Effect of Injection Timing on Vibration, Noise and Emission Characteristics of Dual Fuel Diesel Engine Using Karanja biodiesel-CNG blends

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Abstract

In this experimental study, we studied the synergistic effect of Injection Timing (IT) and five fuel fractions on the noise, vibration and emission aspects of a dualfuel diesel engine. Aswe varied ITbetween 19°, 23° and 27°, we maintained other operating conditions at a constant which were derived from theTOPSIS method,the theory of it is specified well in the research methodology section. Vibrations were found to be less while operating at IT 19° which got lowered on using D90KB10-C6, whereas same IT also kept exhaust [77.5 dB(A)] and combustion [89.1dB(A)] noise level in check on using same fuel fraction. The emission parameters of CO, HC and CO_2 were found to be high for advanced injection timing, NO_X and Smoke emissions were higher for advanced timing, which was caused by the usage of D90KB10-C6 showing the influence of additives (CNG) in curbing emission. Here the existing studies primarily focus on emissions and performance, while the simultaneous investigation of combustion-induced vibration and noise characteristics in dual-fuel CI engines remains limited. Hence, we conducted the complete analysis of the Diesel engine while hitting all the crucial parameters that represents the performance of the engine.

Keywords: Compression ratio; Noise; Vibration; CNG;Injection Timing

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1. Introduction.

Today, the global transition toward low-carbon transportation is accelerating the adoption of electric vehicles, however the conventional compression ignition (CI) diesel engines will remain most indispensable in Heavy-duty and Industrial applications due to infrastructure and operational constraints. Therefore, enhancing diesel engine efficiency while reducing emissions, combustion-induced vibration, and noise through renewable fuels and advanced combustion strategies represents a practical and scientifically significant approach to achieve sustainable mobility during the energy transition. In particular, the CR, IT and IP are some of the most important variables influencing the above characteristics [1-4]. Many studies have shown that fuel blends along with changing variables can give better results than single fuel performance [5-9].Thus, reduced noise and vibration, lower emission parameters that remain below the threshold set by pollution controlling government agencies and higher efficiencies i.e. BTE, ME, and SFC, for better performance and moderate combustion characteristics, including CP, RoPR, and NHRRcan help us to keep the pace of progress for conventional vehicles.

In this study, we investigate the influence of IT in detail. The Threestages of operation, including advanced injection timing, standard timing and advanced injection timing were evaluated to obtain a better enhanced synergistic effect of fuel fraction and Injection Timing for different parameters.Such as vibration, noise, and emission there are some of most common challenges in governing a dual-fuel diesel engine is uncontrolled noise and vibration as fuel blendsand gaseous additives entering the combustion chamber may cause a rapid pressure rise and delayed ignition. This not only increases the vibration and noise, but also triggers the excess emission of pollutants and smoke owing to incomplete combustion. Many studies have shown that the emission parameters tend to increase with the use of hydrocarbon-rich fuel blends [10-11]. Here, the role of injection timing is entered, as it can tackle these challenges with its role of building the pressure inside the cylinder [12]. Of the three stages of operation, each has its' own characteristics and influences the operation of the engine in a varied manner. First, the retarded IT of 19 deg. in this study tended to reduce the peak pressure in the combustion chamber and help bring about smooth and complete combustion [13], whereas for advanced IT i.e. 27deg. In this study, the blended fuel with air improves and complete combustion can be achieved, thereby lowering the emission parameters [14]. Standard IT i.e. 23deg. help strike the right balance between the two extremes and provide better overall performance [15].

Many studies in recent years have found that Injection Timing has helped us to control the different performance-related aspects of using different fuel blends. In a study utilizing an increasing proportion of biofuel blend, the more IT tended to achieve TDC, leading to lower performance and increased emission parameters [16]. It was found that advanced IT improved the performance of diesel engineand reduced HC, CO, and smoke emissions when using a biofuel blend and alumina nanoparticles as additives [17]. A Study focusing on emissions of engines on IT change found that injection timing strongly influences combustion, in which delayed injection increases turbulence along with worsening the mixture homogeneity and, raised CO and soot, while optimized standard timing improved combustion, lowered HC and soot, but tends to increase NOx emission [18-19]. Using a ternary fuel blend, it was found that advanced IT improved combustion efficiency and engine performance, as the ternary blend including diesel, biodiesel and gasoline allowed balancing ignition quality, volatility, and oxygen content more effectively than binary blends [20]. Furthermore, a research group focused on understanding the effect of the ternary composition of acetone, butanol and ethanol with diesel was shown to be a promising fuel blend to enhance the performance of engines, and a specific process of recalculating exhaust gas to lower the NOx emission was found to be effective [21].Many studies have pointed towards the Exhaust Gas Recirculation technique as an efficient technique to control not only NO_Xparameters but also CO_2 and other sooty gases [22-24]. As Injection Timing has subtle control over combustion characteristics, recent studies have found thatAdvanced injection timing induces an increase in CP but also has an ill effect of repeated knocking leading to wear and tear of mechanical parts. When a comprehensive study was conducted on a diesel engine, the advanced injection timing led to an increase in expansion work, thereby enhancing the overall output of the chambers [25-26].An innovative study to utilize 20% of plastic oil in diesel blend accessed the retarding and advanced IT to get BTE as performance output and emission parameters of NO_X, CO, HC and Smoke wherein it was understood that advanced IT boosted the BTE as compared to retarding IT as retarding one generated less CP, the emission parameters were also lower with implementing advanced IT [27].

After a brief understanding of the transformative impact of IT and Fuel Fraction on different aspects of diesel engines, such as performance, combustion & emissions, many studies were found to have a narrow scope for the characteristic behavior of the fuel fraction. Thus, in an attempt to have a broad scope for ternary fuel fractions utilized in this study, we evaluated the Noise and Vibration, Emission. The fuel fraction consisted of Diesel-Karanja Biodiesel-CNG, of which CNG used as an additive played a significant role in determining the nature of the graphs representing performance-related aspects. The synergistic effect of the fuel blend and IT in the 3 stages of operation led to better performance of the dual-fuel diesel engine, especially at an advanced IT (i.e. 27deg.)An in-depth analysis of data recorded during trials at different stages is discussed in later part of Results and Discussion section.

1. Methodology

2.1 Experimental Test Rig for Dual-Fuel Diesel Engine

In Fig. 1, the built-up test rig is illustrated in which all the trials of 5-Fuel blend in accordance with static and variable parameters were performed using a single cylinder diesel engine. The general specifications of the engine used in the experiment are listed in Table 1. The Blended fuel from a single fuel tank is carried to the combustion chamber viamultiple valves. The operational conditions for the test rig can be varied for different engine levels, which makes it more adaptable to changesin IT, IP, speed, load, and compression ratio (CR). To understand the effect of variable and static parameters concisely, first, static parameters and the compression ratio, which was set to 16:1, leading to better atomization of the blend fuel for combustion, the load was maintained at 6kg for all the trials taken, which led to a moderate in-cylinder pressure, and the injection pressure was set to 400bar, which helped to maintain spray penetration and combustion pressure in the speed was set at 1500 rpm. Moving to the variable parameter in this research, we have varied the Injection Timing for 3 stages i.e. 19^o, 23^o and 27^o, which helps in maintaining balanced combustion phasing and assisting the right time of ignition for better performance and reduced noise and vibration (loss of energy).Furthermore, the configuration of the same is much simpler as the engine is linked to a digital controller to maintain the desired medium load was maintained using a compactable CNG regulator positioned up-stream of the orifice.

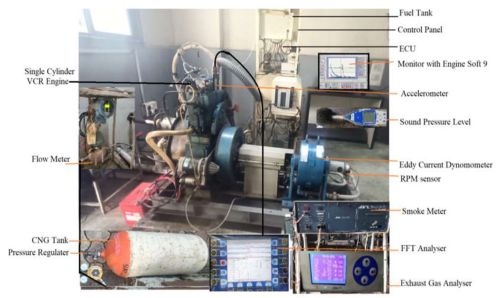

Fig 1. Experimental test rig for Dual fuel diesel engine

Further the blended fuel was supplied using multiple valves for better reach in which the highly-reactive fuel entered the cylinders via a high-pressure common-rail injector. CNG was introduced in three fuel fractions at rate of 2,4 and 6 ms which is an important factor affecting the trajectory of performance, representing graphs of the complete homogenous and incomplete mixing of CNG with the blended fuel. Discussing the output interpreters, two units of SLM-109, a device made by Envirotech, were used to interpret the noise level (dB), of which one was kept one meter away from the tailpipe to obtain the readings of exhaust noise generated, and the second device was kept away from the combustion engine exactly at a distance of one meter to obtain the readings of combustion noise for different stages of operation. To interpret the output of vibrations produced along the X, Y, and Z axes to obtain vertical horizontal and laterally produced vibrations,an accelerometer was employed that the recorded the output in terms of RMS velocity and the major role of the FFT analyzer, which stimulated the active connection with the accelerometer, the data were converted into readable data. Furthermore, the emission through the tail pipe was measured using a smoke meter, which analyzed and calculated five different pollutants, including CO, CO2, NO_X, HC, and O2. The general specifications of the SLM-109,smoke meter and five gas analysers are mentioned in Table 2 and Table 3. Performance related outputs were recorded using a dynamometer for the three stages of trial. Engine Soft software(version 9.0) was utilized to interpret and analyse the complex outputs gained from three stages of trial for all five-fuel fraction which including RoPR, brake thermal efficiency, and mechanical thermal efficiency. The operating parameters are clearly mentioned in Table 5.

2.2 Fuel Used:

Diesel was used as a reference for evaluating the performance in accordance with the to change (in %) in performance using fuel fractions. The commonly used, transesterification process was followed to convert the triglycerides present in Karanja oil into fatty acid methyl esters, finally producing biodiesel [28-29]. A mixture of Karanja oil and sodium hydroxide (as an alkaline catalyst) was set at an optimum temperature of 600C for time duration of 90 min. Further, the crude solution gained which was kept still to settlefor 10 hrs, leading to the formation of 2-distingushable layers of which the upper one was the biodiesel phase with low density and the second was the glycerol phase. The upper layer was the product of interest and was collected and washed repeatedly with hot water until a trace amount of unwanted matter was washed out. Later, the product was dried (by heating at 1150C) to removed moisture, which may higher the smooth performance of the biofuel, and finally filtered. Table 4. Represented Blended Properties of Diesel-Biodiesel (Karanja).Showcase properties of blended fuels. As The blend of Diesel and Karanja Biodiesel is further associated with and additive i.e. CNG at three flow rates of 2%, 4% and 6% (ms).

2.3 Measuring system:

In this section the details and purpose of measuring systems are mentioned.

A Sound Level Meter (SLM-109) manufacture by Envirotech was used to accurately capture and record the engine noise readings. An accelerometer (Specifications: AC 102-1A; S.N-135222; CE) was used to measure vibrations in 3-Axial positions. A four-channel FFT analyzer(Model-ADASH 4400VAPro; Type-A4400, Serial No-623658; Made in EU) was used to interpret the vibrational signals. An exhaust gas analyzer was employed to quantify pollutants. The specifications are listed in Table 2. A smoke meter was employed to quantify the opacity of the exhaust, and its specifications are listed in Table 3.

To get noise characteristics the SLM-109 by Envirotech was employed, first Sound level meter was kept at distance of one meter from the tail pipe to collect the noise reading whereas second one was kept at 1meter distance from Combustion engine to acquire the noise readings generated while combustion process.

Table 1. Engine specifications.

Type of Engine	Single cylinder, Four stroke, VCR with Open ECU for Diesel mode
Product and Make	VCR Engine 244, Made by Kirloskar
Bore(D) and Stroke (L)	87.5 mm, 110 mm
Displacement Volume	661 CC
Dynamometer	Dynamometer -eddy current
Range of C.R	12 to 18
Rated Power	3.75 KW at 1500 rpm
Injection timing	23° BTDC
Ignition System	Compression Ignition
Cooling medium	Water cooled

Dynamometer collected data regarding performance of system in response to fuel blend. Lastly, all this data was quantified on Computer. The software used to interpret and analyse the obtained performance was Engine Soft9.0 software. Total of 3 levels were set with static as well as variable parameter, the compression ratio for 3 levels was 16,17 and 18.

Table2. Specification of 5 gas analyser.

Measurement data	Measurement	Resolution
CO	0–15 %Vol	0.00 1%Vol
HC	0–2000 ppm Vol	1 ppm/10 ppm (0–2000 ppm) (>2000 ppm)
CO_2	0–20 %Vol	0.1 %Vol
O_2	0–25 %Vol	0.01 %Vol
NO_X	0–5000 ppm Vol	1 ppm Vol
Oil Temperature	0 degrees C 125 degrees C	1 degrees C
Lambda	0–9.9999	0.001

Table3. Specifications of Smoke meter.

Measurement Range	**Opacity** 0-100% **Absorption** 0-99.99
Resolution Opacity 0.1% Absorption 0.01 m^{-1}	
Accuracy	Better than +/-0.m3 of measurement values
Operating Temperature	5-50 degrees C
Linearity check	50% of measurement range (automatic)
Measurement Length	0.43 mm +/- 0.005 mm
Dimensions	570*1250*500mm (W*H*D)

Table 4. Blended Properties of Diesel-Biodiesel (Karanja).

Property	Density @ 15°C (kg/m³)	Viscosity @ 40°C (cSt)	Cetane Number	Calorific Value (LHV)	Flash Point °C	Auto-ignition
Diesel	~830–860	2–4	45–55	~42–45 MJ/kg	~60–80	~250
Karanja Biodiesel (B100)	~870–900	4–6.5	50–60	~37–40 MJ/kg	>130	~256–270
CNG	~0.717 (at STP)	Not applicable	~15–20	~48–50 MJ/kg	-188	~540–600
ASTM Standard	D287	D445	D613	D4809T	D938T	E569

Table 5. Operating parameters

Controlled Parameters	**Level – 1(IT-19⁰)**	**Level- 2(IT-23⁰)**	**Level- 3(IT-27⁰)**
5-Fuel Fraction D-Diesel KB- Karanja biodiesel C- CNG % (in ms)	D100- 0 D90KB10-C0 D90KB10-C2 D90KB10-C4 D90KB10-C6	D100- 0 D90KB10-C0 D90KB10-C2 D90KB10-C4 D90KB10-C6	D100- 0 D90KB10-C0 D90KB10-C2 D90KB10-C4 D90KB10-C6
Injection pressure (IP)	400 bar	400 bar	400 bar
Load	6 kg	6 kg	6 kg
Speed of engine	1500 rpm	1500 rpm	1500 rpm
Compression Ratio (C.R)	16:1	16:1	16:1

3.*Result and discussion:*

Throughout the experiment, the injection timing was variable, whereas the other parameterswere kept static. The other static variables were a load of 6 kg(medium),CR of 16,injection pressure of 400 bar and speed of 1500 rpm. These parameters were selected based on recent studies using the TOPSIS method which evaluates multiple alternatives simultaneously and determines the optimal choice based on minimum distance from the ideal best solution and maximum distance from the ideal worst solution to the engine performance. [30]. The Injection timing was maintained for three stages that is, 19°, 23° and 27°., which are mentioned in each graph representing different stages of operation for the usage of five fuel fractions.

3.1 Vibration of the engine:

Fig. 2 shows the spectra of vibration along all 3-Axisand the RMS total for five fuel fractions at different injection timings. Regarding the vibrations data along the X-axis, It was observed that, the lowest vibrations are observed at IT 23 deg. for fuel fraction D90KB10-C6 i.e. 4.9 mm/s with reduced vibrations of 51.01% as compared to D100, which is optimum among all as this was due to lower rate of pressure rise while combustion process. However, we observed frequentvariations were observed depending on the fuel fraction usage. When the introduction of CNG was performed with meagre quantity, it caused an increase in vibrations at IT 19 deg. i.e. 8.29 mm/s as compared to the prior (8.25 mm/s).Vibration at an IT of 23 deg. maintained decreasing trend withintroduction of Karanja biodiesel followed by C.N.G which further reduced for higher proportions of CNG (2%, 4% and 6% CNG), similar observation of lowering vibrations on increasing intake of CNG was recorded in a research work on diesel dual fuel engine [31]. Furthermore, at IT 19, the initial vibration was low as compared to the other two, further an instant drop using IT 23 deg. which showed the lowest vibration with a fuel fraction of D90KB10-C6.

Similarly, the vibrations in the I.T 19deg. were low along the Y-axis as initially, the vibrations were lowest and the lowest RMS was observed for IT 19 deg. with fuel D100. common increase in vibration of 8.3% was observed for all three ITs with introduction of Karanja Biodiesel which is in fuel fraction of D90KB10-C0. This increase in vibration signifies that variation in fuel properties such as viscosity, cetane number on usage of blend caused a shift in effective timing, the second cause of high vibration horizontally, considering the medium IT of 23 deg. here these changes altered the rate of pressure rise and combustion phasing which results in higher combustion-induced excitation forces and increased engine vibration. Shows that the cyclic variation in pressure was higher than that of D100 with the introduction of *Karanja* Biodiesel, and the pattern of increasing vibration of using *Karanja* biodiesel was also recorded by an Indian research group using KB20 along with diesel [32].

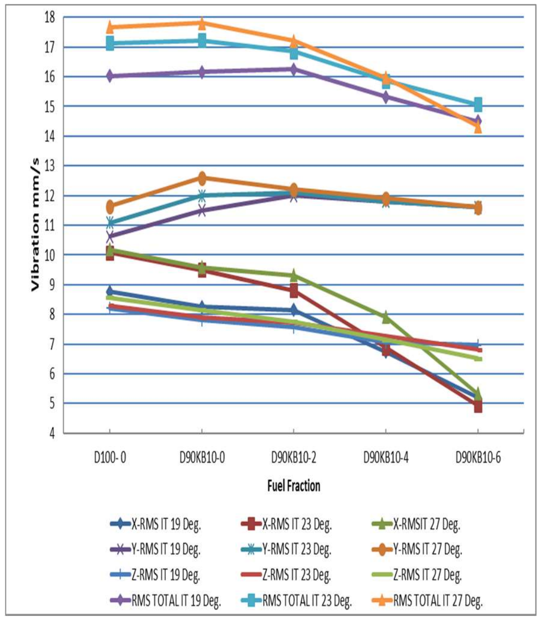

Fig.2. Vibrations recorded along X, Y and Z axis at 3 stages of operation, along with RMS vibrations.

Further, as CNG flow through, the vibrational trend was restricted to a certain extent for all three stages, especially for IT 27 deg. (i.e. 3rd stage of operation) which showed 4.89% of dip i.e. from 12.6 to 12.2 for D90KB10-C0 and D90KB10-C2. A steady increase in CNG led to lower vibrations.

The recorded lateral vibration (Z-axis) recorded was quite low compared to that inother two directions. The linear descending nature of graph signifies that lateral vibration kept reducing with introduction of blended fuel followed by the additive CNG, especially 4% and 6% CNG used in last two fuel fractions showed maximum reduction in vibrations i.e. 15, 17 and 23 % for ITs19, 23 and 27 deg. compared with D100 for their respective stages of operation; which was the optimum condition for the lowest vibration. Upon introduction of blend in fuel fraction D90KB10-C0, only 4.9% decrease was noted (similar for all stages) as compared to D100 for IT 19, 23 and 27 deg., but uneven decrease on introduction of CNG (D90KB10-C2) was observed i.e. 7.83, 6.83 and 9.34 percent for ITs 19, 23 and 27 deg. highlighted the interference of the amount of CNG atomization leading to non-homogenous environment for combustion [33]. However, the advanced timing of injection reduced the delay in combustion, leading to fewer vibrations at 3rdstage of operation. Furthermore, the resultant RMS vibrations, that is, cumulative quantification of vibrations along the X, Y, and Z axis are plotted in fig.2., using a simple formula R(Total) = $(X^2+Y^2+Z^2)^{½}$.slight increase in vibrations when using fuel fraction D90KB10-C0 as compared to D100 for all three stages was found i.e. 0.84%, 0.53% and 0.74% increase at IT 19,23 and 24. Using CNG the overall vibration reduced for 2nd and 3rd stage i.e. 1.65 and 2.66 % decrease as compared to D100 at 2nd and 3rd stage, but kept increasing for 1st stage (IT 19) for which rms values increased from 16.16 to 16.24 for fuel fraction of D90KB10-C0 and D90KB10-C2. This was observed as delay in combustion phasing and cycle-to-cycle combustion instability under retarded injection conditions leading to reduction in the Vibrations produced.The second stage showed least increase in vibration with the introduction of Karanja Biodiesel and the lowest vibrations values were found for the same stage of operation using the fuel fraction of D90KB10-C6 i.e. 14.33 mm/s. Similarly, for the other two stages increasing the percentage of CNG reduced vibrational signals.

3.2 Noise of the engine.

Noise is generated at two specific parts of the engine, that is, at the tail pipe, is generally known as exhaust noise and the second is near the combustion chamber which is known as combustion noise. Both were recorded using a calibrated SPL, kept at a distance of 1 m from the combustion chamber and tail pipe, and provided insight into the variations influenced by the synergistic effect of the variable IT and Fuel fraction used in the trials. The role of CNG and IT in governing the noise level is discussed in this section.

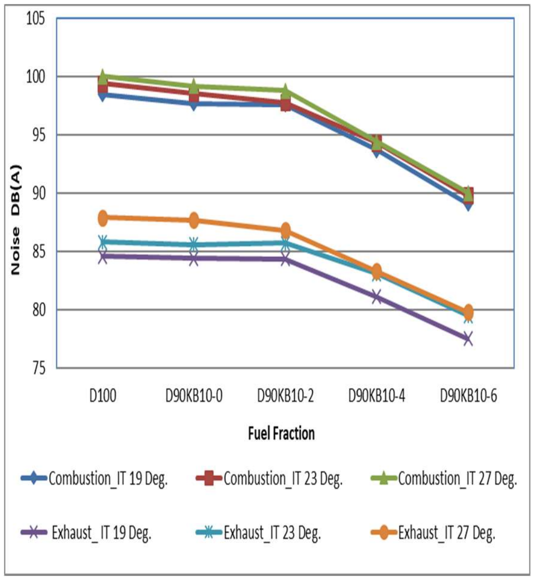

Fig.3. Combustion and Exhaust noise recorded at 3 stages of operation.

Fig.3 shows the Combustion and Exhaust Noise parameters for three different stages of operation denoted by six distinguishable lines in the graph. Discussing Combustion noise, with first sight one clearly understands that the nature of the graph is reduced with the order of fuel fraction used with steep reduction on using D90KB10-C4 and D90KB10-C6. Upon fuelling the engine with D90KB10-C0 slight constant reduction in noise was observed as compared to D100 for all three stages i.e. 0.81%. A fine observation of the fuel usage of D90KB10-C0 and D90KB10-C2 was that even after usage of additive, that is, CNG the lowering in noise was almost negligible, as in terms of percentage, it was just 0.91, 1.61 and 1.21 as compared to D100 for three consecutive stages, This was due to improper mixing of CNG in blended fuel when it flowed in the least quantity which is also supported by a recent study using CN-Diesel on the same type of engine [34]. Further, the noise reduced with higher percentage as the CNG fraction in overall fuel increased, for fuel fraction of D90KB10-C4 and D90KB10-C6 the combustion noise was 93.7dB(A) and 89.1dB(A) for IT of 19deg. Here we have noticed that in combustion noise is primarily governed by ignition delay, heat release rate, and the resulting rate of cylinder pressure rise. Whereas, exhaust noise is generated by pressure pulsations during the exhaust blowdown process, which are influenced by combustion intensity, exhaust gas temperature, and mass flow characteristics.

. Further, the maximum noise recorded at exhaust for stage-3 (88dB(A)) is visibly less than that of combustion noise (100dB(A)), further the introduction of *karanja*biodiesel has shown meagre and constant reduction in noise for all three stages i.e. 0.23% reduction as compared to D100. The maximum reduction in the consecutive fuel fraction, that is, D90KB10-C0andD90KB10-C2, is observed at 3rd stage as at an advanced timing (IT 27deg.) showing 5.29% showing that even after meagre amount of CNG is flown, the advanced injection timing is aligned with the combustion hence making it least noisy. Subsequently, with anincrease in the CNG in the fuel fraction, the noise level reduced. For IT 19deg. The least exhaust noise, was observed i.e. 77.5dB(A) using fuel fraction D90KB10-C6 and for the same fuel fraction with IT 27deg. The second lowest exhaust noise was found to be 79.8dB(A).On the scale of dB(A) with advancingInjection Timing, the noise tended to decrease aswas also interpreted in a study on non-road diesel engines [35],whereas the fuel fraction also played a significant role in additives, that is,CNG in this research work [36].

3.3 Emission of the engine.

The content of smoke emitted after the combustion stage was also considered in the scope of this research work to categorize the pollutants and record the amount of each type of pollutant emitted. Herein, we broadly categorized emitted substances into four major gases, that is, CO, CO2, HC, NOx, and the last was consideredsmoke opacity. Of the four gases CO and CO_2 were measured as percentages by volume; the HC and NOx were measured as PPM. A 5-gas analyser was used to measure the pollutants.

3.3.1 Emission parameters of HC, CO2, and CO.

Fig.4 shows the emission of HC,CO_2, CO which were influenced by varying the IT and fuel fraction used at different stages. In particular, the influence of the fuel fraction is more on the emission as the incomplete combustion of fuel is directly associated with different pollutant that are emitted in accordance with the synergy of IT and fuel fraction. For pure diesel D100 the CO emissions were the lowest. As Karanja biodiesel was introduced in fuel fraction of D90KB10-C0 there was absolutely no change in emissions i.e. 0% as compared with D100 for all three stages. Furthermore, with CNG introduction meagre amount of change was observed for stage 1 i.e. 15% rise as against D100; and stage 3 i.e.66% increase as against D100; moreover,no change was observed in emission for stage 2 which indicates a balanced combustion process with sufficient flame propagation and combustion stability. Lastly the fuel fraction of D90KB10-C4 and D90KB10-C6, the emission doubled as compared to D100, for the respective stage of operation, the cause of increasing CO emission is ternary fuel blend we were using for trials along with which advanced IT has shown relatively less emission [37].

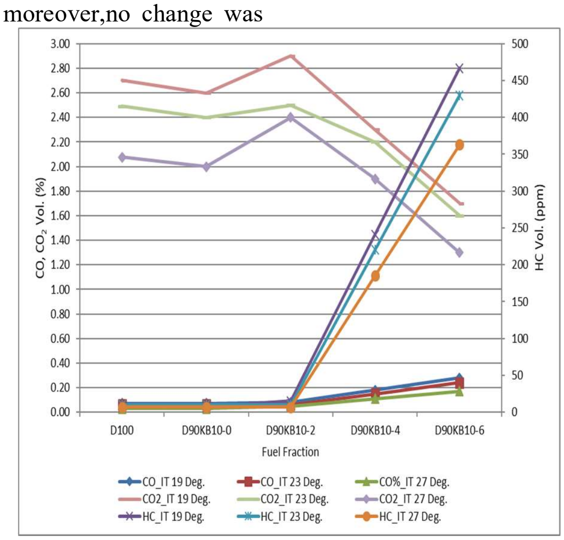

Fig 4. Recorded emission of CO_2, CO and HC using five different fuel fractions at 3 stages of operation.

The maximum emission of HC was observed at first stage of operation i.e.0.28 % vol. (%) for fuel fraction of D90KB10-C6 at IT 19deg. Due to flame quenching and unburned CNG trapped in crevice volumes. Furthermore, the analysis of recorded emissions of hydrocarbons in graph shows stable nature of emission until the D90KB10-C2 was implemented, as soon as the CNG percentage increased by just 2% of next two fuel fractions the emission level significantly increased. The lowest emission was observed for D100 for all three stages, whereas, even after introducing the blended fuel the graph showed zero change asthe oxygenated nature and higher cetane number of prepared biodiesel helped to promote complete combustion. Furthermore, with a small amount of CNG introduced in 3rd fuel fraction (i.e. D90KB10-C2), a slight variation was observed as the methane in the CNG may be unburned owing to non-homogenous mixing in the total fuel. As the CNG increased by 2% in D90KB10-C4 the HC emission significantly increased, which was recorded to be 241Vol.(ppm), 220 Vol.(ppm) and 185Vol.(ppm) for IT 19deg., 23deg. and 27deg.; which further raised to 463Vol.(ppm) on using D90KB10-C6 at IT 19deg. which was maximum among all. A similar trend was observed for other two stages which was similar to HC emission parameters recorded at retarding IT in a recent study [38].

Lastly, CO_2 emissions showed mixed nature of readings as seen in the graph line decreased on addition of Karanja Biodiesel by 3.7% for all three stages with respect to D100. This did not continue for the next fuel fraction as with introduction of CNG, the CO_2 emission stepped up which was minimum for IT 23deg. that just 0.31% increase in emissions was compared to D100 at same stage. For D90KB10-C2 the maximum rise in emission was observed at 3rd stage i.e. for IT of 27 deg. Furthermore with a higher percentage of CNG in the fuel fraction the emission parameters decrease with a steep slope. The lowest emissions were found when using the fuel fraction of D90KB10-C6, of which the lowest emissions were produced by 3rd stage of operation that is. IT 27deg. of just 1.3% as it helped for maintaining better premixing and combustion duration which was least observed CO_2 emission coinciding with recent study where at advanced IT the emission lowered [39]. Considering the other side i.e. high emission, the maximum emission of CO_2 was found while using fuel fraction of D90KB10-C2 at 1st stage which was Vol. (%).

3.3.2 NO_X Emission PPM and Smoke opacity Vol. (%).

Fig. 5 shows the emission of NO_X and Smoke Opacity at different stages with respect to 5-fuel fraction at different stages of operation. First, discussions about the emission of NO_X which was low while operating at the first stage as compared to the other two showcasing that the IT 19deg. led to a cleaner combustion. Again, the mixed nature of the graph is observed as the emission decreases for D90KB10-C0 and again picks up the emission by introducing CNG in merge quantities. The 3rd stage of operation showed the highest emission of NO_X using D90KB10-C2 which was found to be 358 PPM, which is consistent with the findings that NO_X emissions increased with advancing IT which has a scientific angle of influence as the greater premixed combustion and higher peak in-cylinder temperatures [40].

Furthermore, the common nature of lowering the emissions was observed in all the three stages. For D90KB10-C4 and D90KB10-C6, the emissions decreased. The emission of NO_X on using D90KB10-C6 was lowest for all three stages and in terms of percentage it was 91.03%, 95.23% and 93.07% of reduction with respect to D100 emission parameters for IT (19,23 and 27) deg. All three stages converged to nearly the same point when using D90KB10-C6, here the emission parameters were 18, 20 and 25 ppm for an IT of 19,23 and 27°. The opacity of smoke was quantified at different stages of the operation. First, the emission was lowest for D100 in the first stage(IT 19deg.) but did not remain the same throughout the trials, because the rate of increment was high for the same. It was 225.75%, 478.62%, and 736.48% for increments of using 2nd, 3rd, 4th fuel fraction with respect to D100.

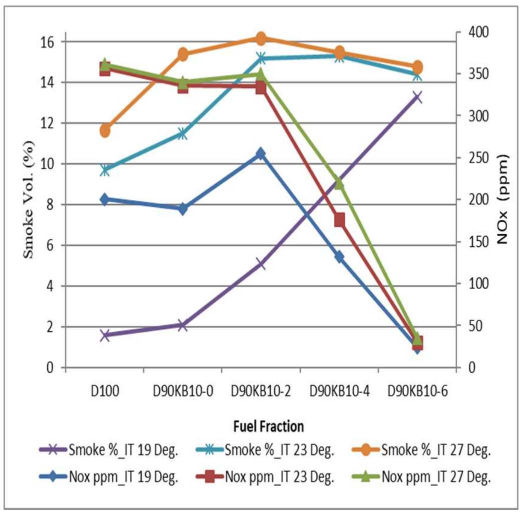

Fig.5. Recorded emission of NO_X and Smoke Opacity using five fuel fractions at 3 stages of operation

In the, second stage of operation the smoke opacity emission increased for the first three fuel fractions but decreased further with the introduction of CNG, indicating that CNG usage helped contain the emission. For stage-3 the emission was similar in nature as compared to stage-2 but the emission was slightly higher than that for the first three fuel fractions, that is, D100, D90KB10-C0 and D90KB10-C2. On using D90KB10-C4 the emission was lower than that of stage-2 for same fuel fraction i.e. 15.11 vol. (%) of smoke opacity as here while the homogeneous CNG-air mixture improved combustion completeness and reduced locally rich combustion zones responsible for soot formation. Furthermore, the smoke opacity reduced for 3rd stage which is in contrast to 1st stage i.e. vivid in the above graph. Overall, with D100, the smoke opacity was the lowest in the first stage, which retarded IT [41-42].

4. Conclusion:

The influence of retarding, medium, and advanced Injection Timing, accompanied by different fuel fractions was quantified to obtain a clear visualrepresentation of various characteristics. Regarding the Noise, Vibration and emission aspects, the fuel fraction influenced the observed parameters more than the variable Injection Timing.

Depending on the Injection Timing, the retarding stage i.e. stage-1 led to lower vibrations for the use of almost all fuel fractions, especially D90KB10-C6, which was also confirmed by the Resultant RMS. On imposing the stage 3, IT 27 deg. led to 4.89% of dip i.e. from 12.6 to 12.2 for D90KB10-C0 and D90KB10-C2 in Vibration level. The stage-3 the of operation exhibited a slightly higher vibration. The influence of CNG led to a further lowering of vibrations, especially with the fuel fraction of D90KB10-C6 which contained a high CNG fraction allowing the homogenous mixing of fuel for a smooth combustion process. Whereas, Karanja Biodiesel usage slightly reduced the vibrations by 4.9-5.8% along X and Z axis but slightly increased vibration along Y-axis. Furthermore, this did not significantly affect the Total RMS value.

Advanced Injection Timing (IT 27deg.), because the generation of a high cylinder pressure results in higher combustion and exhaust noise. On the other end, retarded IT i.e. 19^0. tends to produce a lower cylinder pressure thereby ensuring a low sound pressure level after combustion. Furthermore, the incomplete burning of the fuel on usage of D90KB10-C2 owing to the presence of a small amount of CNG and unequal mixing of the same led to a slight increase in combustion noise, which on increasing the CNG fraction reduced to the lowest noise recorded among all fuel fractions. The least exhaust noise, was observed i.e. 77.5 dB(A) using fuel fraction D90KB10-C6 and for the same fuel fraction with IT 27 deg. which was found to be least among all other levels of operations which showed that noise reduced with higher percentage as the CNG fraction.

In the case of the emission parameters, the emissions of CO, HC, and CO_2 were found to be high when retarding the injection timing that is IT $19^{0.}$ This was due to the high incomplete combustion and delay in ignition, whereas the emission of NO_X on using D90KB10-C6 was lowest for all three stages and in terms of percentage it was 91.03%, 95.23% and 93.07% of reduction with respect to D100 emission parameters for IT (19,23 and 27) deg. and smoke was found to be high for advanced injection timing i.e. IT 27^0 but with higher CNG the smoke opacity reduced for 3rd stage.This was due to the high C.P and temperature synergistically favouring the production of NO_X in bulk, but the fuel fraction of D90KB10-C6 NO_X emission decreased as CNG suppressed NO_X formation. The influence of the fuel fraction, especially on the use of additives such as CNG, increased whenCO and HC emissions increased exponentially as the fraction of CNG increased, which was the case for fuel fractionsD90KB10-C4 and D90KB10-C6. Overall, the effect of variable ITs' was constant and not affected by the change in fuel fraction as none of the 3-stage line in the graph crossed each other except in the case of smoke opacity. Further, having the future perspective we can spur our imagination towards practical and sustainable approach for enhancing the performance of existing diesel engines during the ongoing transition toward cleaner transportation systems.Along-with this transition, the life-cycle assessment of biodiesel-CNG dual-fuel engines should also be investigated to evaluate their carbon-neutral energy systems.

Abbreviations

IP :	Injection pressure
IT	Injection Timing
SPL	Sound Pressure Level
KB	Karanja Biodiesel
D	Diesel
RoPR	Rate of Pressure Rise
NHRR	Net heat Release Rate
CR	Compression Ratio
RMS	Root Mean Square
RPM	Rotation Per Minute
CNG	Compressed Natural Gas
CP	Cylinder Pressure
SFC	Specific Fuel Consumption
ME	Mechanical Efficiency
BTE	Brake Thermal Efficiency
NO_X	Nitrogen Oxides
CO_2	Carbon Dioxide
HC	Hydrocarbon Molecules
CO	Carbon Monoxide

-Statements and Declarations

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References:

[1] Sayin, C. and Gumus, M., 2011. Impact of compression ratio and injection parameters on the performance and emissions of a DI diesel engine fueled with biodiesel-blended diesel fuel. *Applied thermal engineering*, 31(16), pp.3182-3188.

[2] Goel, V., Kumar, N. and Singh, P., 2018. Impact of modified parameters on diesel engine characteristics using biodiesel: A review. *Renewable and Sustainable Energy Reviews*, 82, pp.2716-2729.

[3] Gumus, M., Sayin, C. and Canakci, M., 2012. The impact of fuel injection pressure on the exhaust emissions of a direct injection diesel engine fueled with biodiesel–diesel fuel blends. *Fuel*, 95, pp.486-494.

[4] Kannan, G.R. and Anand, R., 2012. Effect of injection pressure and injection timing on DI diesel engine fuelled with biodiesel from waste cooking oil. *Biomass and bioenergy*, 46, pp.343-352.

[5] Mehta, B., Swarnkar, A. and Subhedar, D., 2025. Performance and emission evaluation of diesel engines using Karanja biodiesel blended with diethyl carbonate. *Results in Engineering*, p.106548.

[6] Huzayyin, A.S., Bawady, A.H., Rady, M.A. and Dawood, A., 2004. Experimental evaluation of diesel engine

performance and emission using blends of jojoba oil and diesel fuel. *Energy conversion and Management*, 45(13-14), pp.2093-2112.

[7] Singh, P., Chauhan, S.R. and Goel, V., 2018. Assessment of diesel engine combustion, performance and emission characteristics fuelled with dual fuel blends. *Renewable energy*, 125, pp.501-510.

[8] Kumbhar, V.S., Shahare, A.S. and Awari, G.K., 2021, November. Influence of injection pressure on performance and emission characteristics of single cylinder RCCI engine fuelled with ethanol gasoline and diesel biodiesel blends. *In Journal of Physics*: Conference Series (Vol. 2070, No. 1, p. 012160).

[9] Kumbhar, V.S., Shahare, A.S. and Awari, G.K., 2022. An experimental investigation on gasoline diesel and biofuelled RCCI combustion and its comparison with the conventional diesel combustion. *Materials Today: Proceedings*, 59, pp.525-533.

[10] Zaglinskis, J. and Rimkus, A., 2023. Research on the performance parameters of a compression-ignition engine fueled by blends of diesel fuel, rapeseed methyl ester and hydrotreated vegetable oil. *Sustainability*, 15(20), p.14690.

[11] Rajkumar, S. and Thangaraja, J., 2019. Effect of biodiesel, biodiesel binary blends, hydrogenated biodiesel and injection parameters on NOx and soot emissions in a turbocharged diesel engine. *Fuel*, 240, pp.101-118.

[12] Sharma, A. and Murugan, S., 2015. Combustion, performance and emission characteristics of a DI diesel engine fuelled with non-petroleum fuel: a study on the role of fuel injection timing. *Journal of the Energy Institute*, 88(4), pp.364-375.

[13] Zhao, Y., Cui, K., Zhu, J., Chen, S., Wang, L.C., Cheruiyot, N.K. and Mutuku, J.K., 2019. Effects of retarding fuel injection timing on toxic organic pollutant emissions from diesel engines. *Aerosol and Air Quality Research*, 19(6), pp.1346-1354.

[14] Nwafor, O.M.I., 2000. Effect of advanced injection timing on the performance of natural gas in diesel engines. *Sadhana*, 25(1), pp.11-20.

[15] Gopinath, S., Devan, P.K., Mohan, C. and Prasad, S.V., 2020. A review on influence of injection timing and injection pressure on DI diesel engine fuelled with low viscous fuel. *Materials Today: Proceedings*, 33, pp.280-286.

[16] Nghia, N.T., Khoa, N.X., Cho, W. and Lim, O., 2021. A study the effect of biodiesel blends and the injection timing on performance and emissions of common rail diesel engines. *Energies*, 15(1), p.242.

[17] Jamuna Rani, G., Rao, Y.H. and Balakrishna, B., 2022. Fuel injection timing impact on diesel engine performance, combustion and emission characteristics of nano additive biodiesel blends. *International Journal of Ambient Energy*, 43(1), pp.2078-2085.

[18] Liu, Z., Zhen, X., Geng, J. and Tian, Z., 2024. Effects of injection timing on mixture formation, combustion, and emission characteristics in a n-butanol direct injection spark ignition engine. *Energy*, 295, p.131059.

[19] Merola, S.S., Irimescu, A., Marchitto, L., Tornatore, C. and Valentino, G., 2017. Effect of injection timing on combustion and soot formation in a direct injection spark ignition engine fueled with butanol. *International Journal of Engine Research*, 18(5-6), pp.490-504.

[20] Zandie, M., Ng, H.K., Said, M.F.M., Cheng, X. and Gan, S., 2023. Performance of a compression ignition engine fuelled with diesel-palm biodiesel-gasoline mixtures: CFD and multi parameter optimisation studies. *Energy*, 274, p.127346.

[21] Duan, X., Xu, Z., Sun, X., Deng, B. and Liu, J., 2021. Effects of injection timing and EGR on combustion and emissions characteristics of the diesel engine fuelled with acetone–butanol–ethanol/diesel blend fuels. *Energy*, 231, p.121069.

[22] Motamed, M.A., Genrup, M. and Nord, L.O., 2024. Part-load thermal efficiency enhancement in gas turbine combined cycles by exhaust gas recirculation. *Applied Thermal Engineering*, 244, p.122716.

[23] Deng, B., Cai, W., Zhang, W., Bian, L., Che, X., Xiang, Y. and Wu, D., 2025. A comprehensive investigation of EGR (exhaust gas recirculation) effects on energy distribution and emissions of a turbo-charging diesel engine under World Harmonized transient cycle. *Energy*, 316, p.134506.

[24] Schäfer, F., Egger, S., Steiner, D., Carré, M. and Eichel, R.A., 2022. Control of oxygen-to-carbon ratio and fuel utilization with regard to solid oxide fuel cell systems with anode exhaust gas recirculation: *A review. Journal of Power Sources*, 524, p.231077.

[25] Baek, H.M., Jung, G.S., Vuong, Q.D., Lee, J.U. and Lee, J.W., 2023. Effect of performance by excessive advanced fuel injection timing on marine diesel engine. *Applied Sciences*, 13(16), p.9263.

[26] Agarwal, A.K., Srivastava, D.K., Dhar, A., Maurya, R.K., Shukla, P.C. and Singh, A.P., 2013. Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. *Fuel*, 111, pp.374-383.

[27] Jatadhara, G.S., Chandrashekar, T.K., Banapurmath, N.R., Basavaraju, N.S. and Setty, K.K.N., 2023. Effect of injection timing in direct injection diesel engine using plastic oil diesel blends with biodiesel as an additive. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 101(2), pp.73-84.

[28] Kumbhar, V.S., Shahare, A.S. and Awari, G.K., 2022. Comparative analysis on single, double and triple fuel injection strategy of single cylinder RCCI engine fueled with ethanol-gasoline/diesel-biodiesel blends. *Materials Today: Proceedings*, 59, pp.1074-1082.

[29] Kumbhar, V.S., Shahare, A. and Awari, G.K., 2021, August. Review on reactivity controlled compression ignition engines: an approach for BSVI emission norms. In IOP Conference Series: *Materials Science and Engineering (Vol. 1170, No. 1, p. 012011). IOP Publishing*.

[30] Gavade, P.G., Jadhav, P.V., Kadam, M.A., Sutar, K.D. & Jadhav, D.B. (2025) 'Application of TOPSIS Method for Multi-Characteristic Optimization of Vibration and Noise Characteristics of a Dual-Fuel CI Engine', *International Research Journal on Advanced Science Hub (IRJASH),* 07(07), pp. 681–689.

[31] Dimitrov, E., 2022, October. Study of the compressed natural gas influence on the noise of a diesel dual-fuel engine. *In AIP Conference Proceedings* (Vol. 2557, No. 1, p. 060006). AIP Publishing LLC.

[32] Patel, C., Agarwal, A.K., Tiwari, N., Lee, S., Lee, C.S. and Park, S., 2016. Combustion, noise, vibrations and spray characterization for Karanja biodiesel fuelled engine. *Applied Thermal Engineering*, 106, pp.506-517.

[33] Uludamar, E., Tosun, E. and Aydın, K., 2016. Experimental and regression analysis of noise and vibration of a compression ignition engine fuelled with various biodiesels. *Fuel*, 177, pp.326-333.

[34] Yuvenda, D., Sudarmanta, B., Jamaludin, J., Muraza, O., Putra, R.P., Lapisa, R., Krismadinata, K., Zainul, R., Asnil, A., Setiyo, M. and Primandari, S.R.P., 2022. Combustion and emission characteristics of CNG-diesel dual fuel engine with variation of air fuel ratio. *Automotive Experiences*, 5(3), pp.507-527.

[35] Zhou, X., Ma, Z., Liu, Y. and Li, A., 2023. Influence of injection system parameters on combustion noise of a small power non-road diesel engine. *International Journal of Automotive Technology*, 24(5), pp.1383-1393.

[36] Chaichan, M.T. and Al-Zubaidi, D.S.M., 2014. Operational parameters influence on resulted noise of multi-cylinders engine runs on dual fuels mode. *Journal of Al-Rafidain University Collage for Science*, 35, pp.186-204.

[37] Ge, J.C., Wu, G., Yoo, B.O. and Choi, N.J., 2022. Effect of injection timing on combustion, emission and particle morphology of an old diesel engine fueled with ternary blends at low idling operations. *Energy,* 253, p.124150.

[38] Mani, M. and Nagarajan, G., 2009. Influence of injection timing on performance, emission and combustion characteristics of a DI diesel engine running on waste plastic oil. *Energy*, 34(10), pp.1617-1623.

[39] Ahmed, S.A., Zhou, S., Zhu, Y., Feng, Y., Malik, A. and Ahmad, N., 2019. Influence of injection timing on performance and exhaust emission of CI engine fuelled with butanol-diesel using a 1D GT-power model. *Processes*, 7(5), p.299.

[40] Fathi, M. and Jafari, B., 2025. Impact of Fuel Injection Timing on Combustion Characteristics and Emissions in a Diesel Engine: *A CFD Study*. P.33-42

[41] Rajendran, S., Dhairiyasamy, R., Jaganathan, S., Murugesan, S., Muthusamy, R., Periannan, S., Muniyappan, G., Jaganathan, B., Srinivasan, K., Elangandhi, H. and Annamalai, E., 2023. Effect of injection timing on combustion, emission and performance characteristics of safflower methyl ester in CI engine. *Results in Engineering*, 20, p.101599.

[42] Katare, P., Kumbhar, V., Tirpude, R., Chan, C. K., & Wong, L. S. (2026). Influence of Main Injection Timing on Performance Characteristics of Medium Duty RCCI Engine Operated on Various Blends of Biofuels. *International Journal of Vehicle Structures & Systems (IJVSS),* 18(1).