Effect of di-methyl carbonate as additive and exhaust gas recirculation on the performance and emission parameters of diesel engine using diesel-biodiesel blends as fuel

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Abstract. The Current situation of petroleum products pressurizes the world to shift towards green fuels. Dimethyl carbonate (DMC) could be considered as high oxygenated, green additive. Adding DMC in biodiesel increases the quality of combustion, hence reducing emissions with improved thermal efficiency. In the present study, DMC has been blended with biodiesel along with 10% Exhaust Gas Recirculation (EGR) and then performance and emission analysis was done. Results show higher Brake Thermal efficiency with 5% DMC in the biodiesel-diesel blend as compared to biodiesel, but lower than that with diesel. Brake Specific Energy Consumption increases with the increase in DMC in the fuel blend at medium and higher loads, which limits the use of DMC in higher content (10%, 15%). Carbon Monoxide and Hydrocarbon emissions reduce with lower content of DMC (5%) at a higher load. There are slight increases in Carbon Di-Oxide at all loads, under the safe limit. The emission of Oxides of Nitrogen (NOx) decreases slightly and this decrease increases with EGR. Higher content of EGR adversely affects the performance and emission characteristics except for NOx and smoke emission. A large decrease in smoke was noted with DMC as an additive in biodiesel due to improved combustion.

1. Introduction

The global environment and depletion of petroleum product sources are demanding the world to think about some alternate way to save energy. At the same time of saving energy, human-produced gases should also be controlled from emitting into the atmosphere. Engines are the main machines, where the conversion of energy from one form to another form takes place [1]. The numbers of these energy transition devices are very large; these machines use fossil fuel for functioning and emit various gases in the atmosphere. Since 1984, 84% of carbon emissions have been emitted to the environment by the combustion of petroleum fuels. Bio-fuels are useful in completing the energy demands along with reduced atmospheric pollution and energy cost. Due to the properties of high thermal efficiency, trustworthiness, flexibility and, low expenditure of diesel engines, these are used in various factories, farming, and carrying [2]. During various operations, diesel engines emit gases, which are responsible for environmental pollution. So to solve the energy shortage problem and to meet environmental rules, alternate green fuels present a great solution [2, 3]. According to the Administration of the United States Energy Information, there is a probability of increasing the consumption of total energy of the
world by 56% in 2040 as compared to 2010. The diesel can be replaced by biodiesel in diesel engines. But using biodiesel reduces performance parameters and also increases the emission of NOx [4]. Using oxygenated additives with biodiesel increases the level of Brake Thermal Efficiency (BTE) and reduces the emission of NOx [5]. DMC can be considered as efficient oxygenated additive for diesel engine using diesel as fuel [6]. Before 1980 DMC had been produced by methanolysis of phosgene, a toxic and corrosive gas. DMC can also be produced by methanol and carbon dioxide to reduce the danger of toxic, corrosive, and explosive compounds; it can also be produced by carbonylation of methanol with oxygen [7]. Grass, manure, or trees are also base source for the production of DMC and it is having lower Cetane Number as compared to diesel [8]. DMC can be used as an additive with biodiesel also as fuel in diesel engines [9, 10, 11]. DMC is a non-toxic [12, 13] and biodegradable chemical[14], having 53% oxygen content by weight in it’s structure [15], it does not have bond between two carbon molecules, which leads to the oxidation of hydrocarbon [16] and produces methoxyformyl radical, which limit the production of soot [17].

DMC is an ester of carbonate [18] which is non-corrosive, safe handling, flammable and insoluble in water [19], and colorless [20]. EGT reduces with an increase in DMC percentage as an additive [20]. DMC is low reactive, provides partially premixed combustion phase in direct ignition diesel engine. Higher content of oxygen improves the burning of fuel during the premixed combustion phase. It is having a lower boiling point. A lower boiling point than diesel is also helpful in spray atomization and mixing, hence results in complete combustion [21]. It is also having great miscibility (100%) with diesel. If the injection is delayed, the emission of NOx is in more control with lower emission of particulate matter, NOx emission and Noise level reduce due to premixed combustion when DMC has been used as an additive with diesel [22]. DMC reduces the viscosity of fuels and have higher latent heat of evaporation as compared to diesel. DMC also have lower Cetane number as compared to biodiesel and when the value of CN reduces, ignition delay takes place. Maximum burning takes place during the premixed combustion phase hence soot oxidation also takes place. Due to this Smoke emission reduces with adding DMC in fuel at all loads. But higher Carbon mono-oxide (CO) and Hydrocarbon (HC) emissions were observed as compared to biodiesel. Peak values of pressure and temperature inside the cylinder also reduce [23].

Due to lower CV, it has to be used as an additive in small proportion. Higher Carbon di-oxide (CO2) and NOx emissions were the results due to higher oxygen content as compared to gasoline. Decrease in CO and HC were notified as compared to gasoline due to complete combustion [24]. With the addition of DMC, the Cetane number of fuel reduces. With DMC as additive TE can be maintained up to Diesel level [25]. BSFC was found to reduce while BTE was found to increase with the use of DMC as additive [26, 27].

HRR is higher with adding DMC as compared to diesel. These are also found that TE is higher due to proper oxygen, which results in the complete combustion, and higher BSFC due to lower CV. CO emission decreases at high engine load while HC emission decreases slightly as compared to diesel. Ignition delay increases and the total duration of combustion decreases. Fuel consumed during diffused combustion phase decreases as compared to diesel [27]. Critical solubility temperature for DMC and diesel is above 273.15 K. DMC can be used in lower quantities in hot areas or where heterogeneous supply is required [28]. Emission of NOx was found to be higher with biodiesel at higher load, but can be controlled with the use of EGR [29].

The present study shows the effect of diesel, biodiesel, DMC, and EGR on brake power, brake specific energy consumption (BSEC), brake thermal efficiency, and emissions (HC, CO, CO2, NOx, and smoke) of 4 strokes direct ignition diesel engine. Here Kusum oil biodiesel has been used as an alternate fuel and dimethyl carbonate has been used as an additive. With 70% diesel, 20% biodiesel, and 5% DMC, only 10% EGR has been used.

2. Materials and Methodology
This paper presents the performance and emission analysis of four strokes, direct ignition, single vertical cylinder diesel engine. Fuels used for this research were blends of Diesel, Schleichera Oleosa Methyl Ester (Kusum Oil Biodiesel/Kusum Oil Methyl Ester/KME/BD) and DMC. 20% by volume of biodiesel (BD20) with 5%, 10%, and 20% by volumes of DMC (BD20DMC5, BD20DMC10, and
BD20DMC15 respectively) were blended in diesel, to be used as fuel for experimentations in the research. EGR was used with 10% of exhaust gases with BD20E5 blend only.

2.1. Test Fuel
Fuel Blends prepared for the study were D, BD20, BD20DMC5, BD20DMC10, and BD20DMC15. Table 1 shows the various properties of KME, diesel, DMC, and all blends used in this study.

| Properties                     | KME  | Diesel | DMC  | BD20 | BD20DMC5 | BD20DMC10 | BD20DMC15 |
|--------------------------------|------|--------|------|------|----------|-----------|-----------|
| Density @ 15°C(kg/m³)          | 857.60 | 820    | 1069.4 | 827.52 | 839.614  | 851.708  | 863.802  |
| Calorific value(kj/kg)         | 37595.50 | 44800 | 15780 | 43359.1 | 41980.14 | 40601.19 | 39222.23 |
| Kinematic Viscosity at 40°C (cSt) | 9.3   | 2.5    | 0.6  | 3.8  | 3.64     | 3.48      | 3.32      |
| Oxygen Content (wt %)           | 11    | 0      | 53.3 | 2.2  | 4.755    | 7.31      | 9.865     |
| Cetane Number                   | 51    | 45     | 35   | 46.2 | 45.64    | 45.08     | 44.52     |

2.2. Experimental Setup
All the observations were taken on the four strokes, direct ignition, and single vertical cylinder diesel engine with a constant compression ratio of 17.5. The experimental setup used for this investigation is shown in figure 1.

Figure 1. Schematic diagram of the experimental setup.
Brake load has been measured by using an eddy current dynamometer. A variation of 1300 RPM to 1600 RPM was noticed in speed. The flow rate of air was measured using an orifice-meter and U tube differential manometer. Temperatures at different points were measured using thermocouples and temperatures can be seen on the control panel. Flow rates of cooling water for the engine and dynamometer were taken from the rotameter. Observations were taken at 0, 5, 10, 15, 20 kgs loads with all fuel blends. Performance parameters that were considered during these experimentations are BP, BSEC, and BTE. Emissions considered during this study were CO, NOx, CO2, HC, and smoke. An exhaust gas analyzer and smoke opacity meter were used to observe the exhaust gas emissions and smoke outflow respectively. Technical details of the engine test rig, dynamometer, and emission measurement devices are given in appendices Table A1, Table B1, and Table C1 respectively.

3. Results and Discussion
The effects of biodiesel, DMC, and EGR on performance and emission parameters have been shown and discussed below.

3.1. Performance Parameters
Variations in BP, BSEC, and BTE with different blends of DMC, diesel, and biodiesel along with EGR have been discussed below.

3.1.1. Brake Power
Figure 2 shows the variation in BP with load with various fuel blends and EGR. BP increases with the increase in load. The reason behind this trend is the linear relationship between load and BP.

![Load v/s BP](image)

**Figure 2.** Variation in BP with various blends.

There is a slight decrease in BP with BD20 due to the lower calorific value (CV) of the biodiesel blend. BP can be maintained up to the level of diesel with the use of DMC. Due to the higher oxygen content of DMC, it helps the fuel to burn completely, hence better burning takes place. It is to be noted that DMC also has a lower CV. Lower CV predominates the higher oxygen content of DMC when used in higher content. Hence when DMC10 and DMC15 were used as fuel, BP reduces and further reduces with the use of EGR. With BD20DMC5+10% EGR as fuel there is a decrease of 6.987% in BP as compared to diesel. A maximum decrease of 14.03% was noted with BD20DMC15 at a lower load as compared to diesel. At medium and higher load, a decrease in BP was found to be negligible.
with BD20DMC5 and BD20DMC5+10% EGR. EGR is used to control NOx emissions, but when EGR is used, the quantity of exhaust gases increases, and the quantity of fresh air decreases in the combustion chamber, hence energy release from the combustion is not proper, which reduces the BP marginally. With BD20DMC5+10% EGR there is a very marginal decrease in BP at medium and higher load, so DMC and EGR can be used in lower content to maintain the brake power.

3.1.2. Brake Specific Energy Consumption (BSEC)
Figure 3 shows the variation in Brake Specific Energy Consumption (BSEC) with load with various fuel blends and EGR. As BD20 is used as fuel in the diesel engine, there is a increase in BSEC due to the lower calorific value of biodiesel at all load. However, biodiesel contains a higher amount of oxygen but the lower calorific value of the BD20 blend predominates, which is the main reason for higher BSEC.

Maximum increase in the BSEC was 15.678% as compared to diesel. The BSEC was found to increase with increase in DMC content in the blends as compared to diesel. Maximum increase in BSEC was 10.013% as compared to diesel with BD20DMC15 at medium load. The main reason of higher BSEC was the lower value of CV of DMC fuel blends, which predominates the higher content of oxygen in DMC. Thus DMC must be used in lower quantity (BD20DMC5) in fuel blends, where higher content of oxygen, higher volatility, and lower viscosity of DMC will be useful in improved burning of fuel and BSEC can be maintained up to the level of the diesel fuel. BSEC further increases with the use of 10% EGR with BD20DMC5. EGR is used to control NOx emissions, but when EGR is used then, the quantity of exhaust gases increases, and the quantity of fresh air decreases in the combustion chamber, hence energy release from the combustion is not proper. Due to this reason, a higher amount of fuel is burnt in a particular time interval, which increases the BSEC slightly as compared to diesel.

![Load v/s BSEC](image-url)
3.1.3. Brake Thermal Efficiency (BTE)
Figure 4 shows the variation in BTE with load with various fuel blends and EGR. BTE is defined as the ratio of power output and total input.

![Load v/s BTE](image)

**Figure 4.** Variation in BTE with various blends.

Figure 4 shows the variation in BTE with load with various fuel blends and EGR. BTE is defined as the ratio of power output and total input. It can be seen from this figure that, with BD20 as fuel BTE is slightly lower than diesel. BTE increases with the use of DMC and it goes up to 2.36% higher as compared to BD20. The reason behind this increase is higher oxygen content, which improves the quality of combustion, hence higher power is produced per unit of input energy, thus increasing the BTE. With a larger quantity of DMC in fuel lower CV plays a negative role and reduces produced power per unit burned energy. It decreases BTE and goes up to 11.28% lower as compared to diesel. EGR is used to control NOx emissions, but when EGR is used then, the quantity of exhaust gases increases and the quantity of fresh air decreases in the combustion chamber, hence energy release from the combustion is not proper. This results in lower power output per unit higher amount of input, thus reducing BTE and maximum reduction goes up to 2.40% as compared to biodiesel, which is considerable.

3.2. Emission Parameters
Variations in CO, HC, CO₂, NOx and smoke with different blends of DMC, diesel, and biodiesel along with EGR have been discussed below.

3.2.1. CO emission
Figure 5 shows the variation in CO emission with load with various fuel blends and EGR. CO is a very harmful gas and can react with atmospheric oxygen to produce CO₂, hence reducing atmospheric oxygen, which results in difficulties in breathing for human beings. One of the main aims of using biodiesel in a diesel engine is the reduction in toxic emissions. As biodiesel contains higher amount of
oxygen than diesel, hence reduction in CO emission has been achieved due to the availability of a larger amount of biodiesel oxygen during the combustion of fuel and this reduction goes up to 30% with BD20 as compared to diesel.

![Load v/s CO emission](image)

**Figure 5.** Variation in CO emission with various blends.

CO emission further reduces with the use of DMC as an additive due to higher oxygen content, higher spray atomization, and the higher air-fuel ratio at higher load and this reduction remains 16% with BD20DMC5 as compared to diesel. With a higher content of DMC also the CO emission remains lower than that with diesel. EGR is used to control NOx emissions, but when EGR is used, the quantity of exhaust gases increases and the quantity of fresh air decreases in the combustion chamber. In exhaust gases, unburnt carbon particles are present, which react with oxygen present in the combustion chamber and increases the CO emission marginally as compared to BD20DMC5 but remain 13.15% lower than that with diesel. Overall the combination shows the reduction in CO emission as compared to diesel.

### 3.2.2. HC emission

Figure 6 shows the variation in HC emission with load with various fuel blends and EGR. Due to the deposition of unburnt HC particles, the engine faces difficulties in functioning. Incomplete combustion is the main reason for the production of unburnt HC. Collection of fuel in the nozzle, small gaps in cylinder walls, piston-cylinder terminals, and incomplete vaporization of fuel are also the reasons for the production of unburnt HC. When BD20 is used then combustion is better than diesel due to the higher amount of oxygen present in the biodiesel. With BD20 HC emission is 6.89% lower than that with diesel. With BD20DMC5 there is a slight increase in Unburnt HC emission due to lower in-cylinder temperature, lower cetane number, higher HRR, and higher latent heat at lower and medium load. But at higher load HC emission remains 7.5% lower than that with diesel. It may be due to increased in-cylinder temperature at a higher engine load. The same trend is shown with BD20DMC10 and BD20DMC15. EGR is used to control NOx emissions, but when EGR is used then, the quantity of
exhaust gases increases and, the quantity of fresh air decreases in the combustion chamber, unburnt charges already exist in the combustion chamber. When re-circulated gases mix with a fresh charge, it results in incomplete combustion and produces HC and goes up to 23.40% higher than that with diesel.

![Load v/s HC Emission](image1)

**Figure 6.** Variation in HC emission with various blends.

### 3.2.3. CO₂ emission

Figure 7 shows the variation in CO₂ emission with load with various fuel blends and EGR.

![Load v/s CO₂ Emission](image2)

**Figure 7.** Variation in CO₂ emission with various blends.
It can be seen from this figure that emission of CO\textsubscript{2} increases slightly with biodiesel, it further increases with the use of DMC. As DMC content increases CO\textsubscript{2} emission also increases. CO\textsubscript{2} emission further increases with the use of EGR. CO\textsubscript{2} emission is the result of complete combustion and this emission was found to be under the safe limit. Higher oxygen content may also be one of the reasons behind the higher emission of CO\textsubscript{2}.

3.2.4. NO\textsubscript{x} emission

Figure 8 shows the variation in NO\textsubscript{x} emission with load with various fuel blends and EGR. From this figure, it is clear that NO\textsubscript{x} emission increases with the use of BD20, due to higher oxygen content and higher exhaust gas temperature and it goes up to 48.38\% higher as compared to diesel. With the use of DMC in lower quantity NO\textsubscript{x} emission reduces slightly due to lower heat value and premixed combustion. With BD20DMC5 NO\textsubscript{x} emission reduces up to 11.84\% as compared to BD20 and higher DMC content further reduces the emission of NO\textsubscript{x}. With 10\% EGR NO\textsubscript{x} emission reduces up to 34.78\% as compared to BD20 and reduces up to 7.4\% as compared to diesel, due to increased total heat capacity of charge and reduced in-cylinder peak temperature.

![Figure 8. Variation in NO\textsubscript{x} emission with various blends.](image)

3.2.5. Smoke outflow

Figure 9 shows the variation in smoke emission with load with various fuel blends and EGR. It can be seen from figure 9 that, smoke outflow reduces with the use of BD20, due to soot oxidation and higher content of oxygen and it reduces up to 5.06\% as compared to diesel. Smoke outflow further reduces with DMC. Reduction in Cetane Number results in ignition delay, thus maximum burning takes place in the premixed combustion phase, due to which soot oxidation takes place and smoke emission reduces. With BD20DMC5, the reduction in smoke outflow goes up to 19.93\% than that with diesel. This reduction has been achieved up to 20.75\% than that with diesel with higher content of DMC (15\%). EGR is used to control NO\textsubscript{x} emissions, but when EGR is used, the quantity of exhaust gases increases, and the quantity of fresh air decreases in the combustion chamber, which promotes the soot formation and thus reduces the smoke emission up to 20.52\% as compared with diesel.
4. Conclusion
The objective of this study was to investigate the effects of the combination of diesel, biodiesel, DMC, and EGR on the performance and emission parameters of the diesel engine. Following conclusions can be drawn from this experimental investigation:

Biodiesel can be used in diesel engines in lower content without any modification in the engine in form of fuel blend with diesel (BD20). BD20 gives a slight reduction in BP and BTE, while BSEC increases marginally. From the emission perspective, BD20 combustion gives lower emission of CO, HC, and smoke. Emission of NOx increases with biodiesel due to higher oxygen content and higher exhaust gas temperature, thus limiting the use of biodiesel in lower content.

Using BD20DMC5 as fuel increases the BP and BTE as compared to BD20. But higher content of DMC (10% and 15%) reduces the brake power due to predomination of lower CV over the high content of oxygen, hence bringing constraints in using DMC in higher content. BSEC can be maintained up to the level that with the diesel, using BD20DMC5 in particular conditions, but it increases with higher content of DMC (10% and 15%) due to the predomination of lower CV over the high content of oxygen. With BD20DMC5 emission of NOx and smoke reduces and these emissions further reduce with higher content of DMC. Emission of CO is lower at higher load but decreases with higher content of DMC at all loads. With BD20DMC5 as fuel HC emission is lower at lower loads only as compared to diesel and BD20, thus limiting the use of DMC in lower content in fuel blends.

Using EGR with BD20DMC5 gives slightly lower BP, and BTE and slightly higher BSEC as compared to diesel, BD20 and BD20DMC5. But EGR reduces the emission of NOx and smoke. Limitations to use EGR are also provided by higher emissions of HC and CO.

BD20 with 75% diesel, 5% DMC, and 10% EGR shows the optimum level of outputs. Further research can be done on the effects of ionized particles of charge on the performance and emission parameters of diesel engines.

Figure 9. Variation in smoke emission with various blends.
### Appendices

#### Table A1. Technical specifications of the Diesel Engine.

| Engine | Kirloskar tv1 |
|--------|---------------|
| Bore x stroke | 87.5mm x 110mm |
| Cubic Capacity | 661 cm³ |
| Compression Ratio: | 17.5:1 |
| Rated output: | 5.2kw at 1500 rpm |
| Fuel injector pressure | 20-25Mpa |
| Injection timing | 23 degree before Top Dead Centre (TDC) |
| No of valves | 2 |
| Valve timing | 4.5 degree |
| Inlet valve opens before TDC | 35.5 degree |
| Inlet valve opens After Bottom Dead Centre (BDC) | 35.5 degree |
| Exhaust valve opens before BDC | 4.5 degree |
| Governor type | Mechanical, centrifugal type |
| Fuel injection type | Mechanical individual pump |

#### Table B1. Technical details of Dynamometer used.

| Description | Specification |
|-------------|---------------|
| Type | Eddy current type |
| Made by and Model No. | Saj test plant Pvt. Ltd. AG10 |
| Loading Sensor Capacity Range | 0 to 50kg |
| Piezo Sensor Diaphragm | Stainless Steel type and Hermetic Scaled |
| Piezo Sensor Range | 5000psi |
| Rotameter Range(Measure the flow rate of cooling water) | 10 to 100 lph |

#### Table C1. Technical details of Emission Measurement Devices.

| Parameter | Range | AVL 437 Smoke Meter | AVL Five Gas Analyzer (Designed for 250 to 8000 rpm) |
|-----------|-------|----------------------|------------------------------------------------------|
| Reproducibility | ±1% (Full-scale reading) | | CO 0 to 10% by volume |
| Measuring Range | 0 to 100% | | CO₂ 0 to 20% by volume |
| Accuracy | 100% (for analog output) | | HC 0 to 20000 ppm |
| | | | NOx 0 to 4000 ppm |

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