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Evaluation of performance characteristics of Jatropha Biodiesel blend in a single-cylinder Diesel Engine: A simulation approach

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Abstract

This study evaluates the performance characteristics of Jatropha biodiesel blends using Ricardo Waive software. A simulation model of a 3.5 kW variable compression ratio diesel engine was developed with all possible geometric parameters. The test was conducted by varying the load from 0.5 kg to 12 kg. Jatropha biodiesel blends were prepared based on Fatty Acid Methyl Ester (FAME) data, including 10JBME (10% Jatropha biodiesel, 90% diesel), 15JBME (15% Jatropha biodiesel, 85% diesel), and 20JBME (20% Jatropha biodiesel, 80% diesel). Performance parameters such as indicated power (IP), brake-specific fuel consumption (BSFC), mechanical efficiency (ME), brake thermal efficiency (BTE), and exhaust gas temperature (EGT) were analyzed. The results showed that deviations in performance characteristics between biodiesel blends and pure diesel were within 5%. Lower blends (e.g., 5JBME) exhibited better IP, ME, and BTE, while higher blends (e.g., 10JBME and 20JBME) improved EGT. These findings indicate that moderate blends strike a balance between fuel efficiency and power output, whereas higher blends may reduce efficiency due to the lower energy content of biodiesel. A 20% Jatropha biodiesel and 80% diesel blend is considered moderate, balancing fuel efficiency and power output.

1. Introduction

Traditional fossil fuels, such as diesel and gasoline, are the primary energy sources for transportation and industrial processes. While global reserves of oil, gas, and coal remain substantial, they are depleting at varying rates, driving the need for renewable and alternative energy sources to address climate change and rising energy demands. This transition requires significant investment and innovation [1].

The scarcity and environmental impact of fossil fuels have intensified the search for sustainable alternatives. Biodiesel presents a viable renewable substitute for petroleum diesel. However, over 95% of biodiesel is derived from edible oils, raising concerns about food security. Non-edible oil crops, such as Jatropha curcas (Jatropha), offer a more sustainable biodiesel source. Despite its potential, several ecological, socioeconomic, legislative, and technological challenges hinder large-scale adoption.

This review explores these challenges, the interactions between influencing factors, oil extraction and biodiesel production technologies, and the performance and emissions of diesel engines using Jatropha biodiesel compared to petroleum diesel. Findings highlight regional variations in production factors and minor differences in engine performance and emissions [2].

Biodiesel, a promising alternative fuel for diesel engines, is produced through the transesterification of vegetable oils, such as soybean cooking oil, with alcohols (methanol, ethanol, and butanol) in the presence of an alkaline catalyst [3]. As a renewable and environmentally

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friendly fuel, biodiesel offers properties comparable to or even superior to conventional diesel.

The ongoing energy crisis and rising global crude oil prices significantly impact economies, especially in countries like India, where reliance on imported edible oils makes their use in CI engines impractical. As a result, research into biodiesel as a sustainable alternative for CI engines is critical.

Extensive studies indicate that biodiesel can be used in pure form or blended with conventional diesel without requiring engine modifications [4].

Biodiesel exhibits comparable brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC) to petroleum diesel in unmodified compression ignition engines (CIE), making it a practical replacement. Additionally, biodiesel offers significant environmental benefits, including lower exhaust emissions than conventional diesel [5]. As a renewable fuel composed of fatty acid methyl esters (FAME), biodiesel has a well-characterized emission profile, producing lower CO and CO_2 emissions and nearly eliminating SO_x emissions compared to petroleum diesel [6].

Jatropha curcas is considered a promising renewable energy crop due to its potential for biodiesel production and environmental benefits, such as soil improvement and pollution reduction [7]. Among extraction methods, screw press extraction has yielded the highest oil output with superior properties. While Jatropha biodiesel can be used in blends up to B100 (pure biodiesel), B20 blends demonstrated the best performance, with only a 9% decrease in engine efficiency compared to diesel fuel [8]. Additionally, Jatropha oil is a viable feedstock for jet biofuel (JBF), offering significant greenhouse gas reductions compared to conventional jet fuel. However, challenges such as feedstock availability and cost competitiveness remain [9].

One-dimensional computational fluid dynamics (CFD) engine simulation software, such as Ricardo WAVE, plays a crucial role in optimizing engine performance by reducing development time through virtual modeling. Once validated, these models allow for optimization of engine parameters before physical prototypes are built [10].

Ricardo WAVE has been used to analyze the effects of a diesel particulate filter (DPF) and biodiesel fuel on exhaust emissions. In a simulation of a Kirloskar TV-1 engine, the DPF significantly reduced harmful pollutants such as CO, HC, and NO_x compared to an unfiltered system. While biodiesel also contributed to emission reduction—B5 to B20 blends lowered CO emissions by 5%—it slightly increased NO_x levels. Overall, the DPF proved more effective in curbing emissions [11].

Additionally, Ricardo WAVE has been employed to determine the optimal blend ratio of Tamanu biodiesel for the Kirloskar TV-1 engine. A B20 (20% Tamanu biodiesel) blend resulted in a 12.2% reduction in CO emissions and a 6.4% decrease in HC emissions compared to diesel, while maintaining similar engine performance. These results suggest that B20 Tamanu biodiesel is a viable option for reducing emissions from compression ignition (CI) engines without compromising efficiency [12].

Furthermore, Ricardo WAVE has been used to explore the performance of a Honda engine fueled by gasoline and compressed natural gas (CNG) under partial throttle conditions. While engine data typically focuses on full-throttle operation, real-world driving often involves partial-throttle usage. This study examines engine behavior at 25%, 75%, and 100% throttle openings, combining experimental data with engine modeling to assess the impact of throttle position on torque, power, and emissions. These findings provide valuable insights into the real-world performance of gasoline and CNG engines, aiding in the optimization of engine design for improved efficiency and emissions control [13].

Numerous studies have utilized simulation software to analyze the performance characteristics of biodiesel blends in single-cylinder diesel engines by varying RPM. However, limited research has focused on evaluating performance characteristics by varying the load. This study aims to bridge this gap by comprehensively assessing the performance of Jatropha biodiesel blends in a single-cylinder diesel engine using a simulation-based approach.

2. Method and methodology

A simulation model was performed in Ricardo WAVE engine software. The model used in this research is shown in Figure 1.

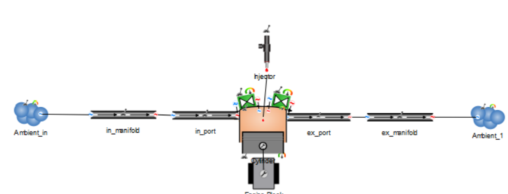

Figure 1: Engine Model in Ricardo WAVE

The components used for the model are: Ambient, inlet manifold, intake and exhaust port, intake and exhaust valve, fuel injector, engine cylinder and the engine block. Ambient in is the surrounding atmosphere of the engine. It consists of the type of ambient, discharge coefficient and the initial conditions of the fluid. In this model, the ambient type and discharge coefficient are default. The initial fluid conditions consist of pressure, temperature and initial velocity of the surrounding air. In this model, the initial pressure of air is 1 bar, the initial temperature is 300 k and the air has no initial velocity.

The inlet manifold is of circular duct type having a left and right diameter of 42 mm and 30.48 mm respectively. The overall length of the inlet manifold duct is 250 mm with a discretization length of 30 mm. Both the inlet and exhaust manifold duct have 0-degree bend angle. The discharge coefficients and pressure loss are used auto for both the manifolds. The initial fluid conditions are the same as the ambient conditions. The exhaust manifold is the same as the inlet manifold and has left and right diameters of 30.76 mm and 42 mm respectively. The overall length of the exhaust manifold duct is 250 mm.

The intake and exhaust ports serve as the ducts or pipes that connect to the intake and exhaust manifold ducts, respectively. Air flows from the ambient environment into the intake manifold and then into the intake port. The intake port features a left diameter of 30.48 mm, a right diameter of 33 mm, an overall length of 153.12 mm, a discretization length of 30 mm, and a bend angle of 75 degrees. Similarly, the exhaust port has a left diameter of 31 mm, a right diameter of 30.76 mm, an overall length of 153.12 mm, a discretization length of 30 mm, and a bend angle of 75 degrees. All other coefficients, losses, and boundary conditions are maintained as constantly provided by the software.

2.1. Intake valve

The intake valve is a lift-type valve with a left-to-right flow orientation. A single valve is used in the model, with a diameter of 33 mm. The valve lift cycle spans 355.5 degrees, meaning it begins lifting at a crank angle of 355.5 degrees. A lift multiplier of 1.414 is applied, with a maximum lift of 12.5 mm. The lift multiplier of 1.414 reflects the combined influence of the crankshaft-to-camshaft rotation ratio and rocker arm movement. The flow coefficient profile follows a standard valve flow coefficient profile provided by the software. The valve lift profile is illustrated in Figure 2.

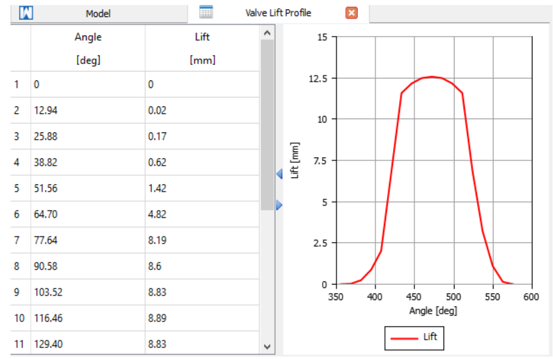

Figure 2: Intake valve lift profile

2.2. Exhaust valve

The exhaust valve is a lift-type valve with a left-to-right flow orientation. A single valve is used in the model, with a diameter of 31 mm. The valve lift cycle spans 144.5 degrees, beginning at a crank angle of 144.5 degrees. A lift multiplier of 1 is applied, with a maximum lift of 8.64 mm. Since the exhaust valve lift is lower than the inlet valve lift, a lift multiplier of 1 is applied. The flow coefficient profile follows a standard valve flow coefficient profile provided by the software. The valve lift profile is shown in Figure 3.

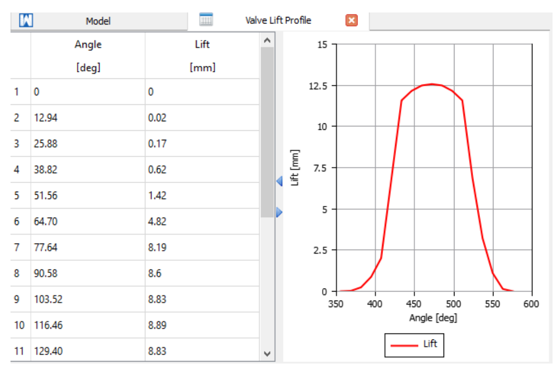

Figure 3: Exhaust Valve lift profile

2.3. Fuel injector

The fuel injector is responsible for delivering fuel into the cylinder. The model uses a Total Fuel-Air Ratio type injector, where the fuel/air ratio and start of injection are specified as F/A and SOI variables. The injection pressure is 220 bar, with a mixture temperature of 350 K. The injector has a 0.3 mm nozzle diameter, 0 mm_3 sac volume, and a spray spread angle of 40 degrees.

2.4. Cylinder

The engine cylinder has a bore of 87.5 mm and a stroke length of 110 mm. The clearance height is 2 mm, and the engine operates at a compression ratio of 17.5. The connecting rod length is 234 mm, with a wrist pin offset of 0.1 mm.

The initial component temperatures in the simulation are:

- Piston: 530 K
- Liner: 570 K
- Head: 580 K
- Intake Valve: 580 K
- Exhaust Valve: 580 K

The model utilizes Diesel Weibe Combustion, and all other properties follow the software's default settings. The default settings used on the combustion model are as follows:

2.4.1. Weibe function parameters

- Burn duration: 50° CA
- Shape factor (m): 2.0
- Efficiency factor (a): 5.0
- Combustion efficiency: 98%
- Heat transfer model: Woschni correlation
- Turbulence model: RNG k–ε model
- Equivalence ratio: 1.2
- Ignition delay model: Hardenberg and Hase correlation
- Cylinder wall temperature: 600 K

2.5. Engine block

The engine block defines key engine geometry and properties, with the cylinder connected to it. The engine configuration is inline, and the mixture type is spray-guided (direct injection). The engine is a single-cylinder, four-stroke design operating at 1500 RPM, cycling through intake, compression, power, and exhaust strokes. The reference conditions are 300 K temperature and 1 bar pressure. Friction and scavenging settings are set to default values as provided by the software.

2.6. Fuel properties

The software uses its default diesel fuel, with the following properties:

- Lower Heating Value (LHV): 44 MJ/kg
- Density at 15°C: 830 kg/m^3
- Viscosity at 40°C: 2.7 mm^2/s
- Cetane Number: 47
- Chemical Formula: $C_{12}H_{23}$
- Specific Heat Capacity: 2.1 kJ/(kg·K)
- Thermal Conductivity: 0.14 W/(m·K)

The properties of Jatropha biodiesel used in the software are as follows [14];

- Lower Heating Value (LHV): 36 MJ/kg
- Density at 15°C: 890 kg/m^3
- Viscosity at 40°C: 4.9 mm^2/s
- Cetane Number: 54
- Chemical Formula: $C_{19}H_{36}O_2$
- Specific Heat Capacity: 2.04 kJ/(kg·K)
- Thermal Conductivity: 0.17 W/(m·K)

2.7. Biofuel blend preparation

Ricardo Wave software allows users to create blended fuels via Command Prompt. A new fuel file can be generated by specifying the blend ratio of two or more predefined fuels. The software provides a standard command-line script for this process.

Using this script, users can define the fuels to be blended and input their respective blend percentages. Once executed, Ricardo Wave generates a fuel file incorporating the specified fuel properties. The command format is as follows:

```
buildfuel -d fuel1.dat fuel2.dat -f
"fraction of fuel1" "fraction of fuel2" -p
"new_blended_file_name"
```

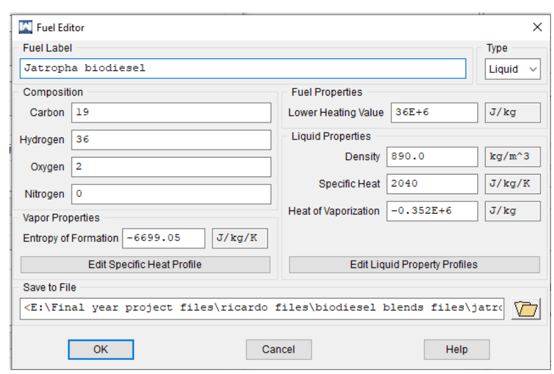

Figure 4: Fuel Editor while preparing Blends of Jatropha Biodiesel

3. Results and discussion

3.1. Performane parameters

Figure 5 illustrates the relationship between IP and Load (kg) for an engine operating at a constant RPM. As the load increases from 0.5 kg to 12 kg, the IP varies as follows:

- Diesel: 1.59 kW to 4.62 kW

- 5JBME: 1.60 kW to 4.89 kW
- 10JBME: 1.58 kW to 5.08 kW
- 20JBME: 1.53 kW to 5.15 kW

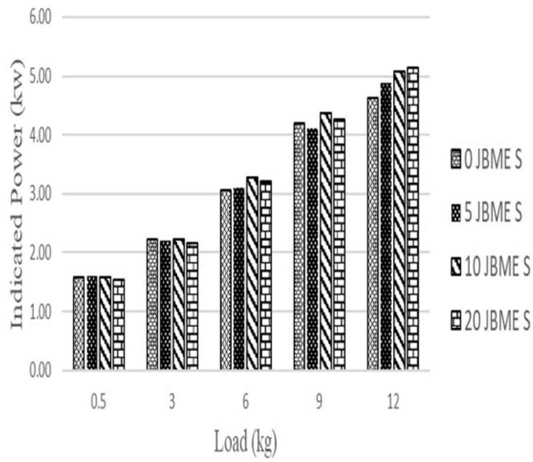

Figure 5: Relation of Indicated Power with Load

Biodiesel blends generally produce higher indicated power compared to conventional diesel. As the blending ratio increases, indicated power also rises. This increase is primarily attributed to higher fuel consumption, a higher cetane number, and a lower calorific value. The higher fuel consumption compensates for the lower energy content of biodiesel, while the higher cetane number enhances combustion characteristics by promoting smoother and more efficient ignition. Additionally, the lower calorific value leads to increased fuel injection to maintain the required energy output, further contributing to improved combustion efficiency and ultimately resulting in greater indicated power [15].

Figure 6 presents the relationship between Mechanical Efficiency (%) and Load (kg) for an engine operating at a constant RPM. As the load increases from 0.5 kg to 12 kg, mechanical efficiency varies as follows:

- Diesel: 8.94% to 75.08%
- 5JBME: 21.45% to 77.02%
- 10JBME: 20.10% to 74.84%
- 20JBME: 9.66% to 68.71%

Blends of biodiesel generally exhibit higher indicated power than conventional diesel. This trend becomes more pronounced as the blending ratio increases, primarily due to three key factors: higher fuel consumption, a higher cetane number, and a lower calorific value.

Since biodiesel has a lower calorific value than diesel,

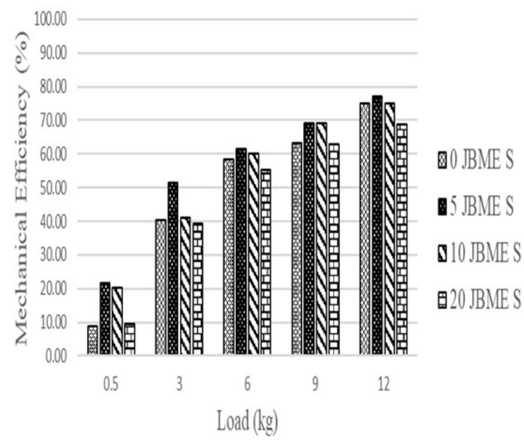

Figure 6: Relation of Mechanical Efficiency with Load

more fuel is required to generate the same amount of energy. As a result, the engine compensates by increasing fuel injection, which leads to a rise in indicated power.

Biodiesel typically has a higher cetane number than conventional diesel, meaning it ignites more readily upon injection. This improved ignition quality enhances the combustion process, reducing ignition delay and leading to more efficient fuel burn, ultimately increasing indicated power.

While biodiesel has a lower energy content per unit mass compared to diesel, the engine compensates by injecting a greater quantity of fuel. This increased fuel input results in more energy release during combustion, contributing to higher indicated power output.

Overall, the combination of improved combustion characteristics and increased fuel injection leads to enhanced indicated power when using biodiesel blends. As the proportion of biodiesel in the blend increases, these effects become more significant, further boosting the engine's indicated power [16].

Figure 7 illustrates the relationship between BSFC (kg/kW h) and Load (kg) at a constant RPM. As the load increases from 0.5 kg to 12 kg, BSFC values are as follows:

- Diesel: 1.91 kg/(kW·h) to 0.270 kg/(kW·h)
- 5JBME: 1.91 kg/(kW·h) to 0.29 kg/(kW·h)
- 10JBME: 1.90 kg/(kW·h) to 0.31 kg/(kW·h)
- 20JBME: 1.88 kg/(kW·h) to 0.30 kg/(kW·h)

Brake-specific fuel consumption (BSFC) decreases as engine load increases because brake power rises more rapidly than the fuel mass injected. This improvement

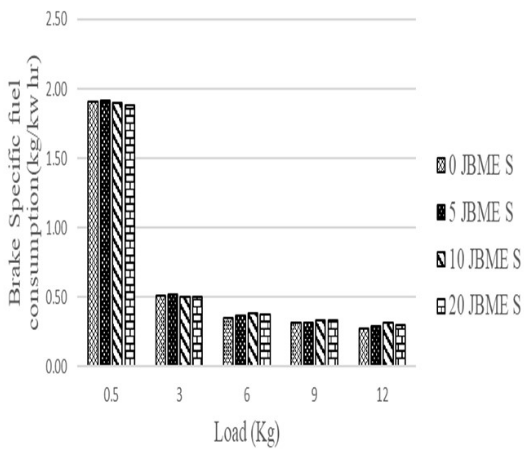

Figure 7: Relation of BSFC with Load

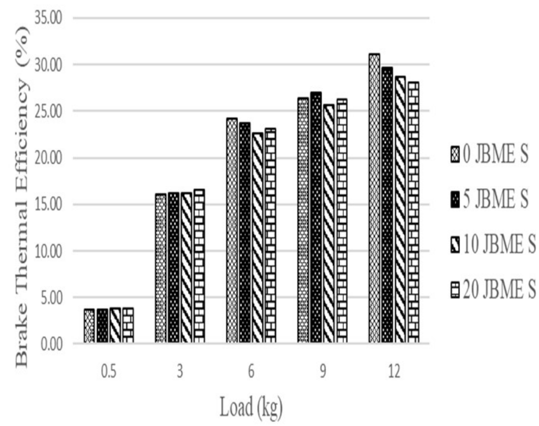

Figure 8: Relation of Brake Thermal Efficiency with load

in fuel efficiency occurs due to better utilization of the injected fuel, as the engine operates closer to its optimal performance range. At higher loads, the combustion process becomes more efficient, with improved air-fuel mixing, reduced heat losses, and higher cylinder pressures, all contributing to lower BSFC.

Despite the lower calorific value of Jatropha biodiesel compared to conventional diesel, BSFC remains relatively consistent across both diesel and biodiesel blends. This is primarily due to the oxygen content in Jatropha biodiesel, which enhances the combustion process. The additional oxygen promotes more complete fuel combustion, reducing unburned hydrocarbons and improving thermal efficiency. This compensates for the lower energy density of Jatropha biodiesel, ensuring that fuel consumption does not significantly increase despite the biodiesel's lower calorific value.

Overall, while biodiesel blends typically require slightly more fuel to produce the same energy output as diesel, the improved combustion characteristics of Jatropha biodiesel help maintain comparable BSFC levels, making it a viable alternative fuel option [16].

Figure 8 shows the relationship between Brake Thermal Efficiency (BTE) and Load (kg). As load increases from 0.5 kg to 12 kg, BTE values are as follows:

- Diesel: 3.72% to 31.01%
- 5JBME: 3.67% to 29.65%
- 10JBME: 3.77% to 28.68%
- 20JBME: 3.82% to 28.08%

Biodiesel blends generally exhibit lower brake thermal efficiency (BTE) than conventional diesel due to their lower calorific value, which means they contain less energy per unit of fuel. As a result, more biodiesel fuel must be injected to generate the same power output, leading to a slight reduction in overall efficiency.

However, as engine load increases, BTE improves because brake power increases at a higher rate than fuel mass consumption. At higher loads, the engine operates under optimal conditions, with improved air-fuel mixing, higher in-cylinder pressures, and elevated combustion temperatures. These factors enhance combustion efficiency, ensuring that more of the fuel's energy is converted into useful work, thereby increasing BTE.

At very high loads, the benefits of improved combustion efficiency begin to diminish. Excessive fuel injection can lead to incomplete combustion due to insufficient time for complete oxidation of the fuel. Additionally, increased frictional and thermal losses within the engine components can offset the gains in efficiency. As a result, beyond a certain threshold, BTE starts to decline due to the combined effects of incomplete combustion, higher exhaust emissions, and increased mechanical losses.

Thus, while biodiesel blends inherently have a lower BTE compared to diesel, they still show improved efficiency at moderate-to-high loads. However, careful load management is necessary to prevent efficiency losses at extreme operating conditions [17].

Figure 9 illustrates the relationship between Exhaust Gas Temperature (EGT) (°C) and Load (kg). As load increases from 0.5 kg to 12 kg, EGT values are as follows:

- Diesel: 130.3°C to 245.0°C
- 5JBME: 131.5°C to 259.1°C
- 10JBME: 130.3°C to 269.1°C

- 20JBME: 129.2°C to 276.4°C

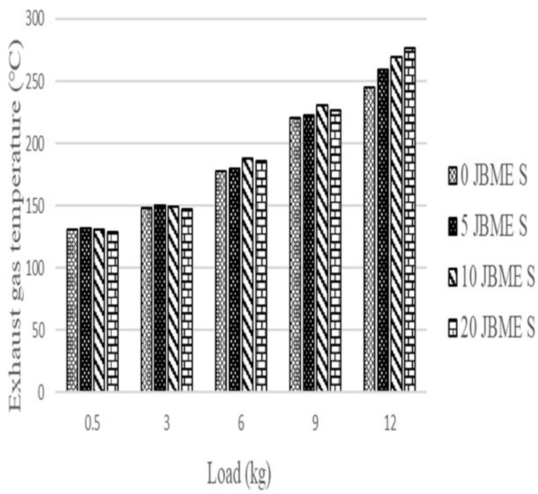

Figure 9: Relation of Exhaust Gas Temperature with Load

At lower biodiesel blend ratios, exhaust gas temperature (EGT) tends to be lower compared to diesel. This is primarily because biodiesel, particularly at lower concentrations, tends to burn more completely than diesel. The higher oxygen content in biodiesel promotes more efficient combustion, ensuring that a greater portion of the fuel's energy is converted into usable power rather than being lost as heat. As a result, there is a reduction in heat loss, leading to lower exhaust temperatures. This improved combustion efficiency helps keep the engine's EGT lower at lower biodiesel blend ratios.

However, as the biodiesel blend ratio increases, EGT typically rises. This is due to the lower calorific value of biodiesel, meaning it contains less energy per unit of fuel compared to conventional diesel. To maintain the same power output, more fuel is injected into the combustion chamber when using higher biodiesel blends. The increased fuel consumption results in higher exhaust temperatures because more fuel is being burned, generating more heat. Additionally, the lower energy content of biodiesel means that more fuel must be combusted to extract the same amount of energy, further raising exhaust temperatures.

In summary, at lower biodiesel blend ratios, the engine benefits from more complete combustion, resulting in lower EGT. However, as the blend ratio increases, the reduced calorific value of biodiesel necessitates more fuel injection to produce the required power, leading to higher EGT due to the increased combustion heat [18].

4. Conclusion

The simulation model of the Kirloskar engine with fatty acid biodiesel blends (5% to 20% by volume) was successfully developed in Ricardo Wave software. Performance analysis confirmed that the engine can operate on these biodiesel blends without any modifications.

The performance deviations observed across different biodiesel blends are influenced by the inherent properties of biodiesel and its impact on engine operation. The deviations were calculated as the percentage difference between the engine's performance on conventional diesel and the JBME blend, relative to conventional diesel data.

4.1. Indicated Power (IP)

- Deviations for 5 JBME, 10 JBME, and 20 JBME were 1.17, 4.16, and 2.32, respectively.
- The higher IP for 5 JBME is likely due to improved combustion efficiency from the oxygenated nature of biodiesel.
- However, at 20 JBME, IP decreases due to the lower calorific value, reducing overall energy output.

4.2. Brake Specific Fuel Consumption (BSFC)

- Deviations for 5 JBME, 10 JBME, and 20 JBME were 2.44, 5.13, and 4.31, respectively.
- Higher BSFC at increased blend ratios reflects biodiesel's lower energy density. More fuel is required to generate the same brake power, leading to increased fuel consumption.

4.3. Exhaust Gas Temperature (EGT)

- Deviations for 5 JBME, 10 JBME, and 20 JBME were 1.95, 4.10, and 3.69, respectively.
- Higher EGT with increased biodiesel content is due to more complete combustion from the oxygen present in biodiesel. However, at higher blends, excess fuel combustion and lower energy value contribute to further temperature rise.

4.4. Mechanical efficiency

- Deviations for 5 JBME, 10 JBME, and 20 JBME were 36.88%, 27.74%, and -1.87%, respectively.
- 5 JBME and 10 JBME show improved efficiency, possibly due to biodiesel's lubricating properties, which reduce frictional losses.

- However, at 20 JBME, efficiency declines due to reduced indicated power without a proportional increase in brake power.

4.5. Brake Thermal Efficiency (BTE)

- Deviations for 5 JBME, 10 JBME, and 20 JBME were -0.95%, -2.99%, and -1.73%, respectively.
- The decrease in BTE across all blends is due to biodiesel's lower calorific value, requiring more fuel to maintain the same brake power.
- At higher loads, incomplete combustion in higher biodiesel blends may further reduce thermal efficiency.

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