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Experimental Investigation on Performance, Combustion, Emission and Vibration Analysis of Diesel Engine Fuelled with Rice Bran Biodiesel and n-Butanol Additive

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ABSTRACT

Substantial growth in emissions, hike in fuel prices, and exhaustion of fossil fuels have given rise to the need for substitute fuels for diesel engines, which are renewable and demote the emission. Also, strict international emission standards force researchers to seek alternative fuels. Vegetable oils are promising alternative biodiesel for a diesel engine, amongst them, rice bran is underutilized, a non-edible source that doesn't create any food security hurdle. The paper focuses on investigating the performance, combustion, emission, and vibration characteristics of diesel engine fuelled with rice bran biodiesel and n-butanol additive (5% constant) at CR 17.5. The engine characteristics of seven biodiesel blends (B5n5, B10n5, B15n5, B20n5, B25n5, B30n5, and B40n5) were measured at various loads under constant speed and compared with diesel fuel. The performance characteristics were observed in moderate quantities as compared to diesel whereas the emissions were found reduced drastically than diesel fuel except for nitrogen oxide (NO_x) emissions. The measured engine cylinder vibration for all blends indicates similar results as diesel fuel hence leading to smooth combustion. The investigation shows that blends from B20n5 to B30n5 have the potential to be used in a diesel engine without any modification.

Keywords: Rice bran Biodiesel; N-Butanol Additive; Engine Performance; Emission; Vibration

INTRODUCTION

The continuous excavation of the earth's crust for fossil fuels and exploitation of natural resources leads to the need for specific attention to the properties of fuels, which directly affects engine performance, combustion, and emission. Depletion of uneven and rarely distributed natural resources, cutthroat energy demands, and the detrimental effect of energy use on the environment through emission motivated researchers to investigate substitutes for conventional fuels (Mahalingam et al. 2018; Mahla et al. 2018; Kumar et al. 2019). With the rapid growth in industrialization, the use of efficient, reliable, and low-cost power sources such as diesel engines has increased tremendously. The major disadvantage of diesel engines is tailpipe emission, which has been affecting mankind and the environment (Girish et al. 2019). Nowadays, biofuels derived from animal fat and vegetable oils are gaining importance as an alternative fuel. Among these, vegetable oils have gained prime importance due to the attractive potential of renewable, non-toxic nature and revitalization of the agricultural economy by boosting farming (Afzal et al. 2018; Singh et al. 2017). The biodiesels can be prepared from vegetable and animal oils but this can be strongly criticized in India due to the ever-growing population which may create an impact on the global food market and food security hurdles. The properties such as good lubricity, higher cetane number, and lower sulfur and aromatic content, biodiesel attracted the researcher to replace conventional petroleum products (Tuccar et al. 2014). Many researchers have also investigated that biodiesel reduces particulate matter, unburnt hydrocarbon, and carbon monoxide emissions (Rashed et al. 2016, Patil et al. 2019). The long-term use of vegetable oils leads to injector coking, piston ring sticking, thickening of lubricating oils, and severe engine deposits (Sriram et al. 2019). This problem can be overcome by implementing preheating, microemulsion, thermal cracking/pyrolysis, blending in small proportions, and transesterification (Chhabra et al. 2017).

India has the largest yield of rice about 2665 kg/hectare. Rice bran is the outer brown layer of rice that is removed during polishing. It is a by-product of the milling process and weights up to 8% of harvested rice heads. Hence, rice bran oil has a positive attraction for biodiesel (Lin et al. 2009). The current experimental research on diesel engine using various fuels reveals that biodiesel secures the first position in all due to less HC and CO emission characteristics and better performance (Goga et al. 2019; Jayaprabakar and Karthikeyan, 2019; Prabhu et al. 2019). The concerns of vegetable-based biodiesel are higher viscosity and density, lower volatility, and subservient performance than conventional diesel. To overcome these troubles different additives are blended in biodiesels based on properties. Higher alcohol can be added to diesel fuel for enhancement of the fuel properties (Pawar et al. 2018). Due to properties such as good calorific value and finite moisture absorbing capacity, n-butanol has gained priority as an additive (Ndaba et al. 2015; Zheng et al. 2015; Ibrahim A. 2016). The long-term use of biodiesel results in a dilemma concerning the operation and endurance of the engine due to properties of biodiesel such as lower energy content, lower volatility, higher pour point, and higher viscosity. To overcome these difficulties, n-butanol is blended in biodiesel, which improves blend stability without any disturbance (Sukjit et al. 2013; Yilmaz et al. 2016; Rakopoulos et al. 2015).

Talamala et al. (2017) have experimented the rice bran biodiesel with isopropanol as an additive and observed that a 2% additive has comparable performance to diesel. Also, thermal efficiency was increased by 4.3% and CO, HC, and smoke emission were decreased by 14%, 36.5%, and 27.5% respectively. The cylinder head vibrations were measured in the vertical direction and it was observed that the vibration signature shows smoother combustion for all blends with the introduction of 2% isopropanol. Sivasubramanian (2018) has reported for papaya seed biodiesel with an n-butanol additive that the blend percentage should be less to get maximum BTE. At medium loads, the addition of n-butanol affects the EGT and shows a decrease in CO, HC, and smoke emissions. Yusri et al. (2015) have used biomass-based fuel and n-butanol additive in a diesel engine to analyze the combustion and emission parameters at various engine speeds with constant BMEP. The combustion characteristics result in lower first and second peak pressure for both speeds by 2 to 5 %. The exhaust pressure was reduced by 7 to 11 % and NO_x was reduced by 11%. Emiroglua and Sen (2017) have studied the influence of alcohol addition in diesel and reported higher peak cylinder pressures, maximum heat release rates, and an increase in NO_x, BSFC, and BTE. Kannan et al. (2011) tested waste cooking oil and observed a 6% increase in BTE and a decrease in CO, HC, NO_x, and smoke emissions by 43.3%, 52.7%, 23%, and 15.5% respectively. Karthikeyan et al. (2016) tested rice bran oil biodiesel with cerium oxide nanoparticles and reported a reduction in HC, CO, and NO_x emissions compared to the B20 blend of rice bran biodiesel. The heat release rate was reported maximum by the addition of cerium oxide. Jayaprabakar and Karthikeyan (2019) have used rice bran oil biodiesel for energy and exergy analysis in a diesel engine and it was asserted that the rice bran biodiesel significantly reduces CO, NO_x, HC, and smoke emissions at all loads. Subbaiah and Gopal (2011) have observed a 20% and 27.47% reduction in smoke by the addition of 7.5% and 2.5% ethanol in rice bran biodiesel respectively. The minimum BSFC was observed at 2.5% addition of ethanol at full load.

Satsangi and Tiwari (2018) have examined the effectiveness of various blends of diesel fuel and n-butanol in diesel engine operated under constant speed and varying load conditions. The engine noise, vibration, emission, and performance parameters were measured, and an established inter-relationship between them resulted in the vibration and noise of test blends being marginally better at lower loads. It also shows a strong correlation between noise, vibration characteristics, combustion, and rate of pressure rise of test blends. The test blend was found to perform improved for NO_x, CO, and smoke emissions. Many investigators reported the influence of premium quality of oxygenating properties leads to considerable reductions in HC and CO_2 emissions and produces less detrimental. (Rashed et al. 2016; Labecki et al. 2012). Balasubramanian and Subramanian (2019) have observed that the increase in CR from 17:1 to 21:1, increases in-cylinder pressure, BTE, and NO_x and decreases smoke and CO emission. A higher CR with retarded injection timing is recommended for improved performance with reduced NO_x emission. Mohit and Rakesh (2017) have optimized engine characteristics such as operating load, compression ratio, and injection pressure using Taguchi's design experiment. The result highlights the reduction in CO, $NO_{x,}$ and particle emissions for butanol/diesel blends. Heidary et al. (2013) reported the highest vibrations for B15 and B10 blends and the lowest for B100 and B20 blends. The vertical vibrational acceleration was reported more than horizontal and axial acceleration. Boonthum et al. (2013) observed vibration signatures on hydrogen-diesel fuelled engine and reported that by increasing hydrogen percentage the acceleration was decreased. Syed et al. (2016) investigated jatropha biodiesel with zinc oxide nanoparticles and recommended B30 and B20 blends for the least vibrations. The abnormal and erratic combustion leads to damage to engine parts and may be subject to vibrations at higher frequencies. The engine is the main source of vibrations due to continuously moving components like a piston, connecting rods, and crankshafts. The subsequent change in gas pressures, an explosion of charge and inertia forces among members trigger vibrations in the engine. The higher frequency may lead to earlier failure of system parts. To diagnose the requirement of maintenance the study of vibrational signatures may provide a reliable tool.

Extensive research has been reported in the field of biodiesel synthesis, engine performance, and emission characteristics (Mallesham et al. 2019). There hasn't been adequate research to report the collective effect on performance, combustion, emission, and vibration characteristics of rice-bran biodiesel with n-butanol additive in a diesel engine. Some literature indicates that rice bran has excellent fuel properties as a substitute fuel and has low emission characteristics. So there is a need to check the suitability of rice-bran biodiesel as an alternative fuel in diesel engines by blending it with diesel fuel and additives (Avinash and Atul 2010, Mohit et al. 2016). In the present study, the rice bran biodiesel with n-butanol additive is selected as a potential alternative used efficiently in an unmodified engine (Yesilyurt et al. 2018). The n-butanol additive has the highest percentage of O_2 content. Also, it has a high calorific value of 34.44 MJ/kg and a high cetane number of 25. The main advantage of the n-butanol additive is its high solubility with diesel fuel. The paper presents the investigations on engine performance, combustion, emission, and vibration characteristics by using a blend of diesel, rice bran biodiesel and n-butanol additive.

METHODS AND MATERIALS

Synthesis of Biodiesel Blends

In this experiment, the rice bran biodiesel is synthesized by using the transesterification method. Transesterification is a process used to produce biodiesels from vegetable oils using catalysts (Kumar et al. 2021). The detailed process of biodiesel preparation is shown in Figure 1. First, the rice bran oil of 1-liter quantity is dried by heating at 110℃ for 2 hours. After drying, the esterification is carried out, in which 0.5% sulphuric acid and 10% methanol are added at 60°C for 60 minutes and stirred by a magnetic stirrer at 600 rpm. The solution is poured into a conical separating funnel and allowed to cool and settle down for 8 hours. Settlement forms two visible heterogeneous layers; the upper one of water, excess methanol and catalyst, and the lower one of esterified oil. The esterified oil is transferred into a beaker and methanol is added. These catalysts are prepared by mixing NaOH (0.5-1.5%) with 10% methanol (Dhamodaran et al. 2017; Sriram et al. 2019). The mixture is added to crude biodiesel and stirred with a magnetic stirrer for 600 rpm at 55℃ temperature for 2 hours. The oil is cooled down and allowed to settle under gravity for 8 hours. This settlement again produces two heterogeneous layers of biodiesel and glycerin

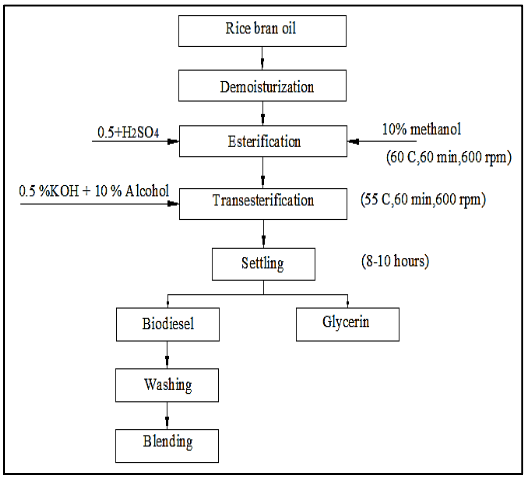

Figure 1 Flowchart of biodiesel preparation (Imtenah et al. 2014)

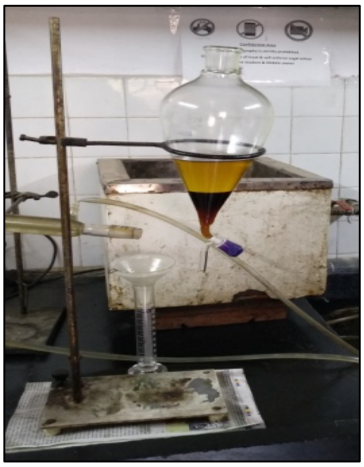

Figure 2 Two visionary layers of the transesterification process

Among the biodiesel, the catalyst, soap, and impurities were removed by distilled water with a 10% volume of biodiesel at 70℃. The water washing is done until the pH of the upper layer matches with the lower layer. The matching of pH is an indication of the removal of all the impurities. The dehydration is carried out and the biodiesel is blended with n-butanol and diesel fuel for 30 minutes in a stirrer (Asokan et al. 2019; Chhabra et al. 2017; Sreedhar et al. 2016). The percentage of biodiesel yield is calculated by using equation (1) (Arun et al. 2018). The percentage yield of biodiesel free from glycerine was 85%. Figure 2 shows the separation of ricebran biodiesel from glycerine. The ricebran biodiesel is mixed with diesel fuel with various propositions and with 5% n-butanol to obtain the various blends.

$$\% \text{ yield} = \frac{\text{Mass of methyl ester produced (g)}}{\text{Mass of oil used for reaction (g)}} \times 100 \tag{1}$$

As presently tested blend fuel of rice bran along with additive n-Butanol is available commercially in the market at a higher price (Pure Rice bran Rs. 180 per liter and Pure n-Butanol Rs. 60 per liter) than existing diesel fuel price (Rs. 75 per liter when the trial was conducted). Although the cost per liter of biodiesel seems higher than the existing diesel fuel price, the biodiesel fuel is renewable and can produce a null effect on the environment in terms of pollution as it is biodiesel where the plant consumes CO_2 produced by emission hence called zero-emission fuels. In addition, if these blended fuels are fully commercialized, the cost of biodiesel blend may be competitive with the existing diesel fuel. It is discovered that the blends employed for testing in this study range from B5 to B40, with a constant of 5% n-butanol in each blend with diesel fuel, demonstrating stability at all operating temperatures and room conditions. Table 1 shows the experimental matrix for biodiesel blends.

Table 1 Experimental matrix of biodiesel blends

Fuel	Rice Bran (%Volume)	n-butanol (%Volume)	Diesel (%Volume)
Diesel	0	0	100
B5n5	5	5	90
B10n5	10	5	85
B15n5	15	5	80
B20n5	20	5	75
B25n5	25	5	70
B30n5	30	5	65
B40n5	40	5	55

Quality Testing Parameter of Biodiesel Blends

The biodiesel blend parameters like density, calorific value, viscosity, cetane number, flash, and fire point were determined. The various properties of prepared biodiesel blends are presented in Table 2. As per the ASTM standard, all blends were tested and validated. The density and viscosity of the biodiesel blend were found slightly more than diesel fuel. The calorific value was found to decrease with increasing blend proportion.

Table 2 Properties of biodiesel blends

Sr. No.	Test Parameters	Standard ASTM D6751	Diesel	Biodiesel blends						
				B5n5	B10n5	B15n5	B20n5	B25n5	B30n5	B40n5
1.	Density gm/cc	D1448	0.830	0.832	0.833	0.834	0.836	0.839	0.840	0.841
2.	Calorific Value MJ/kg	D6751	42.50	42.38	42.30	42.22	42.09	41.96	41.82	41.78
3.	Cetane Number	D613	49	46	47	49	50.1	51	51	52
4.	Viscosity mm^2/sec	D445	2.70	2.73	2.79	2.83	2.89	2.95	2.98	3.11
5.	Flash Point ℃	D93	64	76	83	89.5	94	99	105	111
6.	Fire Point ℃	D93	71	80	89	94	101	105	111	119
7.	Cloud Point ℃	D2500	-4	2	2.5	2.8	3.0	3.7	4.2	5.5
8.	Pour Point ℃	D2500	-9	-5.3	-4.5	-2.1	1.0	1.8	2.9	3.4
9.	Ash %	D874	0.05	0.05	0.07	0.06	0.05	0.04	0.04	0.04

Experimental Test Setup

The experimental setup has been prepared for controlling and monitoring the various engine variables such as speed, load, fuel flow, and airflow. A single-cylinder, four-stroke, water-cooled, multi-fuel engine was used to conduct the experimentation. The layout of the experimental setup is presented in Figure 3. The sensors are used for the measurement of fuel injection pressure, and engine speed. The load is applied with an eddy current dynamometer from 2 to 18 Nm. Before the start of the engine water level was checked and the water flow rate was maintained at 250 lit/hr at 2 bars. The injection timing is 13 degrees before TDC. The experiment was carried out at a constant CR of 17.5 and 1500 rpm by varying load from 0 to 18 Nm for all blends. The diesel and all blends of rice bran biodiesel with 5% additives are tested for BSFC, EGT, BTE, and mechanical efficiency by using EPA (Engine Performance Analysis) software. The emission parameters like HC, CO, and NO_x are measured on AVL DSS laboratory equipment.

Table 3 Technical specification of the experimental setup.

Sr. No.	Engine Parameter	Specification
1	Model	Kirloskar
2	Engine Type	Single Cylinder, 4 stroke, CI Engine
3	Bore/ Stroke	87.5 mm/110 mm
4	Rated Power	5 BHP at 1500 rpm and CR 17.5
5	Capacity	662 cc
6	Loading	Eddy current dynamometer

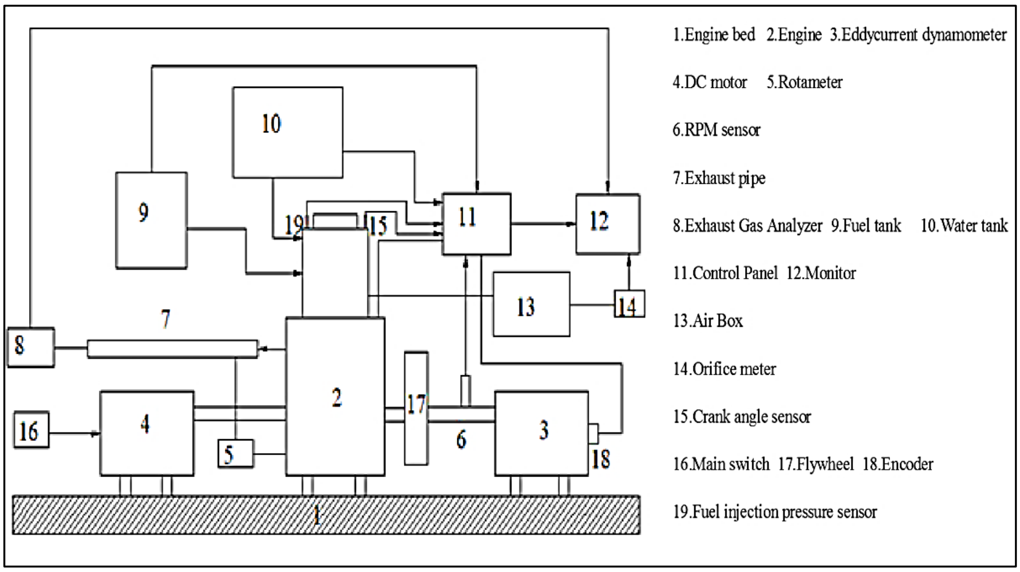

Figure 3 Experimental layout of engine setup

The details of the uncertainty of measurement for various parameters are given in Table 4. The major reasons behind the uncertainty are instrument calibration, environmental conditions, selection of proper instruments, and human errors during experimentation. The accuracy analysis of the experimental setup was conducted using the method explained by J. P. Holman. (Dubey and Gupta 2017; Santhosh and Padmanaban 2016). The percentage uncertainty of the experiment is 0.75%, calculated using equation (2).

Total percentage of uncertainty of the experiment = Square root of uncertainty of {(Engine Speed)^2 + (Temperature)^2 + (Time)^2 + (Engine Torque)^2 + (Fuel Volume Flow rate)^2 + (Air Flow Rate)^2 + (Cylinder Pressure)^2+ (NO_X)^2 + (HC)^2 + (CO)^2 +(CO_2)^2 + (Crank Angle encoder)^2} (2)

The engine performance characteristics such as Engine brake power, BSFC, BTE, and Mechanical Efficiency are evaluated using commercial software based on the following expressions (Ibrahim et al. 2013, Amarnath and Prabhakaran 2012),

$$BHP = \frac{2\pi NT}{60000} \tag{3}$$

$$\dot{m}_f = \left(\frac{60}{t}\right) \times \left(\frac{X}{1000}\right) \times \rho \times 60$$

$$BSFC = \frac{\dot{m}_f}{BHP} \tag{4}$$

$$BTE = \frac{BHP}{\dot{m}_f \times CV} \times 3600 \tag{5}$$

$$IHP = \frac{P \times L \times A \times N}{1000} \tag{6}$$

$$\text{Mechanical Efficiency} = \frac{BHP}{IHP} \times 100 \tag{7}$$

Where T is engine torque (Nm), N is engine speed (rpm), $\dot{m}_f$ is engine fuel flow rate (kg/h), CV is fuel calorific value (kJ/kg), P is indicated pressure in the cylinder (N/m^2), L is stroke length engine (m), A is piston area (m^2), BHP is brake power (kW), IHP is indicated power (kW), t is Time required by '*X*' c.c. of fuel, ρ is specific gravity of fuel.

Table 4 Uncertainty of measurement

Sr. No.	Parameter	Accuracy	Maximum Uncertainty (%)
1.	Engine speed	± 2 rpm	±0.2
2.	Temperature	± 1°C	± 0.16
3.	Time	± 2 sec	±0.25
4.	Engine Torque	± 0.05 Nm	± 0.4
5.	Fuel mass flow rate	± 0.01 kg/s	±0.2
6.	Air velocity	± 0.02 m/s	± 0.25
7.	Cylinder pressure	± 5 bar	± 0.2
8.	NO_x	± 5 ppm vol	± 0.1
9.	HC	± 4 ppm vol	± 0.2
10.	CO	± 0.02% vol	± 0.2
11.	CO_2	± 0.3% vol	±0.15
12.	Crank angle encoder	±0.5°CA	± 0.02

Equation (9) gives integrated heat release (Q) for the corresponding crank angle (θ), in-cylinder pressure (p), and volume (V) (Ibrahim, 2016).

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma-1}\, p \,\frac{dV}{d\theta} + \frac{1}{\gamma-1}\, V \,\frac{dp}{d\theta} \tag{8}$$

$$Q = \int_{\theta_1}^{\theta_2} \frac{dQ}{d\theta}\, d\theta \tag{9}$$

Where γ is the specific heat ratio of the in-cylinder contents

The Heat supplied by fuel, Heat carried away by exhaust gases, Heat carried away by cooling water, and Heat unaccounted is calculated using the following equations,

$$\text{Heat Supplied by Fuel (Q) kJ/min} = \left\{\frac{\dot{m}_f}{60}\right\} \times CV \tag{10}$$

$$\text{Heat Carried by Exhaust Gases } (Q_g) \text{ kJ/min} = M_g \text{ x } C_{pg} \text{ x } (T_{goe} - T) \tag{11}$$

$$\text{Heat carried by cooling water } (Q_w) \text{ kJ/min} = Mw \text{ x } C_{pw} \text{ x } (T_{woc} - T_{wic}) \tag{12}$$

$$\text{Heat Unaccounted} = Q - (Q_b + Q_w + Q_g) \quad (13)$$

Where M_g is the mass of gas, C_{pg} is the Specific heat of gas, C_{pw} is the Specific heat of water, M_w is the mass of water flowing through the calorimeter per minute, T_{goe} is Exhaust Gas outlet Temperature From the Engine, T_{woc} is Water Outlet temperature from Calorimeter, T_{wic} is Water Inlet temperature to Calorimeter, T is Room Temperature, Q_b is Heat equivalent of BP.

RESULTS AND DISCUSSION

The experimentation was performed at a fixed CR of 17.5 and speed of 1500 rpm with varying load from 0 to 18 Nm on a multi-fuel engine using B5n5, B10n5, B15n5, B20n5, B25n5, B30n5, and B40n5 biodiesel blends to investigate the performance, combustion, emission, and vibration characteristic.

Performance Characteristics

The key performance indicators of the diesel engine are BSFC, BTE, Mechanical Efficiency, and EGT. In this section, the engine performance characteristics against brake power are presented for seven biodiesel blends. Figure 4 illustrates the variation of BSFC against Brake Power for all biodiesel blends. BSFC is largely dependent on the heating value of fuel, as biodiesel has lower heating values, it requires more fuel to produce the same amount of energy. The decrease in BSFC is observed with an increase in engine load for all proportions of the blend as well as diesel. It is noticed that with an increase in blend proportion, the BSFC was also increased by 13 to 35% as compared to diesel. The maximum BSFC observed was 0.42 (kg/kW-hr) at the B40n5 blend and the minimum BSFC observed was 0.35 (kg/kW-hr) at the B10n5 blend, which is 27% and 11% more than diesel fuel respectively. The BSFC for all blends was observed slightly higher as compared to diesel fuel for all conditions due to a percentage increase in brake power with the load as compared to fuel consumption.

The brake thermal efficiency of ricebran biodiesel with n-butanol additive at different load conditions is illustrated in Figure 5. The diesel shows the lowest 20.51% BTE while the B15n5 shows 24.28% highest BTE for a full load. It is perceived that BTE increases up to B15n5 blends and further increases in blends show a decrease in trend due to higher viscosity, lower calorific value, and low air-fuel mixing of biodiesel at higher concentrations. The BTE was observed higher for all the biodiesel blends than diesel due to oxygenated molecules of biodiesel which promoted complete combustion. The BTE increases gradually with respect to load. When the load is increased from minimum to maximum the BTE was increased from 0.32% to 24.28% for the B15n5 blend.

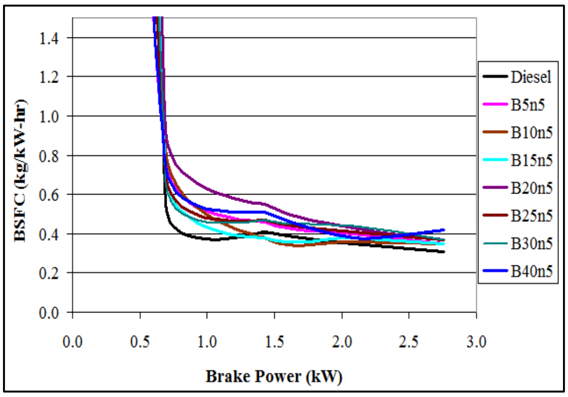

Figure 4 BSFC vs brake power

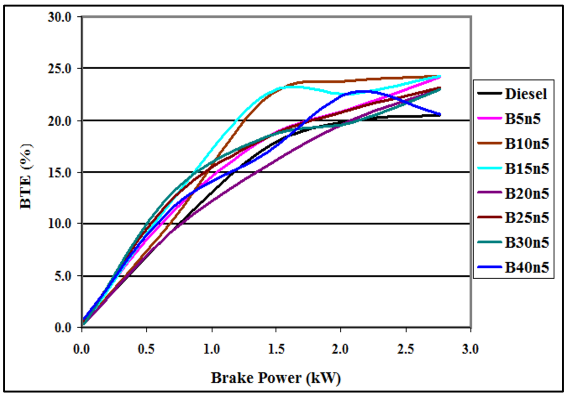

Figure 5 BTE vs brake power

The variations of mechanical efficiency with brake power for all the biodiesel blends are presented in

Figure 6. The mechanical efficiency was observed increasing steadily with an increase in brake power for all the biodiesel blends. The maximum 55.52% mechanical efficiency was reported at B30n5 blend for full load condition whereas diesel shows 55.1%. The increasing engine load increases the power generation, leading to mechanical efficiency as mechanical efficiency is directly proportional to the brake power. The mechanical efficiency of all biodiesel blends was reported very close to diesel fuel.

The variations of EGT of the biodiesel blends with brake power are demonstrated in Figure 7. The results indicate that exhaust temperature was increased with engine load. The EGT indicates an increasing trend as compared to diesel fuel for all biodiesel blends. At full load condition the EGT of B5n5, B10n5, B15n5, B20n5, B25n5, B30n5 and B40n5 blends were increased by 23.58%, 16.88%,19.27 %, 19.05 %, 17.96%, 32.01%, 46.66% respectively as compared to diesel fuel. The average EGT varies from 150℃ to 450℃ with no load to full load condition. The average EGT found for all blends between 150℃ to 450℃ is shown in Figure 7. The higher EGT indicates the possibility of incomplete or partial combustion for the used blends. However, the measured HC emissions for these blends showed lowered emissions than diesel fuel as shown in Figure 12. It can be attributed that the blends are burning completely due to oxygenated additives leading to a higher temperature of the products of the combustion that are released in the exhaust of the engine.

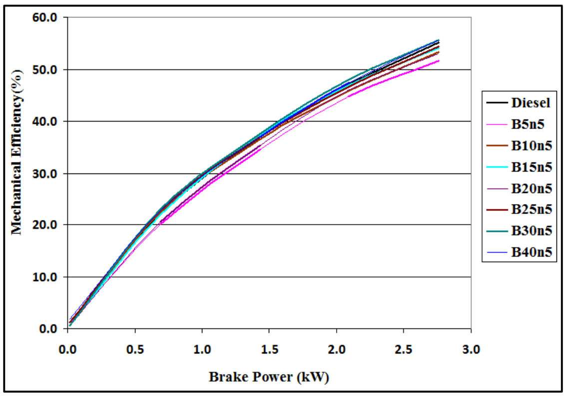

Figure 6 Mechanical efficiency vs brake power

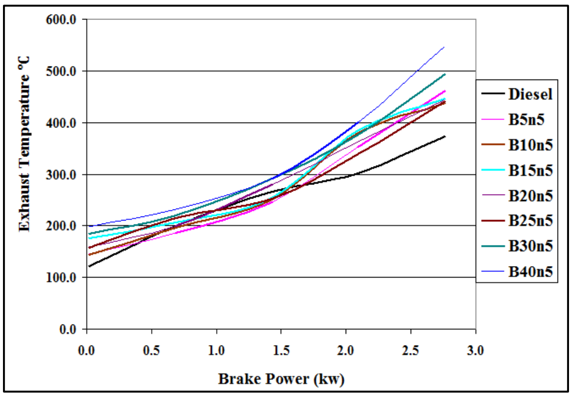

Figure 7 EGT to brake power

Combustion Characteristics

The combustion characteristics such as cylinder pressure, A/F ratio, integrated heat release, and heat balance sheet were analyzed for all seven blends. Figure 8 shows the variation in-cylinder pressure with the engine crank angle at full load condition. It is noticed that for full load conditions, pressure trends are almost similar for all the blends. At the B15n5 blend, the maximum pressure of 48.1 bar was recorded as compared to diesel 41.4 bar. The lowest cylinder pressure attained was 43.22 bar for B40n5 at full load conditions due to the larger ignition delay observed for B40n5 whereas B15n5 had the shortest ignition delay period.

The variation in the A/F ratio with brake power is presented in Figure 9 for all blends. It indicates that an increase in brake power decreases the A/F ratio. The A/F ratio of all the blends is more than diesel except for the B40n5 blend. At full load condition, the maximum A/F ratio obtained is 27.34 at B10n5 and B15n5 blends and the minimum obtained is 23.03 at B40n5 blend. It is emphasized that the A/F ratio decreases with an increase in the blend proposition.

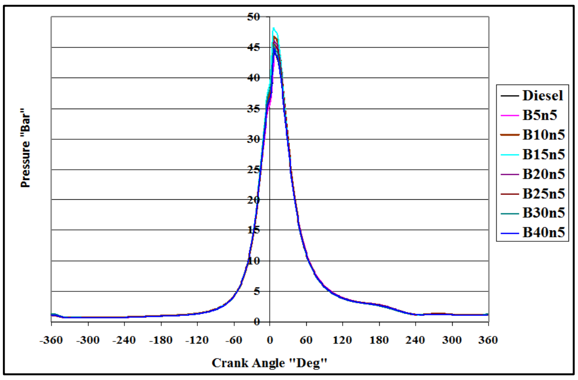

Figure 8 Combustion pressure vs crank angle

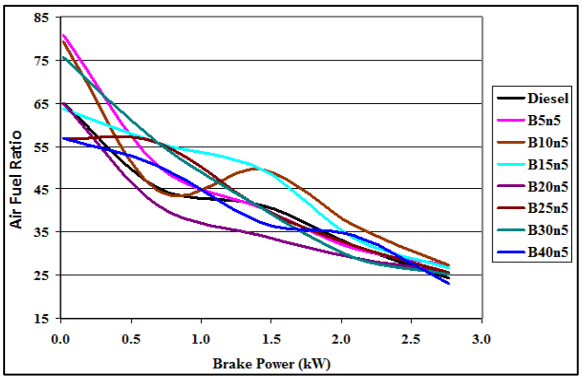

Figure 9 A/F ratio vs Brake Power

Figure 10 shows integrated heat release at full load conditions. The integrated heat release rate was observed minimum at the B30n5 blend and maximum at the B5n5 blend. For other blends, trends are almost similar to diesel. Figure 11 shows the heat balance sheet at full load condition for all the blends and diesel. From B5n5 to B15n5 blends, heat equivalent to brake power is higher than diesel as more oxygen is available for complete combustion. The complete combustion of these blends releases more heat hence showing higher exhaust gas heat loss. It is also seen that unaccounted heat loss is higher for B25n5 and B30n5 blends.

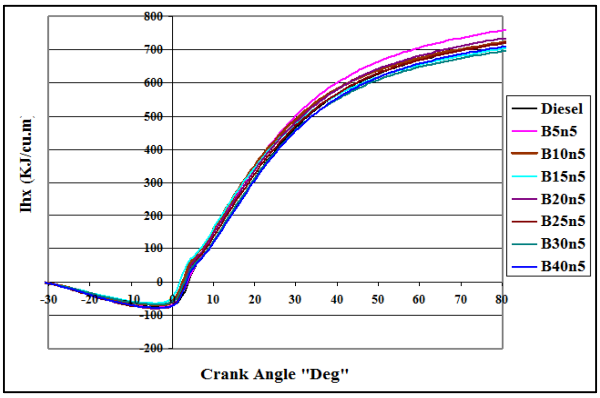

Figure 10 Integrated Heat Release at full load condition

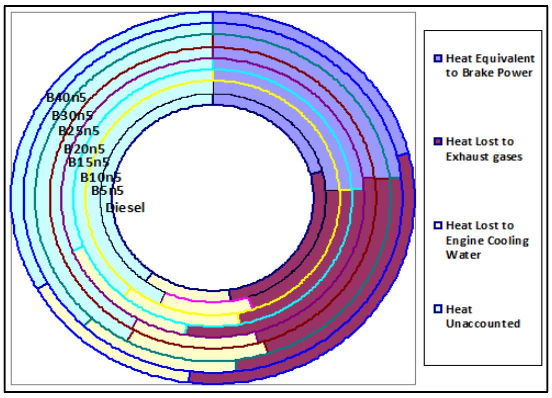

Figure 11 Heat balance sheet at full load condition

Emission Characteristics of Engine

The emission from the automobile tailpipe pollutes the air and leads to global warming and depletion of the ozone layer due to which the researcher has given more focus on the emission characteristics of the engine. The HC, CO, CO_2, and NO_x emissions were analyzed with engine brake power. Figure 12 shows the variation in HC emission with brake power for all blends. The engine load and proportion of the fuel injected increase the hydrocarbon emission. The result shows a reduction in HC emission for all the blends at different brake power compared with diesel fuel. The reduction in HC emission for B5n5, B10n5, B15n5, B20n5, B25n5, B30n5 and B40n5 blends as compared to diesel fuel was 4.47%, 10.33%, 12.79%, 7.55%, 45.45%, 65.49%, 77.66% respectively.

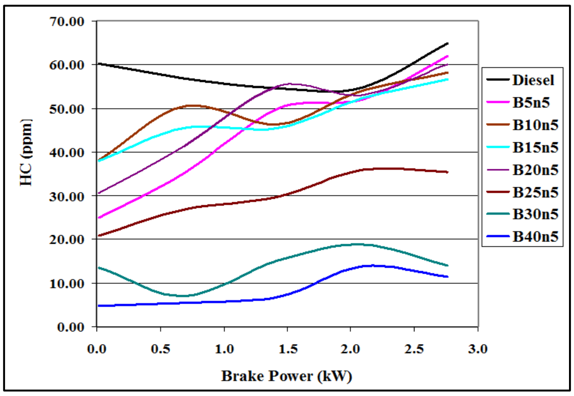

Figure 12 HC emission vs brake power

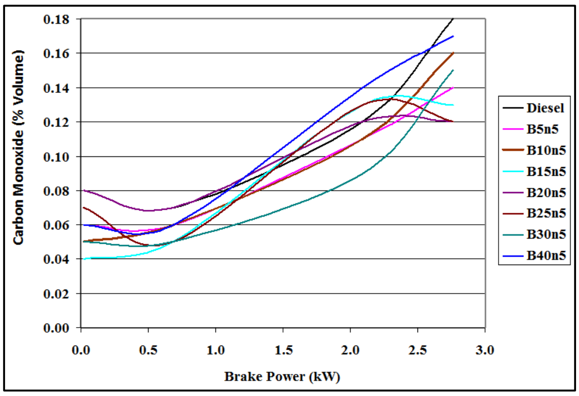

Figure 13 CO emission vs brake power

Figure 13 represents the variation in CO emission with brake power for all blends. It is observed that CO emission was decreased for all the blends in comparison to conventional diesel. The decrease in carbon monoxide emission is an indication of complete combustion. The reduction in CO emission of biodiesel blends was reduced by 6% to 29% as compared to diesel engine. The least CO emission was observed for B20n5 and B25n5 blends at full load conditions. Figure 14 shows CO_2 emissions for all blends (B5n5, B10n5, B15n5, B20n5, B25n5, B30n5, and B40n5) and diesel fuel. The increase in engine load increases the CO_2 emission. The CO_2 emission level is observed less for all the blends except B5n5 than for diesel. At the B30n5 blend, the lowest CO_2 emission observed is 65% less than diesel fuel, which shows complete combustion. The variation of NO_x emission with engine brake power is presented in Figure 15. The NO_x emission is observed increasing with an engine brake power for all biodiesel blends. The high combustion temperature diffuses the triple bond of nitrogen, which combines with oxygen available in rice bran, leading to an increase in NO_x formation.

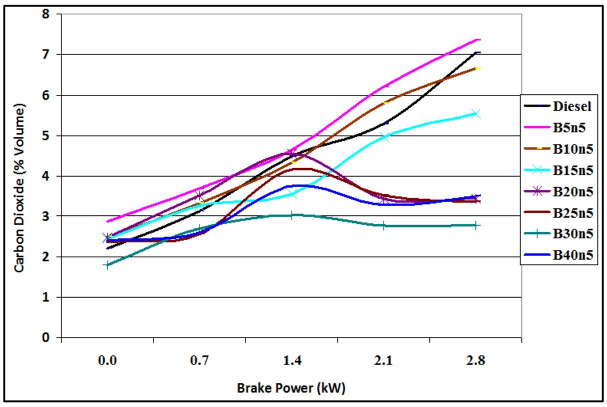

Figure 14 CO_2 emission vs brake power

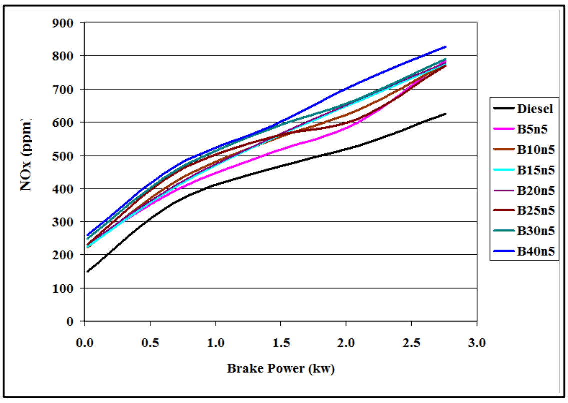

Figure 15 NO_x emission vs brake power

Vibration Characteristics of the Engine Head and Crankshaft Bearing

Figure 16 and 17 shows the root mean square vibrations measured at the crankshaft bearing and cylinder head in a vertical, horizontal, and axial direction at full load condition respectively. Since in the experimental setup engine is mounted vertically, the vibration recorded on the engine cylinder head in vertical and horizontal direction rightly reflects the combustion trend of the engine (Talamala et al. 2017). All the biodiesel blends have been carefully monitored to detect the combustion frequencies and vibration amplitudes by fast Fourier transformer (Jaikumar et al. 2019).

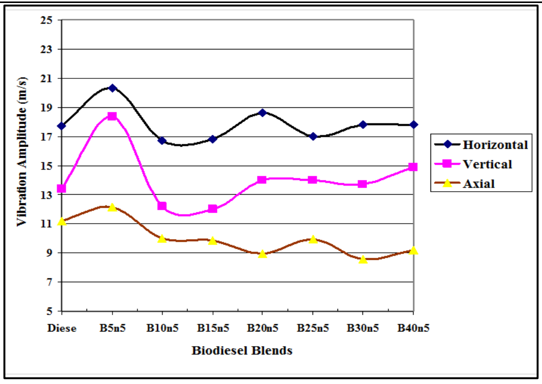

Figure 16 Root mean square values of vibration amplitudes at crankshaft bearing

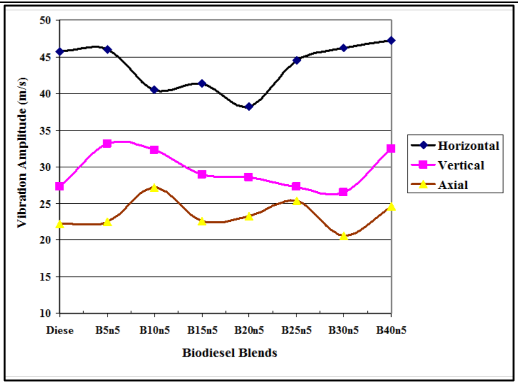

Figure 17 Root mean square values of vibration amplitudes at the cylinder head

The vibrations measured at the cylinder head in the vertical direction indicate that vibration amplitudes for all the blends are in the expected range. The minimum vibration amplitude of 16.7 m/s was observed at B10n5 and B15n5 blends whereas the maximum vibration amplitude of 20.32 m/s was observed at B05n5 blend at crankshaft bearing in the horizontal position. The overall vibration trend at the crankshaft bearing indicates that the vibration amplitude for all the blends was in the expected range. At the cylinder head, the maximum vibration amplitude was recorded for diesel, B5n5, B30n5, and B40n5 blends, which are above 46 m/s, and the lowest vibration amplitude was recorded for B10n5, B15n5, and B20n5 blend. For all chosen blends, during the performance of the selected test engine, it is seen that the engine was started easily and operated smoothly under all operating conditions. This can be more clearly seen with the measured engine vibrations as shown in Figures 16 and 17. In addition, the starting ability of the engine while running with these blends was found good enough as compared to pure diesel fuel.

CONCLUSIONS

The experimental investigations for the effect of rice bran biodiesel with the addition of 5% n-butanol additive to diesel are presented for engine performance, combustion, emission, and vibration characteristics. The variable compression ratio engine with a computer interface operated successfully with the selected matrix of biodiesel. The following are the specific conclusions for rice bran biodiesel with 5% n-butanol additive at CR 17.5 under various loading conditions based on the experimental investigation.

- The viscosity and density of biodiesel blends were found to increase with the increase in blend concentration. The calorific value reported as subservient to diesel shows a decreasing trend with the proportion of biodiesel. The B05n5 blend shows the highest calorific value 42000 kJ/kg.
- The BSFC reduces sharply with the increase in brake power. It is reported higher than diesel. The highest BSFC 374.17g/kW-hr for the B40n5 blend for full load conditions was reported.
- The BTE and mechanical efficiency were observed increasing with an increase in brake power for all blends. The B30n5 blend showed the highest mechanical efficiency of 55.52% approximately equal to diesel fuel.
- The B30n5 and B40n5 blends show the lowest HC emission of 14 and 11.5 ppm respectively. The range of HC emission reported between 11- 65 ppm. The CO emission of B20n5, B25n5, and B30n5 blends was found 0.12%, 0.12%, and 0.13% volume respectively. The CO_2 emission was found lowest at the B30n5 blend, which is 65 % less than diesel. All the emissions except NO_x were found to reduce drastically than diesel.
- The investigation shows that B20n5, B25n5, and B30n5 biodiesel blends have the potential to replace conventional diesel fuel at selected operating conditions.

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