuel. Also, it is essential to note that the influence of engine load on the HC emission, which reduces at higher preheating temperatures.

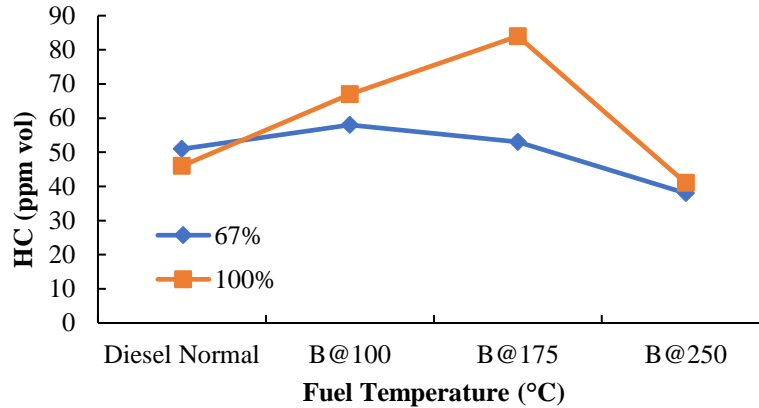


Figure 7. HC against fuel temperature at 67% and 100% of full load

Figure 8 shows NOx emissions at 67% and 100% load with different fuel temperatures. Nitrogen Oxides are formed by the reaction of oxygen with nitrogen at higher in-cylinder temperatures. Therefore, the presence of NOx is an indication of improved combustion since it results in increased in-cylinder temperature. At 100°C and 175°C, biodiesel has lower NOx emission than normal diesel, but at 250°C, it tends to increase by a small amount of 3.8% and 6% for 67% and 100% load, respectively. This result proves that preheating of biodiesel helps in improving the combustion process consequently increasing in-cylinder temperature and leads to the increase of NOx. It is important to note that the NOx levels of B@250 are in close agreement with normal diesel.

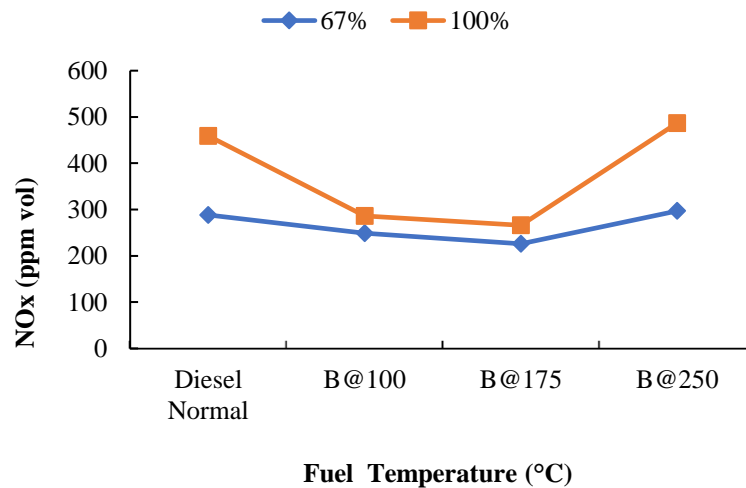


Figure 8. NOx against fuel temperature at 67% and 100% of full load

This experimental study has brought out very interesting results, which are clearly indicating that biodiesel can effectively substitute diesel, which is a mineral based fuel and its availability is depleting fast. Earlier work using biodiesel has optimized blending of biodiesel with diesel in 20:80 proportion. Many efforts to increase the blend proportions have not been promising, however, the present work has enabled the use of 100% biodiesel efficiently, which is on par with standard diesel. The only additional requirement being of preheating biodiesel in the temperature range from 100°C to 250°C. It is important to note that unblended biodiesel B100, is renewable, non-toxic, free from sulfur, biodegradable, and highly cost-effective. Hence it can be used as the best alternative fuel for compression ignition engines.

CONCLUSION

It has been an interesting pursuit to find an effective alternative to mineral based fuels and the present work has demonstrated that biodiesel can replace the standard diesel oil used worldwide. In view of this objective 100% biodiesel or B100 has been used at elevated temperatures ranging from 100°C to 250°C in a diesel engine. Experiments have been conducted at various loads and at a constant speed and based on the study following conclusions are drawn:

- (1) Injecting biodiesel at a very high-temperature ranging from 100°C to 250°C, has resulted in flash boiling of fuel leading to rapid atomization, reduced delay period, and improved combustion process.
- (2) High-temperature injection has resulted in lower brake specific fuel consumption with a corresponding increase in thermal efficiency, particularly at higher loads. This is a promising outcome that makes biodiesel to become an effective alternative to mineral-based oils.
- (3) Apart from demonstrating better performance, B100 has performed very well in regard to emissions, where-in CO and HC emissions are very low with an insignificant increase in NO_x levels. Hence use of B100 proves to be highly beneficial to the environment. Furthermore, lower emissions indicate better combustion or better utilization of fuel.

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