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Optimization of nozzle hole number for dual fuel operation using biodiesel blends: a response surface methodology approach

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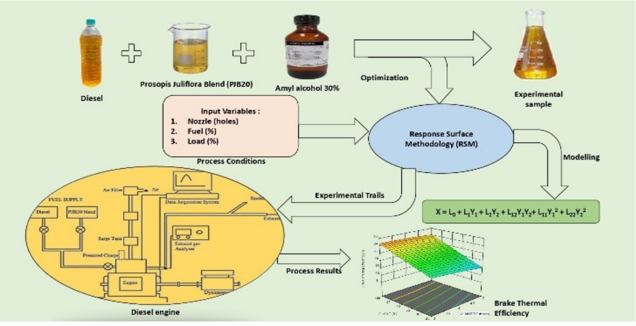
Graphical abstract



Abstract

Injector nozzle hole design is vital for enhancing sustainability by improving engine performance and reducing emissions. The study aims to investigate the impact of altering the number of nozzle holes (3, 4, and 5) on the performance of diesel, prosopis juliflora biodiesel (PJB20), and a blend of PJB20 with amyl alcohol in dual fuel mode. For optimization of engine, response surface methodology was used with the input parameters of load (25, 50, and 100%), nozzle hole (3, 4, and 5), and fuel blends (Diesel, PJB20, and PJB20-amyl alcohol) whereas the output response of Brake thermal efficiency (BTE) and Nitrous oxide (NOx) are taken as factors. The Derringer Desirability technique was used to optimize central composite design. Utilizing PJB20-amyl alcohol 30% through a 4-hole nozzle increased BTE by 3.30% and 8.32% in comparison to three-hole and five-hole nozzles. The nozzle holes were 23.1, 23.89, and 21.9% compared to 25.95% for neat diesel. Additionally, the NOx levels were 883, 1062, and 940 ppm compared to 1405 ppm for neat diesel operation with a 3-hole nozzle. PJB20 -30% amyl alcohol blend produced less, CO and HC while NOx emissions enhanced while comparing with diesel and PJB20. The optimized specifications of the dual fuel resulted in maximum performance and minimum emissions found at a four-hole nozzle, a fuel blend of 27.40%, and an 86% load. It was determined that the predicted responses for BTE and NOx were 24.84% and 1056.7 ppm respectively. Finally, the numerical and experimental data indicate that the 4 hole mixture of PJB20–30% amyl alcohol produces maximum engine efficiency and minimum emissions, that are optimized.

Keywords: Nozzle hole geometry, PJB20, amyl alcohol, optimization, response surface models and engine emissions

1. Introduction

Dual fuel engine operations are the most essential area that needs to be researched on a global scale in order to achieve high fuel efficiency. This is because dual fuels do not suffer from throttling losses and have a more compression ratio. Dual fuel engine is the most efficient method for operating the lean mixture, which allows for the temperature of combustion to be kept in a minimum while also adhering to the stringent environmental regulations. When compared to a conventional engine, the combustion happens at all regions and the mixture is ignited evenly over the entire space before the actual combustion takes place. The intensive research and development initiatives carried out by dual fuel engine are directed toward the reduction of emissions of NOx and particulate matter (Akhilendra Pratap Singh *et al*. 2012; Allasi *et al*. 2023; Arturo *et al*. 2003).

Akhilendra Pratap Singh *et al*. (2012) the experiments focused on two-cylinder engines with one in dual engine and the other in CI mode. Exhaust gas recirculation of 0, 10, and 20% regulated heat release and cylinder temperature. Low-temperature diesel chemistry and high-temperature reactivity create two heat release stages in diesel dual combustion. Combustion behaviour was determined using three air fuel ratio tests. By reducing combustion and introducing non-reactive species, exhaust gas recirculation decreased homogeneous charge and

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NOx formation. Allasi, H. L *et al*. (2023) found that influence of the synthesized CeO2 and ethanol on the biodiesel made from neem oil was investigated using a number of different metrics, including performance, emission, and combustion. Hybrid cerium oxide nanoparticles and ethanol exhibit superior performance due to improved atomization and oxygen buffering. Arturo de Risi *et al*. (2003) reported loss of efficiency and lower power output in the diesel engine compared with the dual mode. In contract to this the various researches made a effort to achieve higher efficiencies. Diesel and biodiesel have been the subject of much research into the effects of different nozzle hole designs and spray properties. The Dual fuel technology applied to biofuel is extremely significant on the cetane number, viscosity, density, heating value, and flash point of the biofuel's composition (Arturo *et al*. 2003; Atmanli *et al*. 2015; Banapurmath *et al*. 2009; Battistoni *et al*. 2019). Banapurmath *et al*. (2009) Using diesel engines with a variety of tested fuels as their primary fuel and with producer gas as a secondary fuel shows that current diesel engines don't need much modifying. When compared to the dual fuel mode, the data reveal that the main fuel utilized in diesel engines produces higher pollutants and better performance. A rise in carbon monoxide emissions and a fall in smoke and nitrogen oxides. Chetan Pawar, 2017 tested the effects of changing the injection pressure on the dual fuel engine with different nozzle diameters (0.2, 0.25, 0.3) and numbers of holes (3, 4, and 5). When comparing injectors with three or five holes, the results show that four holes reduce CO, HC and smoke. In addition, they found that a nozzle with four holes improved efficiency over one with three or five holes. Reason being, increased spreading is a result of smaller SMDs brought about by improved atomization. Choi *et al*. (2015) The study examines the impact of combustion behavioural shape and double-row nozzles on diesel emissions. The actual piston and 12-hole double-row nozzle had the best emissions for traditional diesel combustion and modest boost pressure. Two-step pistons with a 12-hole double-row nozzle have enhanced NOx and PM emissions, reduced THC emissions, and reduced CO, PM, and THC emissions. Dilsher Khan *et al*. (2022) experimentally studied the performance and emissions of a biogas-biodiesel dual fuel engine using butanol blends in various amounts were experimentally examined and reported. A 20% palm oil biodiesel with 80% neat diesel to make the fuel. To make B5, 95 percent BD20 and 5 percent butanol are mixed. CI engine is converted to flow biogas at 10, 15 and 20 lpm. BTE, CO, and NOX emissions were evaluated at 10, 20, 30, and 40 N-m engine loads. Research suggests using B5 and B10 mixed fuel instead of diesel fuel. Ganesh botla *et al*. (2024) Furthermore, optimization studies have been conducted to determine the best operating parameters for thermal cracking HDPE waste polymers into valuable products. RSM improves independent variables to boost value-added product yields.

Gawale Ganesh *et al*. (2020) reported the experimental and numerical investigations on two-fuel engine that ran on diesel and ethanol. The NOx emissions decrease and thermal efficiency increases at moderate load to full load respectively. CO2, CO and HC emissions increases. The dual mode allows for the utilization of ethanol or other alternative fuels to enhance energy efficiency and lower NOX emissions. Guo Hao *et al*. (2019) used PCC nozzle angle and PCC nozzle diameter to study the operation of a marine 2-stroke dual engines. Improved flame propagation, engine performance and decrease emission, also flame propagation direction and speed and leads to knocking. RSM employs a statistical approach for experimental design and optimization (Ibham *et al*. 2023; Sushrut *et al*. 2023). He *et al*. (2016) compared the flow and spray behaviour were examined utilizing a trio of min-sac nozzles that share a common output diameter but feature distinct hole shapes. Hole cavitation collapse increases flow turbulence and lowers spray cone angle. Vehicle performance and pollution can be enhanced by fine-tuning the nozzle's geometry. The combustion depends on the fuel injection process and their parameter by Jan Monieta *et al*. (2021)

Jinbao Zheng *et al*. (2022) found narrow spray angle nozzle works well with early pilot injection and low loads, while the old nozzle is more thermally efficient with large loads and the same injection strategy. Under high loads, the narrow spray angle nozzles have small holes and low spray penetration. Junho Alcohol *et al*. (2022) did the work on main injector with 8 holes of 1500 and additional injector with 4 holes of 900 at 1200 rpm, 0.11 MPa of intake pressure and equivalence ratio of 0.5 are used to reduce the global warming conditions on dual fuel combustion (natural gas and diesel). It concludes, additional injector has better combustion and also GWI were decreased by 5.6% with the main injector. Kamaraj *et al*. (2018) investigate the design Expert software was used to assess experimental outcomes. A second-degree polynomial quadratic model was used to predict output responses. The overall attractiveness for the entire model was 0.7506, with a compression ratio of 19.31 and blend ratios of 20% for SFOME and 15.72% for T-CSNL in volume proportion. The ability to learn and model complex relationships is crucial for IC engines, as many of the parameters relating inputs and outputs are nonlinear. Nozzle hole geometry plays an essential role in decreasing the environmental effect of internal combustion engines by lowering emissions, increasing fuel efficiency, and improving overall combustion performance. Automotive manufacturers and researchers may help to make the environment more sustainable and safety for current and future generations by focusing on nozzle geometry optimization. Many studies are conducted to examine the relationship between nozzle design and factors such as ignition delay, combustion stability, pollutant production, and fuel consumption by Kenta Kikuchi *et al*. (2022; Krishnamoorthi *et al*. (2018) carried the work on blends with B10, B20 and B40 Niger seed oil blends were tested as fuels, with the B20 blend exhibiting the most promising results when supplemented with hydrogen at 15 lpm, 10 lpm and 5 lpm respectively. The results optimized that when the hydrogen flow rate increased, the vibration and noise levels of B20 are reduced by using response surface methodology. Nandakumar *et al*. (2020) reported that increased nozzle holes from 3 to 5 and examined engine characteristics for the higher blend b50. At full load, increasing b50 nozzle holes from 3 to 5 increased heat rate and in-cylinder pressure. Higher nozzle holes reduced ignition time interval, combustion phenomenon, and improving combustion rate. Efficiency increases for 5 hole nozzle geometry compared to 3 hole. The augmentation of nozzle orifices resulted in a decrease in HC, CO, and smoke emissions, while concurrently leading to an increase in NOX emissions. Nordgrenet *et al*. (2004) studied the combustion process with altering hole diameters and spray angles. Dual generates more unburned hydrocarbons but less NOx. Direct infusion reduces HC. HC and NOx are swapped in experiments. Injection timing, pressure, and nozzle configuration were evaluated in relation to mixture homogeneity. Start of injection (SOI) adjustments in NOx emission level cause different NOx levels at different nozzle injectors. HC emission depends on injector timing.

Onofrio *et al*. (2021) showed the impact of hole number and size on direct injection diesel engine emissions and performance. Injector hole size and number combinations used in investigations. At 75% load NOx, particle, and BSFC are the emissions and performance results. Both numerical and experimental investigations may evaluate complex flow processes and spray dynamics, whereas experimental studies validate and reveal engine behavior by (Sagari, *et al*. 2020). Patrick Rorimpandey *et al*. (2024) experimentally carried the work between H2 and diesel-pilot jets were injected by two converging single-hole injectors. Result shows that increasing time separation, burnt diesel products and cool down, necessitating longer jet-jet interaction to ignite hydrogen. Prabhu Kishore *et al*. (2024) employs high-reactivity jatropha oil combined with diesel and low-reactivity 1-hexanaol. Different fuel approach increased BTE by 36.83% and decreased BSFC by 19.48%. The hazardous pollutants smoke, UHC, CO, and CO2 by 55.86%, 30%, 52.33%, and 46.3%. Prathiba Rex *et al*. (2024) Focussed on polypropylene waste (PPW) and polyethylene terephthalate (PETW) were pyrolyzed in a semi-batch reactor at 500°C for the studies. Lastly, waste plastics pyrolysis is a suitable option to produce diesel-like fuel. Because biodiesel typically has a fuel with higher flash point, higher pour point and greater calorific value, it is possible to get the best possible performance from a dual fuel engine by using biodiesel as the fuel (Banapurmath *et al*. 2009; Chetan *et al*. 2017; Junho *et al*. 2022; Shijun *et al*. 2018; Shiquan *et al*. 2024; Yaliwal, *et al*. 2016; Zhiyong *et al*. 2022). Rajesh *et al*. (2022) discovered the pyrolyzed PP based polymer oil and pure diesel were tested. Using 4% plastic oil, the indicated power differs by approximately 0.01 kW at a load of 0.04 kg and rises to approximately 0.02 kW at a weight of 17.04 kg. At a weight of 0.04 kg, the braking power for 4% plastic oil is 0.02 kW, which is the same as the BP for diesel operation under identical conditions. In comparison to diesel, the braking power for 4% plastic oil varies by approximately 0.02 kW under higher load conditions. Rajesh *et al*. (2022) observed a significant increase in the SFC of the biodiesel that contained 18% (BD18) polymer oil when it was loaded with 4.4 kg, 9.03 kg, and 12.6 kg. With a plastic fuel addition of 6% (BD6) at 17.04 kg, it had a high specific fuel capacity (SFC). In every instance, the pure diesel shown a significant SPC, which was then followed by the addition of 12% (BD12) polymer oil.

Shijun Dong *et al*. (2017) showed the DI diesel engine by dual mode using ethanol and diesel by varying nozzle hole number from 4, 5, 6 and 8. The result indicated that by using ethanol and diesel dual fuel blends maximum pressure increases and combustion duration was extended for 4 hole nozzle compared with 5, 6 and 8 hole nozzle. For 4-hole nozzle the NOx emission decreases and soot emission increases. Biodiesel is produced from renewable natural resources that do not result in the formation of any hazardous waste products Shiquan Feng *et al*. (2024) were work carried on dual fuel combustion model and simulates nozzle diesel and methanol flows using geometric and empirical approaches. A suitable spray angle is 13°, and the discharge coefficient affects engine performance if more than the spray angle. Tanaji Balawant Shinde *et al*. (2012) reported that brake power, torque, and BMEP performance characteristics increases engine performance. Proper fuel combustion inside the cylinder before exhaust valve opening reduces exhaust temperature. The baseline and modified engine examination results were validated with 10% variation in practically all engine performance parameters.

Yaliwal *et al*. (2016) studied combustion chamber designs and nozzle hole diameter ranging from 0.2, 0.25 and 0.3 and number of nozzle hole from 3, 4 and 5 hole was used. Finally, 4 hole with 0.25 mm diameter with re-entrant type of combustion chamber shows higher efficiency and reduced emission. They also reported that the more research and technology should be developed in dual fuel mode for various fuels. Zhiyong Li *et al*. (2022) shows that increasing the number of nozzles and reducing the diameter of the nozzles enhances fuel efficiency and reduces emissions of exhaust pollutants. Recent research has interest in altering the geometry of nozzle holes within injector nozzles geometries to enhance performance and for future applications.

In contrast, there is a lack of research on injector nozzle number and diameter, and what little there is focuses on that parameter. Within this context, the current research intends to make a contribution by investigating nozzle holes on engine performance and emissions. A fuel injector's nozzle diameter and number of nozzles are two critical parameters that significantly impact the injection parameter of the fuels under test. The fuel injection process and their associated parameter depend on air and fuel mixing, fuel evaporation and atomization. The proposed solution needs to prioritize environmental sustainability and actively contribute to a net decrease in overall greenhouse gas emissions. The current field of research focuses on investigating the performance and emission characteristics of dual fuel engines fuelled by prosopis juliflora oil methyl ester (PJOME) biofuels. It was decided to take injectors with different numbers of nozzle holes, such as those with 3 holes, 4 holes and 5 holes of each 0.23 mm diameter. The fuel mixture utilized in this research study consist of Diesel, PJB20 and PJB20 - amyl alcohol 30% consecutively. Contemporary diesel engines can take 30% consecutive amyl alcohol blends without engine modification. In older engines, higher biodiesel content (B50 or B100) can cause reduce energy density, impact fuel economy, power output, fuel filter clogging, injector deposits, and rubber and plastic compatibility concerns.

2. Experimental procedure

The experimental inquiry employs an engine layout, as illustrated in **Figure (1)** below, which consists of a single cylinder diesel engine. This engine is air cooled, vertically oriented, and utilizes direct injection technology. The system has the ability to provide a power output of 5.2 kilowatts while maintaining a constant rotational speed of 1500 rpm. It operates with a compression ratio of 16, 230 bar, 27^0 bTDC and injector nozzle of 3hole, 4hole and 5hole. Additionally, it is connected to an dynamometer. The input side of the engine is comprised of an air heater, an anti-pulsating drum and a device for detecting air temperature. The exhaust system of the engine comprises 3 components: an exhaust gas analyzer, an EGT indicator, and a smoke sampler. The configuration additionally includes an independent fuel measurement apparatus for quantifying the consumption of biodiesel blend. The test rig is equipped with a 64-bit data acquisition (DAQ) device for the purpose of capturing data on crank angle and cylinder pressure. The engine load was applied with a swinging field electrical dynamometer. It utilized in this study was comprised of a 5-kilo volt amp of AC, operating at a voltage of 230 V and a rotational speed of 1500 rpm. The alternator was securely mounted on a sturdy frame and its bearings specifically designed. The output power was determined through precise measurement of the reaction torque using a load cell of the strain gauge type. **Figure (2)** displays the injector with 3 hole, 4 hole and 5 hole nozzle geometry.

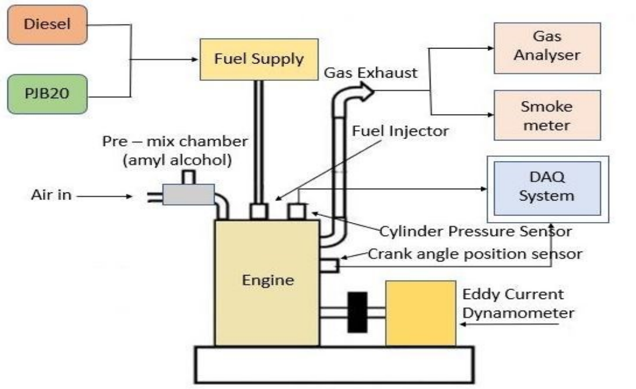


Figure 1. Experimental Layout

In the present research study, we have explored the new possibility of using prosopis juliflora as a raw material in biodiesel production through transesterification, which is the conventional method used for preparing biodiesel from non-food grade oils. This process starts by combining the prosopis oil extract with methanol, in the presence of potassium hydroxide as the catalyst. One of the most important things about this stage is the excess of alcohol, such as a 3:1 ratio between acrylate and oil, ensuring that the reactants get into sufficiently close contact for the reaction to convert the oil into biodiesel. The reaction also includes heating up the oil from prosopis juliflora with sodium hydroxide as a catalyst to 65°c for an hour. This stirring is done for good reaction kinetics and also for complete conversion of the oil. Generally, transesterification mechanism always yields two-layered products; the top layer consists of the desired product methyl ester also referred to as biodiesel while the bottom layer is glycerin that is excess. Separation of the clear top phase rich in biodiesel is then performed after the completion of the reaction. The biodiesel produced from transesterification requires further purification since the impurities exist in the separation step. This is done by calcium chloride further purification to dry the biodiesel and remove any water content present. From the above results, it was evident that about 90% of prosopis juliflora oil is converted into biodiesel which shows this oil can be utilized efficiently for biodiesel production. Amyl alcohol or pentanol are colorless liquid with typical odour and are generally produced from waste ethanol, though they are also synthesized. In biodiesel and dual-fuel engine researches, amyl alcohol, also known as pentanol, was utilized as an additive based on their favourable properties concerning combustion phenomenon, which are greater than that of ethanol and methanol; thus, they have a broader prospect as an additive with higher energy density. Moreover, amyl alcohol tends to make atomization and efficiency of combustion increase when blended into biodiesel. **Table 1** presents the properties of tested fuel.

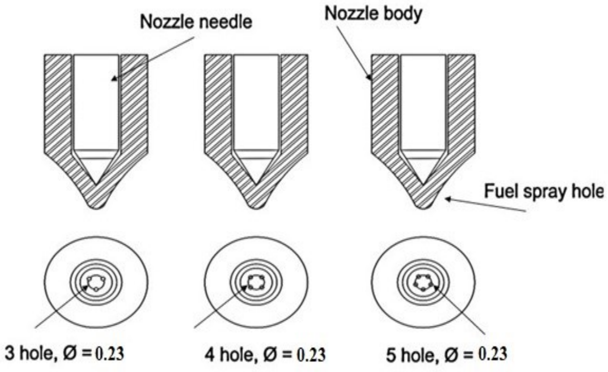


Figure 2. Injector with 3 hole, 4 hole and 5 hole nozzle geometry

2.1. Uncertainty analysis for experiments

The exhaust gas emissions measurement and performance parameter computation uncertainties are shown in **Table 2**. When determining the uncertainty of parameters that have been assessed based on two or more independent parameters,

$$\frac{Uy}{Y} = \sqrt{\left(\frac{Ux1}{x1}\right)^2 + \left(\frac{Ux2}{x2}\right)^2 + \left(\frac{Uxn}{xn}\right)^2} \quad (1)$$

The uncertainty Uy and the testing value y are respectively obtained from the evaluated parameters X_1, X_2, ...Xn.

Table 1. Tested properties of Diesel, PJB20 and Amyl alcohol

Properties	ASTM standard	Diesel	PJB20	Amyl alcohol
Density (kg/m^3) @20°C	875-900	840	839	815
Calorific Value (kJ/kg)	42000	43000	41769	34650
Viscosity (cSt)	1.9-6.0	2.5-3.2	2.854	2.89
Flashpoint (°C)	>60	65	82	71
Fire point (°C)	>65	78	90	77
Cetane number	47	45-55	45	20 - 25
Research Octane number (RON)	93	20-30	26	81
Auto-ignition temperature (°C)	204-538	316	320	421

Table 2. Experimental uncertainties

Parameters	BP	BTE	Pressure	TFC	SFC	EGT	NOx	CO	CO$_2$	HC
% uncertainty	±2.01	±2.10	±0.14	±0.669	±2.11	±0.25	±0.0001	±0.1	±0.5	±0.0005

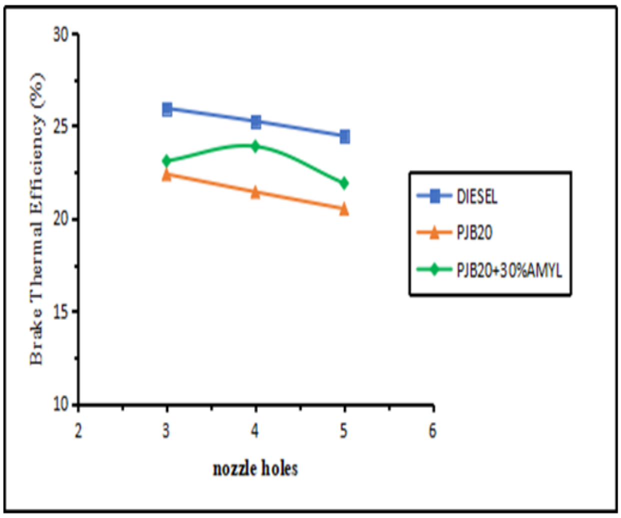


Figure 3. Brake thermal efficiency with nozzle holes

Uncertainties in performance parameters are calculated as given below,

Uncertainty in Brake power,

$$\frac{\Delta BP}{BP}=\sqrt{\left(\left(\frac{\Delta N}{N}\right)^2+\left(\frac{\Delta W}{W}\right)^2\right)} \quad \text{(a)}$$

Uncertainty in Brake thermal efficiency

$$\frac{\Delta BTE}{BTE}=\sqrt{\left(\left(\frac{\Delta BP}{BP}\right)^2+\left(\frac{\Delta mf}{mf}\right)^2\right)} \quad \text{(b)}$$

Uncertainty in specific fuel consumption,

$$\frac{\Delta SFC}{SFC}=\sqrt{\left(\left(\frac{\Delta mf}{mf}\right)^2+\left(\frac{\Delta BP}{BP}\right)^2\right)} \quad \text{(c)}$$

Measured exhaust emission values are subject to uncertainty based on the measurement range and resolution of the instrument for each emission component, and the values are calculated and expressed as follows: HC = ±0.005%, O_2 = ±0.04%,

CO = ±0.1%, CO_2 = ±0.5%, NO_x = ±0.00011% respectively.

In order to calculate the overall uncertainty of an experiment, one must add the uncertainties of each instrument and this is what is shown below.

The total percentage of experiment uncertainty,

$$\sqrt{\begin{array}{l}\left(\frac{\Delta BTE}{BTE}\right)^2+\left(\frac{\Delta TFC}{TFC}\right)^2+\left(\frac{\Delta SFC}{SFC}\right)^2+\left(\frac{\Delta BP}{BP}\right)^2+\left(\frac{\Delta CO}{CO}\right)^2\\+\left(\frac{\Delta HC}{HC}\right)^2+\left(\frac{\Delta NOX}{NOX}\right)^2+\left(\frac{\Delta P}{P}\right)^2+\left(\frac{\Delta EGT}{EGT}\right)^2\end{array}}$$

$$\sqrt{\begin{array}{l}(0.0210)^2+(0.0069)^2+(0.0211)^2+(0.02)^2+(0.001)^2\\+(0.00005)^2+(0.000001)^2+(0.0014)^2+(0.0025)^2\end{array}}$$

$$=\pm 3.664\%$$

2.2. Response Surface Methodology (RSM)

RSM is a numerical approach and data analysis tool widely used in designing and optimizing experiments involving multiple variables [15], [31], [35]. RSM provides actionable insights by clarifying the process of fitting models to collected data [10]. RSM was performed employing the central composite design were used for the design matrix, version 12.0 software containing 20 runs and it deals with three input variable of number of nozzle hole, fuel blend and loads which potentially affect the output responses of BTE for performance characteristics and NO_X for emission characteristics. The nozzle hole is varied from 3 to 5 holes, fuel blend is from 0 to 30% and load varies from 0 to 100%. **Table 3** shows the many factor combinations that were considered in the trials, and the appropriate response values were recorded according to the run order of the design matrix. Using regression and a second-order polynomial model, we evaluated the experimental output values. Significant theoretically, the created second-order polynomial equation establishes a link between input and output variables. The last step was to use fit models to generate response plots, which displayed the anticipated output responses. Every possible operating state of the yield is examined by this model. This model depends on the quadratic equation (1).

$$X = L_0 + L_1Y_1 + L_2Y_2 + L_{12}Y_1Y_2 + L_{11}Y_1^2 + L_{22}Y_2^2 \quad (1)$$

Where,

L_0 is the constant,

L_1 & L_2 is the coefficient. of linear term,

L_{12} is the coefficient of cross term,

L_{11} & L_{22} is the coefficient of quadratic term,

Y_1 and Y_2 are in-dependent operating variables respectively and

X is the output response.

After the experiment, the analysis of variance (ANOVA) was made use of in order to examine the model. The Desirability approach of RSM is carried out in order to carry out optimization, and the solution that has the maximum desirability is taken to be the optimal solution.

3. Result and discussion

The study analyzed the performance and emission characteristics of altering the nozzle hole numbers and it also examined the influence of diesel with PJB20 and PJB20-amyl alcohol 30% on dual fuel operation. The experiment was performed on a DI diesel engine, the impact of nozzle hole number was carried out only on full load condition while the speed being held at 1500 rpm during the entire experiment. Throughout the testing experiment, the fuel injection pressure was maintained at 230 bar, the injection timing was maintained at 27^0 bTDC, and the compression ratio was maintained at 16. In addition, the geometry of the nozzle hole was changed from three holes, four hole and five holes with RSM was performed for optimization.

Table 3. Design Matrix

Run Order	Variable A	Variable B	Variable C	Response 1 BTE (%)	Response 2 NOx (ppm)
	Nozzle (holes)	Fuel blend (%)	Load (%)		
1	4	20	25	16.26	569.25
2	3	30	25	18.26	435.6
3	4	20	50	18.26	879.75
4	4	20	50	18.26	879.75
5	4	20	100	21.43	1150
6	5	0	25	19.85	574.2
7	4	30	50	20.89	810.9
8	5	20	50	17.26	795.6
9	5	0	100	24.46	1166
10	3	30	100	23.44	883
11	4	20	50	18.26	879.75
12	3	20	50	18.73	956.25
13	3	0	100	25.95	1405
14	4	20	50	18.26	879.75
15	4	20	50	18.26	879.75
16	4	20	50	18.26	879.75
17	5	30	25	16.56	465.3
18	4	0	50	19.15	956.25
19	5	30	100	21.9	940
20	3	0	25	20.26	693

3.1. Effect on brake thermal efficiency

Figure (3) shows the relationship between the brake thermal efficiency with number of nozzle holes for the fuel blends of diesel, PJB20 and PJB20-amyl alcohol 30% for the 3 hole, 4 hole and 5 hole nozzle geometry. Greater BTE was seen with a three-hole nozzle with neat diesel and 3 hole nozzle for PJB20 fueled with diesel and 4 hole nozzle for PJB20 fueled with amyl alcohol 30% operation. On operation with PJB20-amyl alcohol 30% were 4 hole resulted in 3.30% and 8.32% higher BTE related to 3 hole nozzle injector and 5 hole nozzle injector. The characteristic nature of fuel atomization with proper spray dispersion the better penetration was observed with 4 hole nozzle instead of 3 and 5 hole nozzles. Among, the breakup and air entrainment goes to good penetration and fine droplets leads to well mixing of amyl alcohol with air and PJB20 mixture. Thus, a four-hole injector nozzle improves premixed combustion. Due to poor mixing with greater PJB20 flow rate inside the combustion chamber, 5 hole nozzles produced huge droplets with low injection velocity, fuel droplet momentum and decreasing BTE. For the same fuel inside the combustion chamber, Similar results were seen with 3-hole nozzle. A decreased fuel concentration in the air and a PJB20 combination with a reduced heat release rate could be the result of inadequate or missing fuel injection. On operation with PJB20 fueled with diesel were 3 hole resulted in 4.28% and 8.35% increased BTE instead of 4 and 5 hole nozzle injector respectively. Poor fuel mixing of PJB20 may have resulted from the higher mass flow rate caused by expanding the perforations. On operation with neat diesel were 3 hole resulted in 2.86% and 3.128% increased BTE instead of 4 and 5 hole nozzle injector respectively. It could be attribute to increasing the holes develops increased flow rate of fuel, lower vaporization, improper combustion and heat release rate. The BTE obtained for PJB20-amyl alcohol 30% actuated at nozzle hole 3, 4 and 5 were 23.1, 23.89 and 21.9% compared to 25.95% for neat diesel operation with 3 hole nozzle injector. Similar results were reported by Chetan Pawar, 2017 and Yaliwal *et al*. (2016).

3.2. Effect on oxides of nitrogen emissions

Figure (4) NOx emission levels for PJB20 fuelled with amyl alcohol 30% dual fuel operation contrasted to PJB20 fuelled with diesel and neat diesel with different types of injector nozzle holes designs over the full load range are represented. NOx levels with PJB20 fuelled with amyl alcohol 30% combination were found to be lower. This is mainly due to combined effect of poor combustion which have higher viscosity, lower energy density of PJB20 along with amyl alcohol 30% is the primary reason for this operation. Lower combustion temperature and inappropriate air consumption may also cause this tendency compared to neat diesel operation. However, PJB20 fuelled with amyl alcohol 30% and 4 hole injector nozzle emitted more NOx from the tail pipe. Higher heat release during pre-mixed amyl alcohol leads to greater atomization, fuel-air mixing, and combustion zone peak pressure and temperature. The 4 hole injector nozzle raised NOx levels by 16.85% and 11.48% contrasted to 3 and 5 hole nozzles. The decreased peak heat in the combustion region may be attributed to increasing the number of nozzle holes and adding fuel with PJB20 and amyl alcohol. At 3 hole injector operation, PJB20 with amyl alcohol flow rate was reduced, resulting in less fuel. PJB20 fuelled with diesel and neat diesel operating with 3 hole nozzle has greater NOx levels than 4 and 5 hole injectors due to better diesel-air mixing and increased combustion rate. The graphs show that a three-hole nozzle increases NOx emissions because nitrogen's reactive component combines with oxygen at a higher combustion zone temperature. The NOx emission obtained for PJB20 fuelled with amyl alcohol 30% condition at nozzle hole 3, 4 and 5 were 883, 1062 and 940 ppm related with 1405 ppm for neat diesel conditions with 3 hole nozzle (Yaliwal *et al*. 2016).

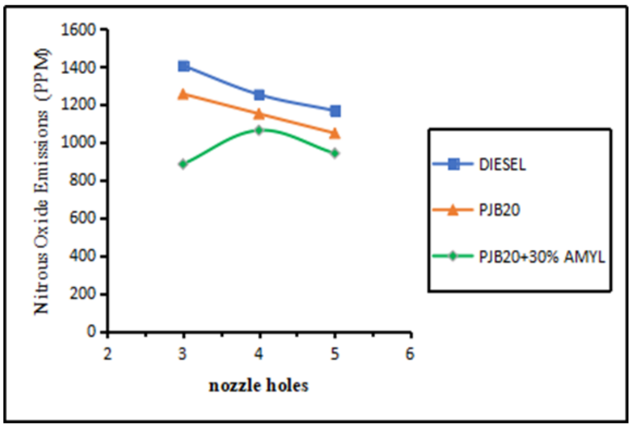


Figure 4. Oxides of nitrogen with nozzle holes

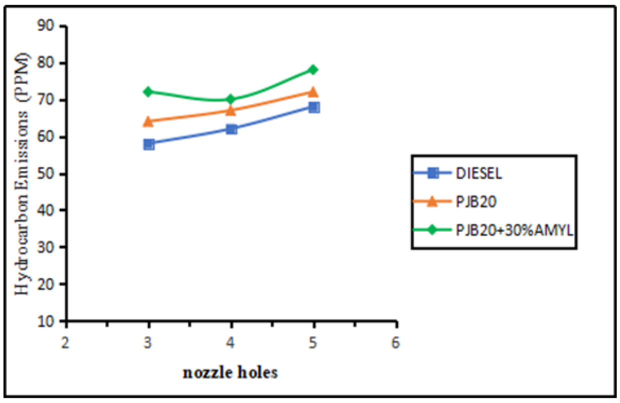


Figure 5. Hydrocarbon emission with nozzle holes

Table 4. Model Evaluation

Model	BTE	NOx
Mean	19.7	853.9
R-squared	0.9377	0.9844
Model degree	Quadratic	Quadratic
Adj. R^2	0.8816	0.8703
Pred. R^2	0.9254	0.8946

3.3. Effect on Unburnt hydrocarbon and Carbon monoxide Emissions

Variation of HC and CO emission levels for diesel, PJB20 and PJB20-amyl alcohol 30% with number of injector nozzle holes designs are represented in **Figure (5) and Figure (6)**. At full load conditions, HC and CO levels with PJB20 fueled with amyl alcohol 30% combination under dual fuel mode of operation were found to be higher compared to PJB20 fueled with diesel and neat diesel. Results of PJB20 fueled with amyl alcohol 30% showed that HC emissions were lower by 2.78 and 7.69% with a 4 hole nozzle compared to 3 and 5 hole nozzles, and CO emissions were lower by 7.63% and 6.14% with a 4 hole nozzle compared to 3 and 5 hole nozzles. It might be because the smaller amount of air and fuel mixed in makes the HC and CO burn more incompletely. The amount of CO formed is much higher when a three-hole injector tip is used with a PJB20 blended fuel mixture, which creates fast flames. When the five-hole injector nozzle is used, on the other hand, HC and CO emissions happen because the air and fuel are not mixed properly, which prevents the fuel from atomizing and vaporizing. This is also because the amyl alcohol 30% mixture does not penetrate well into the compressed air with PJB20, which results in more fuel deposition. In addition, PJB20 fueled with diesel operation with 3 hole injector nozzle results the lower HC and CO emission levels compared to the dual fuel operation with 4 and 5 hole injector nozzle. This might be because the PJB20 blended fuel mixture mixes air and fuel better, which makes the spray better with the 4 hole nozzle injector. Also, the same thing was seen when neat diesel was used on a 3-hole injector nozzle. It gave off less HC and CO than a 4 or 5 hole injector nozzle. This is because adding more holes to the nozzle makes the fuel move faster. The PJB20 that was fuelled with 30% amyl alcohol had HC emission levels of 72, 70, and 78 ppm for holes 3, 4, and 5. This is higher than the 58 ppm for neat diesel running with a 3-hole nozzle injector. Also, the CO emissions from a PJB20 engine that was fuelled with 30% amyl alcohol were 0.38, 0.35, and 0.37%, respectively, compared to 0.29% for a diesel engine running on its own with a three-hole nozzle injector. (Chetan *et al*. 2017; Yaliwal *et al*. 2016).

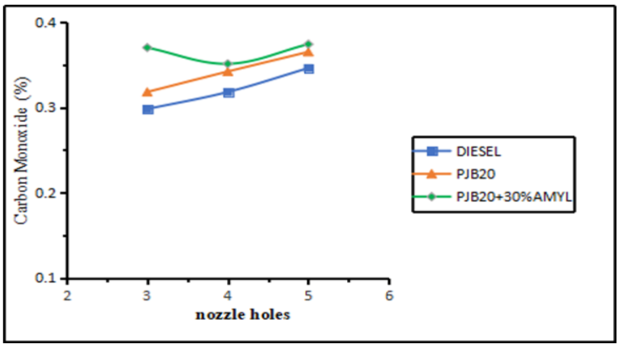


Figure 6. Carbon Monoxide with nozzle holes

Table 5. Criteria for Optimization

Factors	Lower levels	Upper levels	Importance	Lower Weight	Upper Weight	Target goal	Desirability
Nozzle	3	5	3	1	1	is in range	1
Fuel blend	0	30	3	1	1	is in range	1
Load	25	100	3	1	1	is in range	1
BTE	16.26	25.95	3	1	1	Maximize	0.951
NOx	435.6	1405	3	1	1	Minimize	0.986

Table 6. Experiments Valuation

Optimized Variables			Value	B_{th} (%)	NO_x (ppm)
Nozzle (holes)	Fuel Blend (%)	Load (%)			
4	27.40	86	Predicted	24.84	1056.7
			Actual	23.89	1062
			Error	0.95	5.3

3.4. Analysis of variance

An analysis instrument known as Analysis of Variance (ANOVA) provides mathematical information regarding the P-value and F-value. The probability that the null hypothesis in our regression model cannot be refuted is denoted by model F. The model is considered significant based on the F-value of 16.72. An F-value of this magnitude could only occur due to noise with a 0.01% probability, whereas model P represents the chance of obtaining an outcome at least as extreme as the one that was observed; P-values below 0.05 indicate that model terms are significant. A, B, C, AB, BC, and C^2 are all significant model parameters in this instance. When values exceed 0.1, it can be inferred that the model terms lacked significance. Reducing the number of insignificant model terms (excluding those necessary for hierarchy support) could potentially enhance the performance of your model. The brake thermal efficiency (Bth) and Nitrous Oxide (NO_X) regression equations are displayed below. (Models: A – nozzle, B – fuel blend and C – load).

$$\begin{aligned} B_{th} &= +22.3650 - 1.0370 \times Nozzle - 0.2749 \times Fuel\ blend \\ &+0.0758 \times Load - 0.011486 \times Nozzle \times Fuel\ blend \\ &-0.002939 \times Nozzle \times Load - 0.000211 \times Fuel\ blend \\ &\times Load + 0.092023 \times Nozzle^2 + 0.009201 \\ &\times Fuel\ blend^2 + 0.000069\ Load^2 \end{aligned} \tag{2}$$

$$\begin{aligned} NO_x &= +354.06 + 60.23 \times Nozzle - 9.310 \times Fuel\ blend + 22.20 \\ &\times Load + 3.4112 \times\ Nozzle \times Fuel\ blend - 0.1925 \times Nozzle \\ &\times Load - 0.086 \times Fuel\ blend \times Load - 20.1143 \times Nozzle^2 \\ &-0.2505\ Fuel\ blend^2 - 0.1004\ Load^2 \end{aligned} \tag{3}$$

3.5. Evaluation of the model

ANOVA is utilized to assess the stability of the BTE model; the results are shown in **Table 4**. Based on the data in the table, the Predicted R^2 of 0.9254 and the Adjusted R^2 of 0.8816 exhibit a reasonable degree of agreement, with a difference of less than 0.2. This may suggest the absence of a significant block effect or a potential issue with the model and/or data. Adeq Precision quantifies the ratio of signal to noise. A ratio in excess of four is preferable. Your 14.180 ratio signifies a sufficient signal. It is possible to navigate the design space using this model. Furthermore, the ANOVA results for the NOx model stability analysis are provided in **Table 4**. The predicted R^2 of 0.8946 and the modified R^2 of 0.8703 are within a reasonable margin of agreement. (i.e.) The discrepancy is under 0.2. Adeq Precision quantifies the ratio of signal to noise. A ratio in excess of 4 is preferable. Your 33.128 ratio signifies a sufficiently strong signal. It is possible to navigate the design space using this model. Similar range of R^2, Adj. R^2, Pre. R^2 and accuracy was observed RSM optimization technique (Shameer *et al*. 2017).

With P-values below 0.0001, the model is determined to be stable based on the data in the table. The table presents regression statistics, including the corrected R^2 and the goodness of fit (R^2), which exhibit a satisfactory level of agreement with one another, as evidenced by the difference of less than 0.2. The R^2 value represents the overall variability of the response when significant factors are accounted for. The adj. R^2 denotes the number of predictors incorporated in the model. It can be deduced from the values of R^2 and adj. R^2 that the model provides an exceptionally good fit to the data. (Atmanli *et al*. 2015)

3.6. Optimization of process parameters by using RSM

Table 5 shown the optimize criteria selected for the parameters used in the engine operation for nozzle hole, fuel blend and load observed in RSM methodology (Ibham *et al*. 2023; Sushrut *et al*. 2023). The goal was given to the responses for the brake thermal efficiency as maximum and nitrous oxide as minimum. In the desirability approach, the performance and emission responses allocated to BTE and NOx, respectively, are assigned the highest priority of 3. There are numerous levels of optimal solutions within the desirability approach, and solutions with high desirability were favoured. By adjusting weights and scaling, the Derringer Desirability technique provides flexibility in setting and prioritizing targets based on specific study objectives. Maximum desirability was achieved at 0.986 under the specified engine conditions (four-hole nozzle, 27.42% fuel blend, and 86% load). According to reference (Atmanli *et al*. 2015), optimal solutions are defined as the value of the factor at which desirability is greatest.

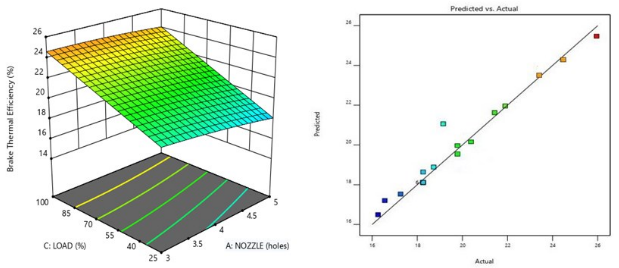


Figure 7. Response Surface for BTE with its Predicted vs Actual graph

Additionally, tests are carried out to find the best settings for a 4-hole nozzle a fuel blend of 27.40%, and a load of 86%. A test that is done three times is used to check the predicted response numbers [4]. **Table 6** shows that the predicted and experimental values are very congruent with one another. This means that the models were correct.

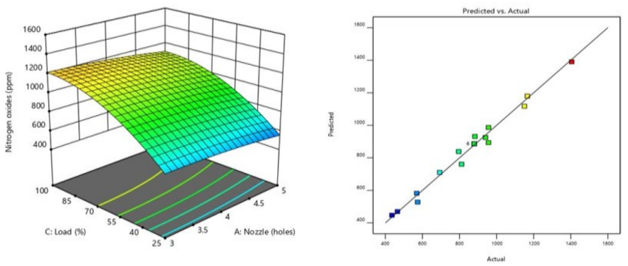


Figure 8. Response Surface for NOx Emissions with its Predicted vs Actual graph

3.7. Response Surface results for BTE and NO$_x$

Figure (7) shows the response surfaces and contour plots of BTE against nozzle, fuel blend and load because it has a direct impact on efficiency and emissions, making them crucial characteristics to monitor throughout operation. The analysis graph help to determine the value of input parameter variation with RSM predicted output responses. The BTE of the fuel blend is to be increasing with increase the amyl alcohol and PJB20 blend mixture ratio. This may due to good penetration and fine droplets leads to well mixing of amyl alcohol with air and PJB20 mixture. The increase of thermal efficiency because of increases the injector nozzle hole from three hole to five hole at full load condition develops maximum fuel entering inside the combustion chamber became better penetration. Optimum BTE was predicted as 24.84% at a combination of 4 hole, 27.40 % fuel blend and 86% of engine load condition at the obtained maximum desirability of 0.951. It is also observed that BTE are high at high load and least at low load of the engine.

NOx emission is depends on engine maximum temperature. **Figure (8)** represents the NOx emission was directly proportional to nozzle hole, fuel blend and engine load. As observed that NOx emission are decreasing with addition of amyl alcohol and PJB20 mixture blend percentage. The results presented in **Table 5** indicate that the maximum NOx emissions of 1405 ppm were recorded at 3 holes, operating with 100% engine load and neat diesel, while the lowest NOx emissions of 435.6 ppm were detected at 3 holes, using 30% fuel blend, and 25% engine load. NOx emission inside the combustion chamber are happens by addition of amyl alcohol and PJB20 blend ratio. In diesel engine, NOx emission are maximum at 100% engine load condition develops high pressure and temperature inside the combustion chamber. There is decreasing NOx emission due to combined effect of amyl alcohol and PJB20 blend with poor combustion which have lower energy density, higher viscosity of PJB20 along with amyl alcohol 30% is the primary reason for this operation. Optimum NOx was predicted as 1056.7 ppm at a combination of 4 hole, 27.40 % fuel blend and 86% of engine load condition at the obtained maximum desirability of 0.986.

4. Conclusions

Experiments were conducted in a dual fuel CI engine to optimize its performance and emission characteristics using response surface methodology (RSM) approaches. This was achieved by adding a PJB20 mixture and pre-mixing amyl alcohol with ambient air. The nozzle hole number were varied to determine the most optimal configuration. The experiment provided the following conclusion by altering the nozzle hole number to 3, 4, and 5 holes for the tested fuels (Diesel, PJB20, and PJB20-amyl alcohol 30%) in a dual fuel engine.

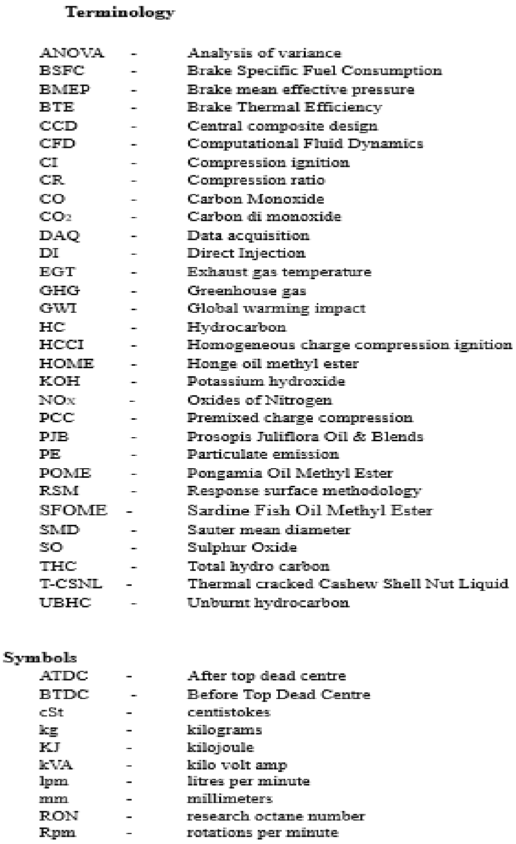
According to the experiment's findings, it was observed that the engine was functioning on a mixture of PJB20-amyl alcohol at a 30% concentration, it exhibited higher BTE and lower BSFC. This was attributed to the use of a 4-hole injector nozzle, which allowed for better fuel penetration and the formation of smaller fuel droplets. As a result, there was improved mixing of the amyl alcohol with the air and PJB20 mixture. On the 3 and 5 holes, partial combustion and a low fuel injection flow rate resulted in a reduction in BTE and an increase in BSFC. Thus, a four-hole injector nozzle enables improved premixed combustion.

The NOx emissions resulting from the combination of PJB20 and amyl alcohol 30% were shown to be lower when using nozzle holes 3, 4° and 5° compared to neat diesel operation with 3-hole. Injector nozzle 4 hole value seen that higher NOx levels by 16.85% and 11.48% in contrast to 3 and 5 hole nozzle.

Under full load conditions, the levels of CO and HC increased as the size of the nozzle hole increased. However, when using a 4 hole injector nozzle, there was a decrease in CO emissions by 0.35% and HC levels by 70 ppm compared to using a 3 hole or 5 hole injector nozzle.

The empirical data was utilized to construct response surface models. The optimal values for predicted BTE and NOx in a dual fuel engine were determined to be 24.843% and 1056.7 ppm respectively. Optimum performance and minimum emissions were attained by utilizing a 4-hole injector nozzle with a fuel blend consisting of 27.40% and operating at a load of 86%. The desirability technique of RSM generated a highest desirability value of 0.951 for BTE and a value of 0.986 for NOx among all the numerical solutions.

The experimental test data and RSM optimized value exhibited strong agreement throughout the entire operation, providing valuable in analysing the impact of different variables on engine performance and emission. The research conducted on amyl alcohol 30% in combination with the PJB20 mixture explores the potential of using these substances as alternative and sustainable fuels for diesel engines. Operating in dual mode necessitates no alteration to the existing diesel engine and offers significant advantages in terms of enhanced BTE while lowered NOx emissions is a foremost global climate challenge compared to neat diesel engine operation.



Terminology

ANOVA - Analysis of variance
BSFC - Brake Specific Fuel Consumption
BMEP - Brake mean effective pressure
BTE - Brake Thermal Efficiency
CCD - Central composite design
CFD - Computational Fluid Dynamics
CI - Compression ignition
CR - Compression ratio
CO - Carbon Monoxide
CO_2 - Carbon di monoxide
DAQ - Data acquisition
DI - Direct Injection
EGT - Exhaust gas temperature
GHG - Greenhouse gas
GWI - Global warming impact
HC - Hydrocarbon
HCCI - Homogeneous charge compression ignition
HOME - Honge oil methyl ester
KOH - Potassium hydroxide
NOx - Oxides of Nitrogen
PCC - Premixed charge compression
PJB - Prosopis Juliflora Oil & Blends
PE - Particulate emission
POME - Pongamia Oil Methyl Ester
RSM - Response surface methodology
SFOME - Sardine Fish Oil Methyl Ester
SMD - Sauter mean diameter
SO - Sulphur Oxide
THC - Total hydro carbon
T-CSNL - Thermal cracked Cashew Shell Nut Liquid
UBHC - Unburnt hydrocarbon

Symbols

ATDC - After top dead centre
BTDC - Before Top Dead Centre
cSt - centistokes
kg - kilograms
KJ - kilojoule
kVA - kilo volt amp
lpm - litres per minute
mm - millimeters
RON - research octane number
Rpm - rotations per minute

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References

Akhilendra P.S., And garwal A.k. (2012). Combustion characteristics of diesel HCCI engine: An experimental investigation using external mixture formation technique *Applied Energy*, **99**, 116–125, https://doi.org/10.1016/j.apenergy.2012.03.060

Allasi H.L., Rajalingam A., Jani S.P. and Uppalapati S. (2023). Influence of Synthesized (Green) Cerium Oxide Nanoparticle With Neem (Azadirachta Indica) Oil Biofuel, *Bulletin of the Chemical Society of Ethiopia*, **37**(2), 477–490. https://doi.org/10.4314/bcse.v37i2.16

Arturo D R., Donateo T. and Laforgia D. (2003). Optimization of the Combustion Chamber of Direct Injection Diesel Engines *SAE Technical Paper* 2003-01-1064, 2003, https://doi.org/10.4271/2003-01-1064.

Atmanli A., Yuksel B., Ileri E., Deniz Karaoglan A. (2015). Response surface methodology based optimization of diesel-n-butanol -cotton oil ternary blend ratios to improve engine performance and exhaust emission characteristics, *Energy Conversion and Management,* **90**, 383–394. https://doi.org/10.1016/j.enconman.2014.11.029

Banapurmath N.R., Tewari P.G., Yaliwal V.S., Satish Kambalimath and Basavarajappa Y.H. (2009). Combustion characteristics of a 4-stroke CI engine operated on Honge oil, Neem and Rice Bran oils when directly injected and dual fuelled with producer gas induction *Renewable Energy*, **34**(7), 1877–1884, https://doi.org/10.1016/j.renene.2008.12.031.

Battistoni M., Som S. and Powell C.F. (2019). Highly resolved Eulerian simulations of fuel spray transients in single and multi-hole injectors: Nozzle flow and near-exit dynamics, Fuel, **251**, 709–729. https://doi.org/10.1016/j.fuel.2019.04.076

Chetan P., Kulkarni P. and Adwant A. (2017). Effect of Nozzle Geometry on The Performance of Dual Fuel engine Operated on Rbome and Producer Gas, *International Journal of Research Publications in Engineering and Technology* [IJRPET], **3**(6).

Choi S., Shin S.H., Lee J., Min K. and Choi H. (2015). The effects of the combustion chamber geometry and a double-row nozzle on the diesel engine emissions, Proceedings of the Institution of Mechanical Engineers, Part D: *Journal of Automobile Engineering*, **229**(5), 590–598. doi:10.1177/0954407014547748

Dilsher K. and Geetesh G. (2022). Evaluation of emission characteristics & performance of a biogas-biodiesel dual fuel engine using blends of butanol in different ratios, *Materials Today: Proceedings*, https://doi.org/10.1016/j.matpr.2022.11.452.

Ganesh B., Barmavatu P., Pohorely M., Jeremias M. and Sikarwar V.S. (2024). Optimization of value-added products using response surface methodology from the HDPE waste plastic by thermal cracking, Thermal Science and Engineering Progress, **50**, 102514, https://doi.org/10.1016/j.tsep.2024.102514.

Gawale G. and Srinivasulu N. (2020). Numerical and experimental investigations on a dual fuel HCCI engine by using ethanol as primary fuel and diesel as secondary fuel for NOX reduction and better performance, *International Journal of Ambient Energy*, **41**, 418–427.

Guo H., Zhou S., Shreka M. and Feng Y. (2019). Effect of Pre-Combustion Chamber Nozzle Parameters on the Performance of a Marine 2-Stroke Dual *Fuel Engine* Processes **7**(12), 876. https://doi.org/10.3390/pr7120876

Halewadimath S.S., Banapurmath N.R., Yaliwal V.S., Gaitonde V.N., Yunus Khan T.M., Vadlamudi C., Krishnappa S. and Sajjan A.M. (2023). Experimental Investigations on Dual-Fuel Engine Fuelled with Tertiary Renewable Fuel Combinations of Biodiesel and Producer-Hydrogen Gas Using Response Surface Methodology, *Sustainability*, **15**, 4483. https://doi.org/10.3390/su15054483

He Z., Guo G., Tao X., Zhong W., Leng X., and Wang Q. (2016). Study of the effect of nozzle hole shape on internal flow and spray characteristics, International Communications in Heat and Mass Transfer, **71**, 1–8. https://doi.org/10.1016/j.icheatmasstransfer.2015.12.002

Huang W., Moon S., Gao Y., Wang J., Ozawa D. and Matsumoto A. (2019). Hole number effect on spray dynamics of multi-hole diesel nozzles: An observation from three- to nine-hole nozzles. *Experimental Thermal and Fluid Science*, **102**, 387–396. https://doi.org/10.1016/j.expthermflusci.2018.12.022

Ibham V., Spraggon M., Fattah I.M.R. and Idris M. (2023). Response surface methodology (RSM) for optimizing engine performance and emissions fuelled with biofuel: Review of RSM for sustainability energy transition, *Results in Engineering*, **18**, 101213. https://doi.org/10.1016/j.rineng.2023.101213.

Jaikumar S., Bhatti S.K., Srinivas V. and Rajasekhar M. (2020). Vibration and noise characteristics of CI engine fueled with Niger seed oil methyl ester blends and hydrogen, *International Journal of Environmental Science and Technology*, **17**(3), 1529–1536. https://doi.org/10.1007/s13762-019-02443-y

Jan M. and Kasyk L. (2021). Optimization of Design and Technology of Injector Nozzles in Terms of Minimizing Energy Losses on Friction in Compression Ignition Engines *Applied Sciences*, **11**(16):7341, DOI:10.3390/app11167341

Jinbao Z., Hao Z., Wang D., Di Y., Peng H., Wu T. and Miao X. (2022). Effect of double-layer hole nozzle with narrow spray angle on combustion and emissions in dual-fuel natural gas engine *Fuel*, **314**, 123090. https://doi.org/10.1016/j.fuel.2021.123090

Junho O.H., Sechul, O.H., Kim C., Lee S., Lee S., Jang H. and Lee J.W. (2022). Effect of multi-angle diesel injector nozzle on emission and efficiency of natural gas/diesel dual-fuel combustion in compression ignition engine, *Fuel*, **316**, 123442. https://doi.org/10.1016/j.fuel.2022.123442

Kamaraj R.K., Thankachi Raghuvaran J.G., Panimayam A.F. and Allasi H.L. (2018). Performance and exhaust emission optimization of a dual fuel engine by response surface methodology, *Energies*, **11**(12), https://doi.org/10.3390/en11123508

Kenta K., Motegi T., Hori T. and Akamatsu F. (2022). Influence of nozzle design parameters on exhaust gas characteristics in practical-scale flameless hydrogen combustion, *International Journal of Hydrogen Energy*, **47**(49), 21287-21297. https://doi.org/10.1016/j.ijhydene.2022.04.230

Krishnamoorthi M., Malayalamurthi R., Mohamed Shameer P. (2018). RSM based optimization of performance and emission characteristics of DI compression ignition engine fuelled with diesel/aegle marmelos oil/diethyl ether blends at varying compression ratio, injection pressure and injection timing, *Fuel*, **221**, 283–297. https://doi.org/10.1016/j.fuel.2018.02.070

Nandakumar C., Raman V., Saravanan C.G., Vikneswaran M., Prasanna Raj Yadav S. and Thirunavukkarasu M. (2021). Effect of nozzle hole geometry on the operation of kapok biodiesel in a diesel engine, *Fuel*, **276**, https://doi.org/10.1016/j.fuel.2020.118114

Nordgren H., Hultqvist A. and Johansson B. (2004). Start of Injection Strategies for HCCI- combustion, *SAE Technical Paper* 2004-01-2990, https://doi.org/10.4271/2004-01-2990

Onofrio G., Napolitano P., Tunestal P. and Beatrice C. (2021). Combustion sensitivity to the nozzle hole size in an active pre-chamber ultra-lean heavy-duty natural gas engine, *Energy*, 235, https://doi.org/10.1016/j.energy.2021.121298

Patrick R., Yip H.L., Srna A., Zhai G., Wehrfritz A., Kook S., Hawkes E.R. and Chan Q.N. (2023). Hydrogen-diesel dual-fuel direct-injection (H2DDI) combustion under compression-ignition engine conditions, *International Journal of Hydrogen Energy*, **48**(2), 766–783. https://doi.org/10.1016/j.ijhydene.2022.09.241.

Prabhu K.N., Gugulothu S.K., Reddy R.V., Barmavatu P. (2024). Trade-off study on environmental aspects of a reactivity controlled compression ignition engine using 1-hexanol and jatropha oil/diesel in dual fuel mode, *Applied Thermal Engineering*, **246**, 122891. https://doi.org/10.1016/j.applthermaleng.2024.122891.

Prathiba R., Rahiman M.K., Barmavatu P., Aryasomayajula Venkata Satya Lakshmi S.B., Meenakshisundaram N. (2024). Catalytic pyrolysis of polypropylene and polyethylene terephthalate waste using graphene oxide-sulfonated zirconia (GO-Szr) and analysis of its oil properties for Bharat Stage VI fuel production, *Environmental Quality Management*, **33**(4), 501–511. https://doi.org/10.1002/tqem.22106

Rajesh S.P., Retnam B S.J., Dhas J E.R., Lenin A. H. and Manjunathan A. (2022). Specific Fuel Consumption and Exhaust Emission Test on Single Cylinder Four-Stroke Diesel Engine using Polyethylene Extract Biodiesel as Fuel *International Journal of Vehicle Structures and Systems*, **14**(3), 2022, 339–341. https://doi.org/10.4273/ijvss.14.3.11

Rajesh S.P., Retnam B.S.J., Devanand M., Lenin A.H. and Manjunathan A. (2022). Performance Analysis on PP blended Bio-Diesel tested on a CI Engine, *International Journal of Vehicle Structures and Systems*, **14**(3), 333–335. https://doi.org/10.4273/ijvss.14.3.09

Sagari J.K., Sukhvinder Kaur B., Vadapalli S., Dadi V.T., Guddanti S.S. and Lakkoju S.K. (2020). Comprehensive performance, combustion, emission, and vibration parameters assessment of diesel engine fuelled with a hybrid of niger seed oil biodiesel and hydrogen: response surface methodology approach, *SN Applied Sciences*, **2**(9), 2020 https://doi.org/10.1007/s42452-020-03304-x

Shameer P.M. and Ramesh K. (2017). Influence of antioxidants on fuel stability of Calophyllum inophyllum biodiesel and RSM-based optimization of engine characteristics at varying injection timing and compression ratio, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **39**(11), 4251–4273. https://doi.org/10.1007/s40430-017-0884-8

Shijun D., Yang C., Ou B., Lu H. and Cheng X. (2018). Experimental investigation on the effects of nozzle-hole number on combustion and emission characteristics of ethanol/diesel dual-fuel engine, *Fuel*, **217**, 1–10, https://doi.org/10.1016/j.fuel.2017.12.024

Shinde T.B. (2012). Experimental investigation on effect of combustion chamber geometry and port fuel injection system for CNG engine, *IOSR Journal of Engineering* (IOSRJEN,) **2**(7), 49–54.

Shiquan F., Zhang S., Zhang H. and Shi J. (2024). Effect of nozzle geometry on combustion of a diesel-methanol dual-fuel direct injection engine, *Fuel*, **357**, 129734. https://doi.org/10.1016/j.fuel.2023.129734

Yaliwal V.S., Banapurmath N.R., Gireesh N.M., Hosmath R.S., Donateo T. and Tewari P.G. (2016). Effect of nozzle and combustion chamber geometry on the performance of a diesel engine operated on dual fuel mode using renewable fuels, *Renewable Energy*, **93**, 483–501, https://doi.org/10.1016/j.renene.2016.03.020

Zhiyong L., Wang Y., Yin Z., Gao Z, Wang Y. and Zhen X. (2022). An exploratory numerical study of a diesel/methanol dual-fuel injector: Effects of nozzle number, nozzle diameter and spray spacial angle on a diesel/methanol dual-fuel direct injection engine, *Fuel*, **318**, 123700, https://doi.org/10.1016/j.fuel.2022.123700