

Monitoring Exhaust Emissions of A Direct Injection Diesel Engine Fueled With Linseed Oil Biodiesel - Hydrogen Dual Fuel

K. Udaya Sri, B S N Murthy, N. Mohan Rao

Abstract This study presents an experimental and analytical investigation on the effects of using methyl ester of linseed oil (MELO)-diesel blend of B10, B20, and B30 with hydrogen injection of 5%, 10%, and 15% in a VCR (Variable Compression Ratio) diesel engine, operated with the compression ratios (CRs) of 15, 16, 17, and 18 on DFM (dual fuel mode). This study also gives emphasis on the optimized emissions of CO, CO₂, NO, and smoke, when the engine was operated with MELO-diesel blends, and hydrogen injections with the variation in engine load, crank angle (CA), using response surface methodology (RSM) with the help of MINITAB programming. During the analysis it was observed that the emissions of CO, CO₂, O₂, NO, and smoke were found to be a function of biodiesel blends, compression ratios, load, and percentage of hydrogen injection. The research results report that, the dual fuel mode of diesel MELO 20% blend with hydrogen injection of about 10% gave optimized results in terms of performance and exhaust emissions, while the optimized CR was 17. The engine was smoothly operated with B20-H10-CR17 over lower emissions compared to diesel, throughout the load spectrum.

Keywords: Diesel Engine; Methyl ester of linseed oil (MELO); Response surface methodology (RSM); Hydrogen; Dual fuel.

I. INTRODUCTION

Energy has become one of the basic needs in day to day life and plays an important role in automobile, locomotive, power plants, public sectors and various categories of industries. Advances in technology made the human life more comfortable, which created lots of energy demand, which is basically dependent on fossil fuels in the global market. But, fossil fuels are non-renewable sources of energy and there's an alert on petroleum diesel in coming decades because, the consumption has drastically gone up because of rapid industrialization. The consumption of mineral diesel can be reduced drastically by the use of biodiesel fuels [1].

Biodiesel is a clean burning and renewable fuel alternative to mineral diesel made predominantly from various type vegetable oils. Biodiesel physical and chemical properties are closely similar to normal diesel; hence it can be mixed and used as a blend with diesel. Biodiesel has better ignition and combustion characteristics due to a high cetane

index, which allows the engine to run more smoothly with less of the knocking compared to typical diesel engines. Biodiesel substantially reduces exhaust emissions such as unburned hydrocarbons (UHC), carbon monoxide (CO) and particulate matter (PM). It contains naturally occurring oxygen, which enables the fuel to burn more completely, but eliminates the black smoke normally associated with diesel engines. Biodiesel operated engines may offer a slight increase in NO_x emissions, but this is dependent on the engine type and its operating environment. Apart from this, biodiesel is biodegradable and nontoxic, which makes it a safer and more environmentally friendly fuel to handle, particularly in sensitive areas. Biodiesel is naturally free of Sulphur and produces no Sulphur dioxide (SO₂), which is considered to be one of the main precursors to acid rain [2-4]. Biodiesel is made from renewable resources, which means it reduces the contribution of carbon dioxide, which is one of the main greenhouse gases to the atmospheres. Biodiesel as a 5% blend with mineral diesel, referred to as B5 is now permitted within the EN590 mineral diesel specification across Europe. In the UK, the recommend blend percentage is B20 which is universally accepted by the end users. Similarly, American truck and bus operators prefer a blend of B20 according to US biodiesel standard ASTM D6751. The B20 blend currently provides commercial vehicle operators in various countries in the world with the optimal cost versus benefit balance [5].

The use of hydrogen with biodiesel gives two fold benefits over the only diesel operation. Hydrogen with its significant combustion characteristic seems to be ascertained itself as the preeminent transportation fuel for the future [6, 7]. Hydrogen finds application as a fuel in CI engines in dual fuel mode (DFM), without any major engine modifications, and without drop in output power. However, operating the CI engine with hydrogen is a big challenge because; hydrogen has a high auto-ignition temperature of about 840 °C and low fire limit. Also, it has some critical issues concern to its safe handling due its high burning speed [6, 8]. This difficulty can be eliminated by the use of fuel having the high auto-ignition property [9]. For this purpose, biodiesel is a righteous option. Because, high cetane number of biodiesel can drastically reduce the ignition delay [10, 11].

At present, the use of hydrogen in CI engines on DFM is an emerging research theme for many researchers [12-19].

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In the recent past, some of the researchers had investigated the critical issues associated with the use of hydrogen in diesel engines. The research results revealed that the use of hydrogen drastically reduces the emissions of CO, HC, CO₂, and smoked, but it contributed an increase in NO emission [6-8, 11, 13, 16-19]. Chintala and Subramanian [6] investigated the use of hydrogen in a diesel engine of rated power 7.4 kW run at 1500 rpm on dual fuel. Their investigation indicated that dual fuel operation gave an improved performance (i.e., BTE increased by about 14-20%) and the combustion characteristics of the engine were also excellent without any knocking phenomenon at a higher compression ratio of 19.5. Another investigation carried by Saravanan et al. [18] on the use of hydrogen in a 3.7 kW, single cylinder CI engine operated on dual fuel mode indicates that the BTE of the engine increased by about 20%, and the NO emission was higher by about 13% compared to diesel. A drastic reduction in the CO, CO₂ and smoke emission was observed, but the HC emission was marginally higher in comparison with diesel throughout the load spectrum. De-Morais et al. [20] investigated the use of hydrogen in a four-cylinder CI engine. They observed that a maximum of about 20% hydrogen energy share is possible to operate the engine smoothly. Beyond this limit, the ignition delay will be longer, and the heat loss to the surrounding through the exhaust will increase drastically. Masood et al. [21] computationally and experimentally investigated the combustion of hydrogen in a CI engine on dual fuel mode

with diesel as the pilot injected fuel. Their investigation reveals that, the efficiency of the engine increased to 30% at a compression ratio of 24.5. Also, they reported that, the emission of CO, CO₂ and smoke decreased, but NO emission increased. This study presents an experimental and analytical investigation on the effects of using methyl ester of linseed oil (MELO) blend of B10, B20, and B30 with the hydrogen induction of 5%, 10%, and 15% in a VCR diesel engine with the compression ratio (CR) of 15, 16, 17, and 18 on DFM. This study also gives emphasis to the optimized emissions of CO, CO₂, NO, and smoke, when the engine was operated with B10, B20, B40 and hydrogen induction of 5%, 10%, and 15% with the variation in engine load, crank angle (CA), and the CR using Response Surface Methodology (RSM) concept by the use of MINITAB.

II. MATERIALS AND METHODS

A. Fuels used

The fuels used in the present investigation are diesel, linseed biodiesel, and hydrogen. The fuels were procured from the local supplier in Moinabad, Telangana, India. The physio-chemical properties of the fuels were examined to check its suitable application in a VCR engine. The detailed properties of diesel and MELO are given in Table 1. The properties of hydrogen are given in Table 2.

Table 1: Properties of diesel and MELO

| Properties | Test method (ASTM) | Diesel | MELO | B10 | B20 | B40 |
|------------------------------|--------------------|---------|---------|---------|---------|---------|
| Density, kg/m ³ | D 4052 | 830 | 870 | 834 | 838 | 846 |
| Cetane number | D 613 | 50 | 56 | 50.6 | 51.2 | 52.4 |
| Calorific value, kJ/kg | D 4809 | 43800 | 40870 | 43507 | 43214 | 42628 |
| Auto-ignition temperature °C | E 659 | 210-350 | 150-330 | 175-340 | 160-310 | 155-300 |
| Fire point, °C | D 93 | 56 | 245 | 180 | 190 | 215 |
| Flash point, °C | D 93 | 50 | 210 | 140 | 150 | 167 |

Table 2: Properties of hydrogen

| Properties | Test method, ASTM | Hydrogen |
|-------------------------------|-------------------|----------|
| Density, kg/m ³ | D 3588 | 0.089 |
| Octane number | D 2699 | 130 |
| Calorific value, MJ/kg | D 1945 | 141.79 |
| Auto-ignition temperature, °C | - | 570 |
| Fire point, °C | - | -240.2 |
| Flash point, °C | - | -253 |

17:1, swept volume 661.45 cm³ and output power of 3.5 kW @ 1500 rpm. The engine run for different CRs like 15, 16, 17, and 18 with MELO blends of conventional diesel, B10, B20, and B40 along with H₂ addition for 5%, 10%, and 15% to test the exhaust emissions. Total five input parameters are chosen to run the engine and the emission results were captured. The layout of the experimental setup is shown in Figure 1. The engine was coupled with an eddy current dynamometer for loading, and the data were captured in a computer. First the engine was set at a CR of 15 and the engine was run with conventional diesel.

B Experimental setup

The engine used in the present investigation was of single cylinder, four stroke, constant speed, water cooled, and diesel engine with a cylinder bore of 87.5 mm, stroke length of 110 mm, connecting rod length 234 mm, compression ratio



The base readings are taken for CR 15. The readings are taken for different loading conditions ranging from no load to full load at constant speed of 1500 rpm. For emission measurement of the engine was carried out with the use of multi gas analyzer MN-05 and the smoke emission was measured with a diesel smoke meter MODEL SM-05. Then 5% hydrogen gas was passed into the intake manifold. Again the readings were taken for different percentages of hydrogen of 10% and 15% at constant speed of 1500 rpm for blend B10.

The experimental results for B10-H₂ 5%, B10-H₂10%, and B10-H₂15% were recorded for CR of 15. The experiments were repeated in similar was for CRs of 16, 17, and 18 with MELO blends of B20, and B40 along with H₂ addition for 5%, 10%, and 15%. The test matrix and the acronyms used for diesel, MELO and MELO-H₂ operation are given in Table 3.

1 Hydrogen cylinder, 2 Hydrogen regulator, 3 Flash back arrestor, 4 Flame arrestor, 5 Hydrogen flow meter, 6 Engine, 7 Clinker pressure sensor, 8 Mixing chamber, 9 Exhaust flow pipe, 10 Calorimeter, 11 Exhaust gas, 12 Exhaust gas analyzer probe, 13 Exhaust gas analyzer, 14 Power supply, 15 Eddy current dynamometer, 16 Engine water inlet pipe line, 17 Flywheel, 18 Fuel tank, 19 U-tube manometer, 20 Loading unit, 21 Rotameter, 22 Computer, 23 Hydrogen gas flow pipe, 24 Exhaust gas, 25 Air supply, 26 Calorimeter water inlet, 27 NI-6210 USB multifunction line, 28 Control panel, 29 Burette.

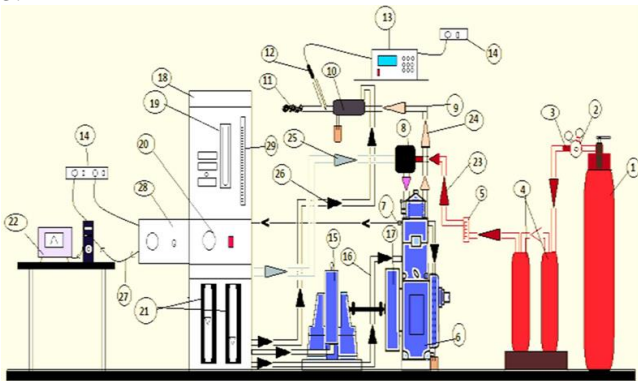


Fig 1: Layout of experimental setup.

Table 3: Test matrix and the acronyms used

| 1 | Mode | Fuel | CR | D-MELO blend, % | H ₂ , % | Acronyms used |
|----|--------|----------------------------|----|-----------------|--------------------|----------------------------|
| 2 | Diesel | Diesel | 15 | B0 | - | Diesel |
| 3 | Dual | Diesel-MELO-H ₂ | 15 | B10 | 5 | B10-H ₂ 5-CR15 |
| 4 | Dual | Diesel-MELO-H ₂ | 15 | B10 | 10 | B10-H ₂ 10-CR15 |
| 5 | Dual | Diesel-MELO-H ₂ | 15 | B10 | 15 | B10-H ₂ 15-CR15 |
| 6 | Dual | Diesel-MELO-H ₂ | 15 | B20 | 5 | B20-H ₂ 5-CR15 |
| 7 | Dual | Diesel-MELO-H ₂ | 15 | B20 | 10 | B20-H ₂ 10-CR15 |
| 8 | Dual | Diesel-MELO-H ₂ | 15 | B20 | 15 | B20-H ₂ 15-CR15 |
| 9 | Dual | Diesel-MELO-H | 15 | B40 | 5 | B40-H ₂ 5-CR15 |
| 10 | Dual | Diesel-MELO-H ₂ | 15 | B40 | 10 | B40-H ₂ 10-CR15 |
| 11 | Dual | Diesel-MELO-H ₂ | 15 | B40 | 15 | B40-H ₂ 15-CR15 |
| 12 | Dual | Diesel-MELO-H | 16 | B10 | 5 | B10-H ₂ 5-CR16 |
| 13 | Dual | Diesel-MELO-H ₂ | 16 | B10 | 10 | B10-H ₂ 10-CR16 |

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|----|------|----------------------------|----|-----|----|----------------------------|
| 14 | Dual | Diesel-MELO-H ₂ | 16 | B10 | 15 | B10-H ₂ 15-CR16 |
| 15 | Dual | Diesel-MELO-H ₂ | 16 | B20 | 5 | B20-H ₂ 5-CR16 |
| 16 | Dual | Diesel-MELO-H ₂ | 16 | B20 | 10 | B20-H ₂ 10-CR16 |
| 17 | Dual | Diesel-MELO-H ₂ | 16 | B20 | 15 | B20-H ₂ 15-CR16 |
| 18 | Dual | Diesel-MELO-H ₂ | 16 | B40 | 5 | B40-H ₂ 5-CR16 |
| 19 | Dual | Diesel-MELO-H ₂ | 16 | B40 | 10 | B40-H ₂ 10-CR16 |
| 20 | Dual | Diesel-MELO-H ₂ | 16 | B40 | 15 | B40-H ₂ 15-CR16 |
| 21 | Dual | Diesel-MELO-H ₂ | 17 | B10 | 5 | B40-H ₂ 5-CR16 |
| 22 | Dual | Diesel-MELO-H ₂ | 17 | B10 | 10 | B10-H ₂ 10-CR17 |
| 23 | Dual | Diesel-MELO-H ₂ | 17 | B10 | 15 | B10-H ₂ 15-CR17 |
| 24 | Dual | Diesel-MELO-H ₂ | 17 | B20 | 5 | B20-H ₂ 5-CR17 |
| 25 | Dual | Diesel-MELO-H ₂ | 17 | B20 | 10 | B20-H ₂ 10-CR17 |
| 26 | Dual | Diesel-MELO-H ₂ | 17 | B20 | 15 | B20-H ₂ 15-CR17 |
| 27 | Dual | Diesel-MELO-H ₂ | 17 | B40 | 5 | B40-H ₂ 5-CR17 |
| 28 | Dual | Diesel-MELO-H ₂ | 17 | B40 | 10 | B40-H ₂ 10-CR17 |
| 29 | Dual | Diesel-MELO-H ₂ | 17 | B40 | 15 | B40-H ₂ 15-CR17 |
| 30 | Dual | Diesel-MELO-H ₂ | 18 | B10 | 5 | B10-H ₂ 5-CR18 |
| 31 | Dual | Diesel-MELO-H ₂ | 18 | B10 | 10 | B10-H ₂ 10-CR18 |
| 32 | Dual | Diesel-MELO-H | 18 | B10 | 15 | B10-H ₂ 15-CR18 |
| 33 | Dual | Diesel-MELO-H ₂ | 18 | B20 | 5 | B20-H ₂ 5-CR18 |
| 34 | Dual | Diesel-MELO-H ₂ | 18 | B20 | 10 | B20-H ₂ 10-CR18 |
| 35 | Dual | Diesel-MELO-H ₂ | 18 | B20 | 15 | B20-H ₂ 15-CR18 |
| 36 | Dual | Diesel-MELO-H ₂ | 18 | B40 | 5 | B40-H ₂ 5-CR18 |
| 37 | Dual | Diesel-MELO-H ₂ | 18 | B40 | 10 | B40-H ₂ 10-CR18 |
| 38 | Dual | Diesel-MELO-H ₂ | 18 | B40 | 15 | B40-H ₂ 15-CR18 |

III. RESULTS AND DISCUSSION

3.1 Response surface regression (RSR) for CO emission

CO emission in engine formed because of incomplete combustion of fuel. If a rich A/F mixture used in the engine, there is no sufficient air for complete combustion to take place resulting in emissions $0.000001D^*D + 0.000122 H_2^*H_2 - 0.01691 CR^*CR - 0.000002 CA^*D - 0.000803 CA^*H_2 + 0.00028 CA^*CR + 0.000713 CA^*L + 0.000005 D^*H_2 + 0.000017 D^*CR - 0.000014 D^*L + 0.001373 H_2^*CR - 0.001165 H_2^*L - 0.00633 CR^*L$

$$CO = -7.09 + 0.0079 CA + 0.001372 D + 0.0009 H_2 + 0.2648 CR + 0.03049 IOP + 0.1194 L + 0.000001D^*D + 0.000122 H_2^*H_2 - 0.01691 CR^*CR - 0.000002 CA^*D - 0.000803 CA^*H_2 + 0.00028 CA^*CR + 0.000713 CA^*L + 0.000005 D^*H_2 + 0.000017 D^*CR - 0.000014 D^*L + 0.001373 H_2^*CR - 0.001165 H_2^*L - 0.00633 CR^*L$$



Effect of compression ratios: Experimental test has been conducted by considering various CR's like 15, 16, 17, and 18 for neat diesel oil and blends B10, B20, and B40. The CO emission in the exhaust for diesel, B10, B20, and B40 are 0.6 g/kWh, 0.58 g/kWh, 0.3 g/kWh, and 0.46 g/kWh, respectively at CR of 15. For B20 at CR 17 the CO emissions are less when compared to diesel, B10, and B40.

Effect of load: Test procedure is carried on VCR Engine by varying loads from no load to full operating load as minimum and maximum loads at constant speed of 1500 rpm. The CO emissions are measured for diesel, B10, B20, and B40 throughout the load spectrum. Experimental results of CO emissions are 0.57 g/kWh for diesel, 0.47 g/kWh for B10, 0.34 g/kWh for B20, and 0.39 g/kWh for B40. CO emissions for the blend B20 shows better results when compared to diesel, B10, and B40. The RSR for CO emission is illustrated in Figure 3.

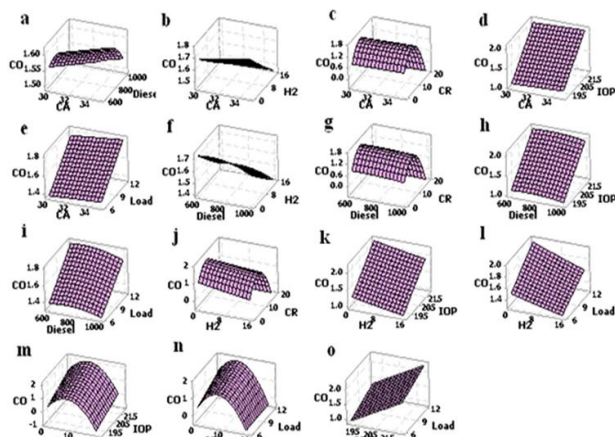


Fig 2: RSR for CO emission.

3.2 Response surface regression (RSR) for CO₂ emission

Causes of CO₂: when VCR engine setup is run with Diesel or any other biodiesel blends for total combustion process in the combustion chamber to attain maximum efficiency. Due to rich or lean fuel mixture's, fuel injection timings, effect of exhaust gas combined with fuel mixture, partial combustion takes place burning fuel partially resulting in harmful exhaust emissions. Daily 82,000 tons of CO₂ is being emitted into the atmosphere in 2 minutes. There exist the inconsistent conclusions; some researches indicated that the CO₂ emission reduces for biodiesel as a result of the low carbon to hydrocarbon ratio, and some researchers showed that the CO₂ emission increases or keeps similar because of more effective combustion. But in any event, the CO₂ emission of biodiesel reduces greatly from the view of the life cycle circulation of CO₂.

Effect of CR: CO₂ emissions are recorded for VCR engine run with 15, 16, 17, and 18 CR's for diesel, B10, B20, and B40 as 168 ppm, 156 ppm, 154 ppm, and 157 ppm. At CR 17 for B20, the CO₂ emissions are far less when compared to other blends and diesel.

$$CO_2 = -20.33 + 0.070 CA + 0.00513 D - 0.0230 H^2 + 0.967 CR + 0.746 L - 0.000005 D^2 + 0.000824 H^2H - 0.0464 CR^2 + 0.000071 CA^2D - 0.00298 CA^2H^2 - 0.00713 CA^2CR + 0.00395 CA^2L + 0.000009 D^2H^2 + 0.000039$$

$$D^2CR - 0.000040 D^2L - 0.00027 H^2CR + 0.00029 H^2L - 0.01789 CR^2L.$$

At full load and full speed for CR 17, B20 gives CO₂ exhaust emissions are 9.62%, whereas for diesel it is 10.11%, for B10 10.07%, and for B40 11.16%.

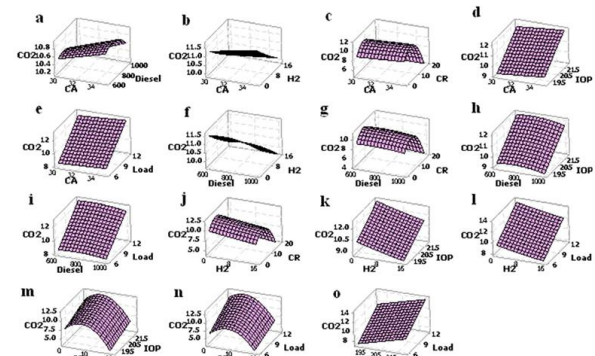


Fig 3: RSR for CO₂ emission.

3.3 Response surface regression (RSR) for O₂ emission

Causes of O₂: The very basic cause of O₂ in exhaust emission is O₂ Sensor. The O₂ sensor is heart of modern fuel injection system. O₂ sensor produces its own voltage based on the difference between the amounts of oxygen inside the exhaust stream as compared to the amount of oxygen outside the exhaust stream. If a lot of oxygen means it's a lean mixture where lot of fuel is not burnt. During the combustion inside the engine O₂ is left over or not left over depends on the amount of fuel burnt. Similarly vice versa, if lot of O₂ is seen in exhaust emissions it shows that it's a lean mixture with voltage less than 0.5 volts. The voltage produced by sensor falls between 0.0 to 1.0 volt.

Effect of CR: Experimental tests are conducted for varying CR's for studying O₂ emissions in the exhaust. O₂ emissions depend on the combustion rate in the combustion chamber. B20 has a high percentage of O₂ emissions of 13.75, whereas for diesel it is 12.87, for B10 13, and for B40 it is 10. The RSR for O₂ emission is illustrated in Figure 6. The RSR model for O₂ emission is given below:

$$O_2 = 36.2 - 0.596 CA - 0.00239 D - 0.041 H^2 - 1.44 CR + 0.027 IOP - 1.168 L + 0.000003 D^2 - 0.00212 H^2H^2 - 0.0024 CR^2 - 0.000244 CA^2D + 0.00565 CA^2H^2 + 0.0430 CA^2CR + 0.00586 CA^2L + 0.000085 D^2H^2 + 0.000154 D^2CR + 0.000216 D^2L - 0.00401 H^2CR - 0.00597 H^2L + 0.0037 CR^2L.$$

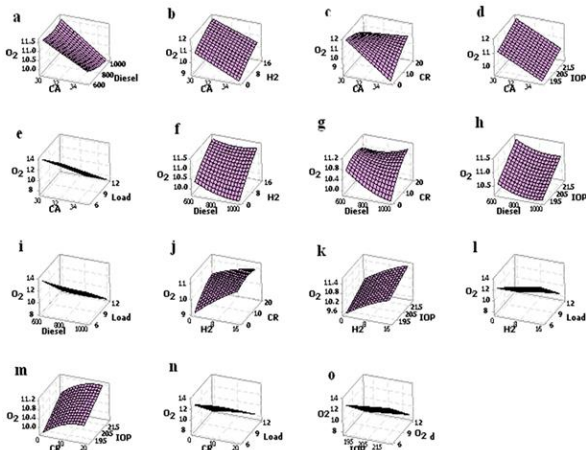


Fig 4: RSR for O₂ emission

3.4 Response surface regression (RSR) for NO emission

Cause of NO: Emissions of NO are due to combustion takes place at high temperatures. This situation occurs when cooling system does not work effectively, because of the lean A/F mixture availability of fuel is less when compared to presence of high ratio of air in the charge. Partial combustion takes place, resulting in incomplete fuel burnt tending to release high NO components in exhaust emissions. The EGR valve is specifically designed to control high temperatures. If the catalytic converter is in bad condition also results in very high levels of NO. EGR fails if speed of engine is greater than 2500 rpm and EGR pass if speed is less than 2500 rpm. Over advanced fuel timing causes more NO emissions in the exhaust.

Effect of CR: As experimental test is conducted for various CR's 15, 16, 17 and 18, the NO emissions are recorded. For CR 17, NO emissions are 10.35% for B20, 10.71% for Diesel, 10.75% for B10, and 31% for B40. NO emissions are maximum for B40.

Effect of Load: If the speed of Engine increases NO emissions also increases. At full load the NO emissions obtained for diesel is 135.93 ppm, for B10 131.25 ppm, for B20 127.69 ppm, and for B40 147 ppm. While comparing the NO emissions of other blends B20 has minimum emissions and B40 gives maximum emissions. The RSR for NO emission is illustrated in Figure 7. The RSR model for NO emission is given below:

$$\text{NO} = 21996 - 347.8 \text{ CA} + 2.08 \text{ D} - 82.9 \text{ H}_2 - 1220 \text{ CR} - 65.3 \text{ IOP} - 78.5 \text{ L} + 0.002142 \text{ D}^2 + 0.784 \text{ H}_2^2 + 37.9 \text{ CR}^2 - 0.0937 \text{ CA} \cdot \text{D} + 0.934 \text{ CA} \cdot \text{H}_2 + 26.37 \text{ CA} \cdot \text{CR} + 4.13 \text{ CA} \cdot \text{L} + 0.0100 \text{ D} \cdot \text{H}_2 - 0.1311 \text{ D} \cdot \text{CR} - 0.0667 \text{ D} \cdot \text{L} - 0.42 \text{ H}_2 \cdot \text{CR} + 5.058 \text{ H}_2 \cdot \text{L} + 1.82 \text{ CR} \cdot \text{L}$$

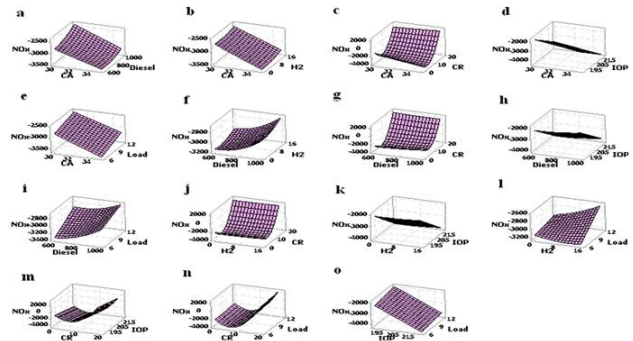


Fig 5: RSR for NO emission.

3.5 Response surface regression (RSR) for smoke emission

Smoke emission: When any engine is run with neat oil or any other blends, emissions are released into atmosphere like, exhaust emissions, and evaporate emissions and crankcase emissions. Smoke is a part of exhaust emission. Engine condition is diagnosed from the color of smoke, i.e. Brown, dark black, white and gray. When smoke is in the brown color vehicle is said to be in good health condition. Dark black color smoke is due to more fuel in the combustion chamber where there is less air flow. Partial fuel undergoes combustion and the other remains as unburned fuel, mileage of vehicle is less. When fuel is mixed with water i.e. fuel stored in any container is used for combustion moisture gets mixed up with moisture in atmosphere and results in white smoke. Injector and fuel tank are faulty also causes white smoke. Grey color smoke is the combination of white and blue smoke where oil and water are burnt along with fuel to assist combustion. For finding the smoke density at various testing models of Engine Model SM-05 smoke meter is used.

Effect of CR: Testing models of VCR engine are done for various compression ratios like 15, 16, 17, and 18 to find smoke density. The optimal values are noticed for CR-17 when compared to other CR's. Diesel operation gives smoke of 13.5%, for B10 smoke is 13.1%, for B20 smoke is 10.5%, and for B40 smoke is 14.2%. When engine is run for no load and full load, the smoke emission observed for no load and full load at CR 17 with blend B20. The RSR for smoke emission is illustrated in Figure 8. The RSR model for smoke emission is given below:

$$\text{Smoke} = -239 + 5.17 \text{ CA} - 0.1105 \text{ D} - 0.72 \text{ H}_2 + 15.45 \text{ CR} + 0.772 \text{ IOP} + 3.58 \text{ L} + 0.000030 \text{ D}^2 + 0.0594 \text{ H}_2^2 - 0.414 \text{ CR}^2 + 0.00362 \text{ CA} \cdot \text{D} + 0.0182 \text{ CA} \cdot \text{H}_2 - 0.431 \text{ CA} \cdot \text{CR} - 0.1881 \text{ CA} \cdot \text{L} - 0.000329 \text{ D} \cdot \text{H}_2 + 0.00162 \text{ D} \cdot \text{CR} + 0.00048 \text{ D} \cdot \text{L} - 0.463 \text{ H}_2 \cdot \text{CR} + 0.0311 \text{ H}_2 \cdot \text{L} + 0.260 \text{ CR} \cdot \text{L}$$



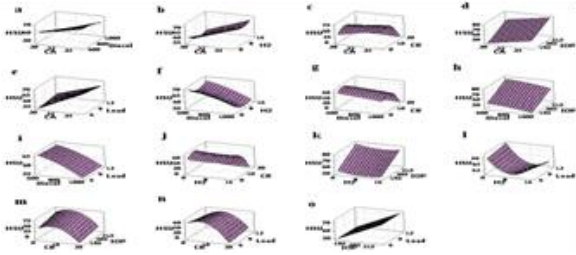


Fig 6: RSR for smoke emission

Optimization results

The following optimization plots indicate the response surface regression of various parameters. Figure 9 shows the optimized results of the emission.

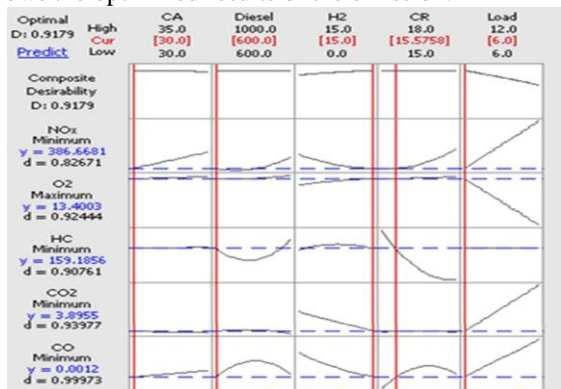


Fig 7: Optimization plots of emissions.

IV. CONCLUSIONS

- Based on the results of this study, it can be concluded that the CO, CO₂, O₂, HC, NO, and smoke emissions of VCR research engine setup in general, were found to be a function of biodiesel blend, compression ratio, load, and hydrogen induction percentage.
- For the same operating conditions, exhaust emission of the engine reduced with increase in the blend. With an increase in compression ratio, load, and hydrogen injection the difference was reduced and the engines exhaust emission and smoke densities at par with neat diesel.
- More precisely, biodiesel blended could be safely blended with neat diesel in 20% at compression ratio 17, full load with constant speed and hydrogen injection of 10% tested for getting low exhaust emissions and smoke when compared to diesel.

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