Combustion and vibration characteristics of variable compression ratio direct injection diesel engine fuelled with diesel-biodiesel and alcohol blends

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Abstract
The objective of the present investigation is to explore the influence of ternary (diesel-biodiesel-alcohol) fuel blends on the combustion and vibration parameters of a variable compression ratio compression ignition engine. Kusum seed oil biodiesel and isobutyl alcohol were blended with conventional diesel to make a ternary fuel. The blend of biodiesel-diesel (B20) was made in proportion of 20% and 80% by volume, respectively. Furthermore, isobutyl alcohol was added at diverse proportions (ie, 0.25%, 0.5%, 0.75%, and 1%). The investigation was carried at different compression ratios (CRs), namely, 16.5, 17.5, and 18.5. The study shows that, upon the addition of isobutyl alcohol, the combustion characteristics (ie, cylinder pressure [CP] and net heat release rate [NHRR]) are significantly enhanced, whereas the mechanical vibration level maintains stable. The CP and NHRR of B20 + 1% isobutyl alcohol are greatly improved for corresponding values of 4.55% and 8.39%, respectively, except for the conventional diesel at CR 18.5. Furthermore, the root mean square velocity (vibration) decreases when increasing the quantity of isobutyl alcohol and attained a minimum with B20 + 1% isobutyl alcohol. The experimental results show that the isobutyl alcohol up to 1% with diesel-biodiesel blends can be used in the CI engine with no further adjustments.

KEYWORDS
combustion, compression ratio, Kusum seed oil biodiesel, RMS velocity, transesterification

Abbreviations: θ, crank angle (°); l, length of connecting rod (m); ΔCA, uncertainty in crank angle; ΔW, uncertainty in load; ΔP, uncertainty in pressure; ΔN, uncertainty in speed; ΔT, uncertainty in temperature; ΔRMS velocity, uncertainty in vibration; ADC, analog to digital converter; B20, KSOME 20% in diesel; CHRR, net heat release rate (J/oCA); CI, compression ignition; CP, cylinder pressure (bar); CR/CRs, compression ratio/compression ratios; D, cylinder bore (m); FFT, fast Fourier transforms; IP, injection pressure; KSOME, Kusum seed oil methyl ester; LDV, laser Doppler vibrometer; m/sec, meter/second; n, number of points within a time period; NaOCH3, sodium methoxide; NHRR, cumulative heat release rate (J/oCA); PDV, Polytec Doppler vibrometer; r, crank radius (m); RMS, root mean square; V, instantaneous cylinder volume (m3); V(t), velocity with respect to time; Vc, clearance volume (m3); VCR, variable compression ratio; VRMS, RMS velocity.

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1 | INTRODUCTION

Increasing costs, exhaustion of fossil fuels, and deficient contribution have formed immense concern on alternative fuel sources. In the existing scenario, several kinds of research have been centered on the need of using biodiesel as an alternative renewable fuel for compression ignition (CI) engine application owing to the quick exhaustion of crude oil, growing natural greenhouse gasses, and rising cost of fuel. Fossil-based fuels causing harmful gas emission and depleting day by day and therefore, the fuel researchers are focusing on the usability of renewable and green energy sources such as biodiesel and alcohol. Among all the energy devices, diesel engines have tremendous characteristics such as high thermal efficiency, superior utilization of air and fuel blend, lower fuel consumption, higher compression ratio (CR), and consistency. But, the major drawback with diesel engines is that they emit huge amounts of exhaust emissions, namely, carbon monoxide (CO), unburnt hydrocarbons (UHC), unburnt nitrogen oxides (NOx), and particulate matter. Since the use of road transport vehicles requires more fuel usage and it produces exhaust gases in larger quantities than other modes of transportation. Indian road transport is one of the largest and multipart transport systems in the world which liberates enormous exhaust emissions. Numerous studies have been carried out on the influence of biodiesel and their blends on the life cycle environment. Hence, the biodiesel could be extended as a favorable alternate feedstock in the diesel engine applications. Biodiesel is a superior oxygenated fuel and it has improved cetane number intended for better combustion characteristics. Jaikumar et al. carried out an experimental study on variable compression ratio (VCR) direct injection CI engine to evaluate engine performance, combustion, and emission parameters running with the blends of Niger seed oil biodiesel. They revealed that the combustion characteristics were slightly better than conventional diesel. CO, UHC, and smoke emissions were observed minor as the NOx has increased. The foremost drawback of diesel engines is huge noise and vibrations which could develop mainly because of engine knocking. Hence, the reduction in vibrations and noise intensity is possible using biodiesel blends. A few investigations have been made to estimate the noise and vibrations relating to combustion characteristics. In addition, Jaikumar et al. assessed the vibration and combustion noise level of the VCR CI engine using diesel-Niger seed oil biodiesel and hydrogen blends. They noticed that the level of vibration and noise was reduced with biodiesel and in dual-fuel operation as well. At higher CRs it was noticed higher vibrations and noise. How et al. carried out an analysis of vibration on a diesel engine fueling with different blend proportions of diesel and biodiesel. The greatest reduction (13.7%) in root mean square (RMS) acceleration was observed with B20. Ong et al. used blends of *Calophyllum inophyllum* biodiesel on CI engine for evaluating the vibration analysis. Their study revealed that the B20 has noticed lesser RMS acceleration than leftover test fuels. Furthermore, numerous researches have been projected to progress the physicochemical properties and to bring down the exhaust emissions of diesel blended biodiesel using different additives. Commonly used oxygenated fuel additives are di-tertiary butyl peroxide, methoxyethyl acetate, tert-butyl alcohol, ethylene glycol monoacetate, dimethoxymethane, and dimethyl carbonate, n-butanol, bioethanol, isobutanol, propane, and so on. Kumar et al. used di-tertiary butyl peroxide added cottonseed oil methyl ester. They concluded that the combustion characteristics were slightly improved with additive-ethanol blended biodiesel. Shah and Ganesh used straight vegetable oils, namely, Karanja oil and Sunflower oil in their investigation with two different fuel additives. Cylinder pressure (CP) and net heat release rate (NHRR) was enhanced with both the fuels upon the addition of additives. But, NOx was reduced only with Karanja oil. Ali et al. reviewed the possibility of diverse biodiesel blends with chemical additives on properties, engine performance, and exhaust emissions. Upon adding up of chemical additives, the fuel properties were marginally improved. Furthermore, the performance of engine was also slightly better by diminishing exhaust emissions. Saridemir and Ağbulut used cottonseed oil biodiesel for assessing the CI engine process parameter. They concluded that the combustion such as CP and NHRR were noticed slightly higher for B20 and B40 apart from diesel whereas for B10 it was observed least. Furthermore, the vibration and noise intensity was obtained minimum for B20 than leftover test fuels. Ağbulut et al. experimented on a variable speed CI engine in use with diesel, biodiesel, and ethanol blends. They stated that the addition of ethanol was improved the CP and NHRR while reduced the exhaust emissions. Ateşgül and Yılmaz investigated the effect of higher alcohol added (propanol, n-butanol, and 1-pentanol) waste cooking oil biodiesel blend (B20) on the CI engine. From their conclusion, the noticeable reduction in emission parameters (CO and NOx) was observed on adding up with alcohol while the UHC was increased. Yılmaz et al. investigated the effect of alcohol, diesel, biodiesel, and vegetable oil blends. Their study exposed that the greater potential to reduce the emissions of CO and NOx upon the dosage of alcohol. Yesilyurt and Aydın used diethyl ether oxygenated fuel additive in use with cottonseed biodiesel. They revealed that the emissions concerning CO, UHC, and NOx were reduced greatly. Yesilyurt et al. examined the influence of ternary mixes of safflower oil biodiesel-diesel and pentanol on the evaluation of CI engine process parameters. They conclude that the combustion was superior caused by the accessibility of more oxygen in pentanol.
Considering various past investigations, numerous researchers have been centered on the usage of different alcohol-diesel-biodiesel blends in diesel engine applications. Extensive gathering of alcohol fuel additives has shown promising outcomes concerning the combustion and emission characteristics. But, no investigations were performed using isobutyl alcohol as an oxygenated fuel additive in CI engine and thus the investigation with isobutyl alcohol additive can be an entirely novel approach. In this regard, the current experimental study was concentrated on the combustion and vibration characteristics of CI engine operating with the blends of diesel-biodiesel-isobutyl alcohol.

2 | MATERIALS AND METHODOLOGY

2.1 | Biodiesel production and physicochemical properties

Biodiesel was produced from raw Kusum seed oil by a chemical reaction process to be an exact transesterification reaction. In the beginning, the raw Kusom oil with a quantity of 600 mL was taken in a round bottom container and continued heating to a temperature of 60°C. Subsequently, a methanol-catalyst mixture (150 mL methanol and 1.5 wt% of NaOCH₃) solution was put into the oil. The reaction was sustained employing stirring apparatus for an hour by retaining a steady-state temperature of 65°C. Following this reaction, the transesterified mixture was shifted to separating conical funnel and kept it for 12 to 15 hours to settle. After the settlement, the upper layer of the conical funnel covers the Kusum seed oil methyl ester while the glycerin sediments at the bottom of the flask. Latterly, the separated biodiesel was permitted to hot water washing treatment to take away the soaps from the biodiesel. This biodiesel was heated again to remove the moisture present in it. Test fuels were made ready by mixing B20 and isobutyl alcohol (2-methyl propane-1-OL or C₄H₁₀O) additive at different proportions. Fuel properties were and presented in Table 1.

2.2 | Experimental setup

The engine used in this investigation is a 4-stroke, single-cylinder, research diesel engine. Figure 1 depicts the schematic of experimental test arrangement. The biodiesel and diesel fuel tanks are provided separately in the experimental test setup. A fuel flow sensor is connected to the engine inlet to quantify fuel utilization. In the engine, an eddy current dynamometer was linked through a load controller. Individual sensors for measuring speed, load, pressure, and fuel are installed with the computerized set up with the engine. The combustion data was recorded using Enginesoft software. In addition to the above arrangement, Polytec Doppler vibrometer-100 is used separately to measure the vibration strength on the engine body fixed position through a laser beam. The laser beam was securely focused on the engine to get the signal. A two-channel fast Fourier transforms analyzer input signal can analyze in the vibsoft-20 software which can process the vibrations signals captured from the engine as per the required form. The complete engine set up specification is presented in Table 2.

The test fuels were prepared by using biodiesel, diesel, and isobutyl alcohol additive. The blending was performed using an ultrasonicator. Before experimenting, the devices were calibrated and checked the condition of the engine. The uncertainty of measuring instruments was depicted in Table 3. Whole experiments were carried out at different CRs of 16.5, 17.5, and 18.5, maximum load condition (100% load), uniform engine speed (1500 rpm), and an injection pressure of 200 bar. B20 was prepared by mixing 20% (by volume) of biodiesel and 80% (by volume) of conventional diesel. Furthermore, the isobutyl alcohol was added to B20 at different proportions of 0.25%, 0.5%, 0.75%, and 1%, respectively. The test fuels named as diesel, B20, B20+0.25% isobutyl alcohol, B20+0.5% isobutyl alcohol, B20+0.75% isobutyl alcohol, and B20+1% isobutyl alcohol. Experiments were sustained repeatedly thrice and the set values were offered as a graphical representation.

NHRR was calculated using first law of thermodynamics as per the subsequent Equation (1).

\[
\frac{\delta q}{\delta \theta} = \frac{1}{\gamma - 1} \frac{\delta p}{\delta \theta} + \frac{\gamma}{\gamma - 1} \frac{\delta V}{\delta \theta} + \frac{\delta q_{\text{Heat}}}{\delta \theta},
\]

where \( \gamma = \frac{c_p}{c_v} \)

\[
V = V_c + A.r \left( 1 - \cos \left( \frac{\pi \theta}{180} \right) + \frac{1}{2} \left( 1 - \sqrt{1 - \lambda^2 \sin^2 \left( \frac{\pi \theta}{180} \right) } \right) \right),
\]
| Fuel property                        | Method        | ASTM limit | Diesel | B100 | B20  | B20 + 0.25% isobutyl alcohol | B20 + 0.5% isobutyl alcohol | B20 + 0.75% isobutyl alcohol | B20 + 1% isobutyl alcohol |
|-------------------------------------|---------------|------------|--------|------|------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Relative density (kg/m³)            | ASTM D-1298   | 860-900    | 832    | 884  | 876  | 875                         | 873                         | 872                         | 869                         |
| Kinematic viscosity (cSt)           | ASTM D-445    | 2.3-6      | 3.22   | 4.2  | 3.8  | 3.75                        | 3.71                        | 3.68                        | 3.67                        |
| Flash point (°C)                    | ASTM D-92     | 132 (min)  | 53     | 155  | 79   | 78                          | 77                          | 77                          | 75                          |
| Calorific value (kJ/kg)             | ASTM D-4809   | 42         | 44.8   | 41.25| 41.82| 41.83                       | 41.84                       | 41.88                       | 41.89                       |
| Cloud point (°C)                    | ASTM D-97     | 6 (max)    | 9      | 9    | 6    | 6                           | 6                           | 7                           | 7                           |
| Cetane index                        | ASTM D-976    | 47 (min)   | 50     | 59   | 56   | 56                          | 55                          | 55                          | 55                          |
| Pour point (evaporation)            | ASTM D-97     | –          | –16    | –8   | –9   | –10                         | –10                         | –11                         | –12                         |
**FIGURE 1**  Schematic representation of experimental setup

1. Fuel sensor 2. Dynamometer 3. Load controller 4. Pressure sensor 6. Speed sensor 5. Crank angle sensor 7. Laser Doppler Vibrometer (LDV) 8. Computer

**TABLE 2**  Engine set-up specifications

| Constraint       | Depiction                          |
|------------------|------------------------------------|
| Type             | TAF-1 (Kirloskar)                  |
| Cylinders        | Single                             |
| Bore/Stroke      | 87.5/110 mm                        |
| Maximum brake power | 3.5 kW                            |
| Maximum speed    | 1500 rpm                           |
| Injection pressure | 200 bar                           |
| CRs              | 16.5, 17.5, and 18.5               |
| Combustion software | Enginesoft                      |
| LDV make         | PDV-100 portable digital vibrometer |
| Vibration software | USB based, dual channel Vibrosoft-20 |

Abbreviations: CRs, compression ratios; LDV, laser Doppler vibrometer.

**TABLE 3**  Accuracy of instruments

| Characteristic            | Range       | Uncertainty (%) |
|---------------------------|-------------|-----------------|
| Load                      | 0-50 kg     | ±0.2            |
| Speed                     | 1200-1800 rpm | ±1             |
| Pressure                  | 0-350 bar   | ±0.2            |
| Crank angle               | 1° resolution | ±0.1         |
| Temperature               | 0°C-100°C   | ±1              |
| Vibration (RMS velocity)  | –           | ±0.6            |

Abbreviation: RMS, root mean square.

\[
\frac{\delta V}{\delta \theta} = \left( \frac{\pi A}{180} \right) r \left\{ \sin \left( \frac{\pi \theta}{180} \right) + \frac{\lambda^2 \sin^2 \left( \frac{\pi \theta}{180} \right)}{2 \times \sqrt{1 - \lambda^2 \sin^2 \left( \frac{\pi \theta}{180} \right)}} \right\},
\]

where \( \lambda = \frac{l}{r}, A = \frac{\pi}{4} D^2 \)
The analyses were rehashed thrice and the mean qualities were introduced in the charts. RMS is characterized for comparing vibrations for different test fuels. The mean values of total velocity in RMS were compared. The following Equation (1) is used to calculate RMS velocity

$$V_{\text{RMS}} = \left[ \frac{1}{n} \sum_{j=1}^{n} V^2(t_j) \right]^{\frac{1}{2}}.$$ (2)

The uncertainty about measured quantities such as load, speed, CP, and the crank angle was calculated as follows.\textsuperscript{22}

$$\text{Uncertainty} = \sqrt{\left( \Delta W \right)^2 + \left( \Delta N \right)^2 + \left( \Delta P \right)^2 + \left( \Delta CA \right)^2 + \left( \Delta T \right)^2 + \left( \Delta \text{RMS velocity} \right)^2}.$$ (3)

The calculated total uncertainty is approximately 1.76%.

3 | RESULTS AND DISCUSSION

The combustion and vibration characteristics of different isobutyl alcohol added test fuels were assessed. All the analysis was carried out at maximum engine load (100% load).

3.1 | Combustion characteristics

The combustion parameters specifically CP and NHRR of different test fuels prepared by isobutyl alcohol and biodiesel blend.

3.1.1 | Cylinder pressure

Figure 2 depicts the variation in peak CP against the crank angle. It was seen that the CP of B20 was enhanced slightly than conventional diesel. This improvement was due to having more oxygen content, cetane number, and better atomization of fuel ensuing a significant reduction in ignition delay. Besides, more fuel accumulation during the ignition delay directed the improved CP.\textsuperscript{6,16} Furthermore, the progressive increase in CP of B20 was observed upon adding together with isobutyl alcohol. Although alcohols exhibit lower cetane numbers, the peak CP of the B20 and isobutyl alcohol blend was noticed much advanced compared with normal diesel. Since the biodiesel and alcohols give progressively due to containing more oxygen. Besides, the latent heat of vaporization of alcohol is high and thus the CP was increased.\textsuperscript{14,17,23} Besides, the CP was improved at elevated CRs despite the fuels.

The foremost reason meant for this improvement was owing to the occurrence of extra oxygen throughout the compression process and the extra secondary fuel ease of use.\textsuperscript{6,24} CP against the CR of all the fuels was depicted in Figure 3. It was observed that the utmost peak CP was attained at CR18.5 with a 1% isobutyl alcohol additive.
3.1.2 Net heat release rate

Figure 4 illustrates the disparity in NHRR concerning the crank angle. The NHRR of B20 has shown somewhat more than normal diesel fuel due to more fuel accumulation during the ignition delay period. The minor ignition delay and extreme oxygen content of biodiesel made this possible. Hence, the mixture burns more quickly in the premixed combustion stage itself than in the diffusion combustion stage and consequently, the NHRR was reached the maximum. It can also be seen that the NHRR of the isobutyl alcohol added B20 was more compared with the base petro-diesel. This was owing to having the alcohol with higher latent heat of vaporization and more oxygen.

Despite the fact that the alcohols having lower heating values and longer ignition delay, the ignition of fuel aggregated in the combustion chamber is rapid resulting in more NHRR. Furthermore, Figure 5 depicts the peak NHRR against the compression ratio.
the CR. NHRR was enhanced at higher CRs owing to more amount of secondary fuel present inside the cylinder which was also a result of the availability of oxygen in huge quantity. CR18.5 noticed higher values of NHRR meant for every individual fuel being tested as above. The increase of NHRR resulted in a domino effect on the rise of CP. At elevated CRs, the NHRR was enhanced due to the superiority of oxygen existence within the combustion chamber. The trends were continual in a similar approach for all the fuels being tested as above. B20+ 1% isobutyl alcohol has noticed a higher value of NHRR than remaining fuel blends.

3.2 Vibration characteristics

The time-domain vibration characteristics of different isobutyl alcohol added B20 were discussed. Figure 6 depicts the variation in time-domain vibration (velocity) signature and Figure 7 shows the RMS velocity (vibration) at different CRs. Since one of the significant commitments for delivering vibration in a diesel engine is because of the knocking tendency which was determined by virtue of inappropriate combustion of fuel. In this manner, the advancement of vibration because of combustion assumes control over the remaining engine parts. The combustion efficiency of this ternary (diesel-biodiesel and isobutyl alcohol) fuel blends is finer due to superior ignition quality of biodiesel and more accessibility of oxygen in alcohol. Consequently, the total combustion happens and results in the lesser tendency of knocking.

![Time variation of vibration](image-url)
FIGURE 7  RMS velocity at different compression ratios.
RMS, root mean square

TABLE 4  Combustion and vibration characteristics of diesel-biodiesel and alcohol blends

| Parameter                  | CR          | CP (bar) | NHRR (J/o) | RMS velocity (m/s) |
|----------------------------|-------------|---------|------------|--------------------|
|                            | CR16.5      | CR17.5  | CR18.5     | CR16.5             | CR17.5             | CR18.5             | CR16.5 | CR17.5 | CR18.5 |
| Diesel                     | 46.52       | 49.1    | 51.82      | 49.55              | 52.29              | 55.64              | 0.07551 | 0.09512 | 0.12486 |
| B20                        | 46.97       | 49.43   | 51.98      | 49.59              | 52.19              | 55.81              | 0.07112 | 0.09252 | 0.11733 |
| B20 + 0.25% isobutyl alcohol| 49.23       | 51.33   | 53.48      | 53.29              | 55.41              | 57.86              | 0.07038 | 0.08931 | 0.09868 |
| B20 + 0.5% isobutyl alcohol | 49.8        | 51.67   | 53.77      | 55.24              | 58.62              | 59.75              | 0.06823 | 0.08153 | 0.0875 |
| B20 + 0.75% isobutyl alcohol| 50.21       | 51.83   | 53.92      | 55.97              | 58.76              | 60.31              | 0.06322 | 0.07846 | 0.08387 |
| B20 + 1% isobutyl alcohol  | 50.73       | 52.63   | 54.18      | 56.16              | 58.76              | 60.31              | 0.06271 | 0.07312 | 0.08268 |

Abbreviations: CP, cylinder pressure; CR, compression ratio; NHRR, net heat release rate; RMS, root mean square.

It could be eminent that the RMS velocity (vibration) of B20 and isobutyl alcohol added diesel-biodiesel blend was lower than the conventional diesel due to their better combustion efficacy. Hence, the combustion superiority implies the reduction in vibration intensity.7,22,26 Furthermore, at upper CRs, the vibration signature has developed more inferable from the quick change in the CP. In this way, there is an essential impact on combustion chamber geometry (specifically the piston) rapidly due to the large thrust produced by combustion gases and thus, more fluctuations in piston moment occur resulting in enhanced vibrations.7 The equivalent trends stayed aware of the entire three CRs expected for all blends. The inferior vibration signature was observed was noticed for B20 + 1% isobutyl alcohol throughout all three CRs. Table 4 represents the values of CP, NHRR, and RMS velocities.

4  | CONCLUSIONS

In view of the accomplished test outcomes, the accompanying conclusions can be outlined below:

- The physicochemical properties of test fuels were determined as indicated by the ASTM standards.
- Combustion parameters to be specific CP and NHRR have improved with diesel-biodiesel and isobutyl alcohol blends. A similar increase in these combustion parameters was noticed with an increase in CRs as well. The maximum CP and NHRR were progressed enormously by 4.55% and 8.39%, respectively, at CR18.5 intended for B20 with 1% isobutyl alcohol.
- RMS velocity (vibrations) of diesel-biodiesel and isobutyl alcohol included blends was seen lower than conventional diesel. The most reduction in RMS velocity was noticed with B20 + 1% isobutyl alcohol by 2.52%. Furthermore, the vibration improvement was seen toward raised CRs disregarding all diesel-biodiesel and isobutyl alcohol.
This examination revealed that the combination of diesel-KSOME blend and isobutyl alcohol can be used with no adjustments in the VCR diesel engine.

However, the engine vibration at a higher CR is not preferable, it can be operated at a rated CR of 17.5.

Further studies can be performed for the assessment of engine performance and exhaust emissions derived resembling CO, CO₂, UHC, NOₓ, and smoke opacity by altering the CRs and the influence of injection operating pressure can also be studied. Finally, the computational fluid dynamic analysis can also be executed relating to combustion and emission for better validation of experimental outcomes.

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AUTHOR CONTRIBUTIONS

Jaikumar Sagari: Conceptualization; data curation; formal analysis; investigation; methodology; resources; supervision; validation; writing-original draft; writing-review and editing. Bhatti Sukhvinder Kaur: Data curation; investigation; methodology; supervision; writing-original draft; writing-review and editing. Srinivas Vadapalli: Conceptualization; methodology; supervision; validation; writing-original draft; writing-review and editing. Rajasekhar M: Formal analysis; methodology; validation; writing-original draft; writing-review and editing. Santosh Kumar L: Data curation; formal analysis; resources; writing-original draft; writing-review and editing.

CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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