Combined effects of various strategies to curtail exhaust emissions in a biomass waste fueled CI engine coupled with SCR system

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ARTICLE INFO

Article history:
Received 23 May 2021
Revised 16 October 2021
Accepted 9 December 2021
Available online xxxx

Keywords:
Grapeseed biodiesel
Nano emulsions
Combustion
Emissions
EGR
SCR

ABSTRACT

This study is an exhaustive investigative on engine performance and combustion features of a conventional diesel engine charged with biodiesel produced from biomass waste. Grapeseed oil methyl ester resulted in poor thermal efficiency with enormous quantity of harmful emissions. As an effort to reduce the engine pollutants, Grapeseed oil methyl ester was doped with zinc oxide nano particles, engine cylinder shape modification and exhaust gas recirculation method was used. Hydrocarbons, carbon monoxide and smoke emissions reduced considerably, whereas reduction in nitrogen oxide emissions was low. Selective catalytic reduction technique at optimized mass flow rate of aqueous urea solution minimized the nitrogen oxide emissions by 76.9% compared to grapeseed oil methyl ester without compromise in brake thermal efficiency.

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1. Introduction

Emerging energy demands and hiking fuel prices are gaining attention as our economy is concerned. Statistical reports show that worldwide fuel consumption increases drastically and the fossil fuel may be available only for the next 50 years [1]. Hence, a deviation towards renewable and recyclable fuels has occurred. Plastic waste, rubber waste and other biomass waste are recycled and utilized as useful energy forms. Biofuels available edible and non-edible sources and second-generation fuels have been extensively studied by many researchers [2]. Canola oil, safflower oil and waste vegetable cooking oil were mixed in suitable proportions for run in compression ignition (CI) engine [3]. Response surface methodology (RSM) study helped to analyze the engine optimal parameters such as brake thermal efficiency (BTE), smoke and carbon dioxide (CO2) emissions. The RSM model constructed using the experimental values shows that the engine gave its best performance at 20.5% with NOx emission of 558 ppm. Biomass converted biofuel has been less explored by investigators in the field of renewable energy forms. Winery factories are widely spread in and around our country contributing to several million hectares of land. The wine production from those industries are enormous, likewise, waste product outlets are also huge. The byproducts from such industries are thrown out, thereby polluting land and atmosphere. Such waste products consist of grape skin, stalks, thin stems and seeds. These are thoroughly pressed and crushed mechanically to extract grapeseed oil which finds medical applications and possess considerable fuel properties. The fatty acid ester of this biomass waste oil is used to energize the conventional CI engine. Performance and emission parameters of the engine were analyzed and did not seem to be convincing.

Many literatures were referred to implement methods that would enhance the combustion characteristics, along with reduction of emissions. Numerical and experimental studies were carried out using sunflower methyl ester at concentration of 10%, 20% and 30% with diesel [4]. These blends yielded high cylinder pressure, which was due to the chemical nature of sunflower oil. This fuel also generated a higher penetration value inside the engine cylinder. Oni et al [5] compared the performance of two different biodiesel sources namely Azadirachta indica and Camelina oil. They were added individually to diesel at concentrations of 5% and 10% by volume. Camelina oil B10 produced better BTE at all possible engine speeds. Also, carbon monoxide (CO) emissions were diminished by 12% compared to diesel. NOx emissions were higher by 19.7% in reference to diesel. Zacharof et al [6] practiced methods of utilizing winery waste that exists in forms of waste

https://doi.org/10.1016/j.jestch.2021.101085
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Please cite this article as: V. Praveena, M. Leenus Jesu Martin and V. Edwin Geo, Combined effects of various strategies to curtail exhaust emissions in a biomass waste fueled CI engine coupled with SCR system, Engineering Science and Technology, an International Journal, https://doi.org/10.1016/j.jestch.2021.101085
28% and 25%. Praveena et al. [20] analyzed the effect of EGR at 5% bTDC and 260 bar fuel pressure. Though piston bowl modification and nano blending helps to enhance the thermal efficiency, sometimes NOx emissions are raised due to the adiabatic flame temperature. Experiments conducted on dual fuel engines with EGR, showed a drop in NOx emissions [19]. 20% blend (B20) of jatropha biodiesel was used as pilot fuel with CNG fuel. EGR with both blends such as CNG with diesel and CNG with B20 jatropha biodiesel reduced NOx emissions by 28% and 25%. Praveena et al. [20] analyzed the effect of EGR at 5%, 10%, 15% and 20% rates on grapeseed oil biodiesel fueled CI engine. 5% EGR reduced NOx emissions by 31.02% and 20% EGR reduced NOx emissions by 61.5%. NOx smoke trade-off was observed at 5% EGR without much loss in BTE. Damodharan et al. [21] suggested EGR to reduce emissions at all ranges of injection timing (advanced and retarded); NOx smoke trade-off was optimum at 25° bTDC and 10% EGR.

Saravanan et al. [22] established the importance of EGR at 10% and 20% in an ethanol fueled CI engine. The conventional engine was modified into a low heat emission engine by coating the piston and cylinder head with ceramic substances. Ethanol was ignited with a glow plug. NOx emissions reduced from 9.7 g/kWh to 6.4 g/kWh and 5.5 g/kWh with 10% and 20% EGR. Higher order alcohols blended with diesel fuel [23] produced less particulate matter (PM) and CO emissions, whereas NOx emissions increased proportionately with concentration levels of octanol (40% v/v). EGR was used to encounter this effect and reduced NOx emissions by 90% at 30% EGR by increased heat absorption by the re-circulated gases.

Water, vinaise, vine shoots etc. for bioconversion and recycling. More concentration was dedicated towards waste remedy and treatment of wine industry waste. Chelladorai et al. [7] studied the role played by unsaturated carbon molecules in a biomass derived biodiesel on the emission characteristics of a diesel engine. Biodiesel derived from coconut oil, grapeseed biomass and wheatgerm biomass were tested. It was found that those fuels produced 31.2%, 30.2% and 27.3% BTE. NOx emissions shoted up for grapeseed biodiesel, followed by wheatgerm oil biodiesel. Praveena et al. [8] blended 20% of butanol and 20% octanol individually to biodiesel. The effects of injection timing and EGR were further studied on the best blend. NOx emissions reduced by 33% in the above process for B20 butanol blend.

1.1. Literature on nano additive particles

Metallic additives and non-metallic additives in nano form exhibit different pattern in combustion phenomena. Iron oxide and graphite nano particles were blended with diesel at different amounts of 50, 100 and 150 mg/l using magnetic agitator. Lower NOx emissions were produced in graphite blends compared to ferric oxide blends. 2.6% reduction in fuel consumption was observed with graphite nano particles blended diesel. Agbulut et al. [9] tested metal nano particles in oxide form in a CI engine at 2000 rpm speed. 100 ppm concentration levels of aluminium oxide (Al₂O₃), titanium oxide (TiO₂) and silicon dioxide (SiO₂) were added to 10% blend of waste cooking oil methyl ester. The nanoadditive blends proved their improved properties on combustion and emission results. There existed a difference in contribution of individual nano particles. The metal oxide with highest thermal conductivity, absorbed high heat and reduced NOx emissions to a significant extent.

Cerium oxide and zinc oxide nano emulsions were clubbed with grapeseed oil biodiesel and were tested in a CI engine. [10]. Those particles were added at 50 and 100 ppm concentration each individually to biodiesel. The physical properties were improved and cetane no. also raised. Water molecules suspended in the emulsive blends uses up heat to undergo latent phase change and reduce NOx emissions by 9–11.2%. Aluminium oxide nano particles added to honge oil biodiesel [11] improved BTE by 10.56% and reduced fuel consumption by 11.6%. 40 ppm concentration gave better results than 20 ppm and 60 ppm Al₂O₃ nanoparticles. Combining nano additive techniques with modification in injection timing were carried out on a water emulsified diesel fuel [12]. SiO₂ nano particle at 25–100 ppm in intervals of 25 ppm and surface tension was subsidized with 1% of Span 80 solution. The injection timing was varied from 19°, 21°, 23° and 25° bTDC. The nano blends performed effectively by increasing the BTE and reducing HC, CO and smoke emissions, while NOx shotted by 6.6% for advanced injection timing.

1.2. Literature on in-cylinder parameters

Design alterations in engine such as injection timing, injection pressure, piston coating, piston profile changes etc. were carried out to enhance the role played by fuel modification [13]. Fuel injection timing and pressure act as primary factors on impacting the combustion and emission parameters. Syzygium cumini biodiesel [14] at 30%, 70% and 100% with injection pressure of 200, 220 to 260 bar and injection timing of 21°, 23° and 25° before TDC (bTDC) were tested and it was found that 28.7% of smoke reduced, where NOx emission increased with 21° bTDC and 260 bar fuel pressure. Variation in combustion chamber shapes to shallow depth and toroidal shape [15] has modified the swirl motion and air fuel momentum inside the cylinder. The shallow depth had high aspect ratio and fuel particles were not properly combusted. Toroidal shape produced high thermal efficiency and enhanced combustion characteristics. Toroidal with re-entrant type provided good results in case of dual fuel operation [16]. Compressed natural gas (CNG) at flow rate of 0.48 kg/h gave the best performance with 26° bTDC and 5 holed nozzle. HC emissions decreased from 60 ppm to 45 ppm, which is the impact of modified engine conditions.

Numerical studies on impact of various bowl geometry like shallow type and toroidal were carried out by Kattela et al. [17]. Different blends of butanol at 10%, 20% and 30% were tested in modified direct injection diesel engines and there happened a decent reduction in HC and CO emissions for both shallow type and toroidal piston bowl shapes. Separated swirl type chambers were modeled and analyzed to understand emission characteristics and combustion pattern [18]. Double swirl systems were simulated and the fuel movement inside both the chambers varied based on angle of individual chambers. These numerical studies were very helpful in improving the air fuel mixture. Another strategy to reduce emissions is the induction of exhaust gas recirculation (EGR). Though piston bowl modification and nano blending helps to enhance the thermal efficiency, sometimes NOx emissions are raised due to the adiabatic flame temperature. Experiments conducted on dual fuel engines with EGR, showed a drop in NOx emissions [19]. 20% blend (B20) of jatropha biodiesel was used as pilot fuel with CNG fuel. EGR with both blends such as CNG with diesel and CNG with B20 jatropha biodiesel reduced NOx emissions by 28% and 25%. Praveena et al. [20] analyzed the effect of EGR at 5%, 10%, 15% and 20% rates on grapeseed oil biodiesel fueled CI engine. 5% EGR reduced NOx emissions by 31.02% and 20% EGR reduced NOx emissions by 61.5%. NOx smoke trade-off was observed at 5% EGR without much loss in BTE. Damodharan et al. [21] suggested EGR to reduce emissions at all ranges of injection timing (advanced and retarded); NOx smoke trade-off was optimum at 25° bTDC and 10% EGR.

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1.3. Literature on post processing methods

In post processing technologies, there are many methods like diesel particulate filter for reducing PM, Selective catalytic reduction (SCR) for reducing NOx, selective non-catalytic reduction (SNCR) for reducing NOx and diesel oxidation catalyst (DOC) for reducing HC and CO emissions are used [24]. SCR systems employing gaseous ammonia are tested by researchers [25]. Numerical simulation details the distribution of ammonia inside the pipe section and the reactions across the catalytic bed. Strontium chloride salt was converted directly into ammonia gas by electrical heating. Vanadium type SCR [26] installed in the exhaust gas pipe is dependent upon the operating temperature of the catalyst. At low temperatures below 200 °C, ammonium nitrate salts are formed that might alter the NOx reduction performance of SCR. Researchers have concentrated on enhancing the mixture concentration of ammonia gas with NOx species in the stipulated time [27–29]. Different mixer geometries like fan type, spiral type and porous were added to the decomposition pipe ahead of SCR and urea injector position was optimized to attain a better NOx conversion SCR. The inevitable injection process has drawn attention as there are problems of the liquid film blocking the pipe passage [30]. Spray bouncing and impinging process portrays the morphological behavior of the urea particles. Numerical simulation based on Kuhnke model denoted the velocity of urea droplets affected by the injection parameters. Diesel particulate filter (DPF) system clubbed with SCR helps to reduce soot and the polycyclic compounds in hydrocarbons [31]. The concentration of aromatic hydrocarbons was further reduced by 30% due to SCR functioning in the heavy load condition. SCR produced high agglomeration of suspended particles and they are less harmful to human inhalation.

Many researchers have worked on individual methods like fuel injection timing variation, fuel blending, after treatment of exhaust gases etc. Past research findings were limited to only different nano particles and their emulsions such as MnO, MgO, Al2O3, CuO, CeO etc on various types of biodiesel but not their influence on after treatment devices. There are a few works that illustrates the combined effect of various technologies to reduce NO emission. This gap was identified and the current work collectively describes the effect of fuel modification, in-cylinder geometry variation, EGR and SCR retrofit system in a CI engine, which effectively reduces NO emission.

2. Materials and methods

2.1. Fuel preparation and blending

Grapeseed oil is produced from grape seeds and grape marc, which is a byproduct of wine making industry. These are collected from various industries, crushed by mechanical pressing to obtain grapeseed oil and oil cake. The oil yielded by this mechanism is about 30%. This biofuel has dual benefits of minimum CO2 emissions and reuse of biomass waste. The oil does not possess suitable properties for CI engine run as per ASTM standards and hence it is trans esterified using methanol in the ratio of 4.5:1 on a mole basis to obtain grapeseed oil methyl ester (GSME). It was possible to achieve a yield of close to 95%.

Fig. 1 shows the steps in biodiesel fuel preparation. To further improve the chemical properties of GSME, zinc oxide (ZnO) nano particles were added to it in emulsion form. The mean size of the nano particles was 36 nm. After carefully analyzing the suitability of these particles and their magnified shape under an electron microscope, the particles were mixed with base fuel in an ultrasonicator for 45 min. Stability tests were conducted on the emulsion for a period of two weeks. The stability period was increased due to addition of Span 80 surfactant in very minute quantity. Table 1 shows the properties of base fuels, diesel and GSME. The blended combination GSME with ZnO nano particle solution is represented as GS + ZnO. The zinc oxide nano particle solution is restricted to 5% by volume with GSME. The thermal conductivity and molecular weight make it comfortable for smoother operation in the CI engine.

2.2. Test engine

Experiments were conducted on a single cylinder CI engine with maximum developed power of 5.2 kW. The injection timing and pressure are fixed as 23° bTDC and 200 bar for all experimental runs. The engine is connected to an eddy current type dynamometer, where the torque produced is measured. Air flow rate and fuel intake volume are measured by orifice, air box and burette- stop watch arrangement. Chromel alumel thermocouples record accurately the temperature of exhaust gases. The combustion characteristics are defined by the calculation of heat release, maximum...
pressure, ignition delay etc using the pressure volume data. Piezo electric transducer that records the pressure fluctuation through sensors is installed. The pressure is recorded for 100 consecutive cycles and recorded in a computer. The engine specifications are mentioned in Table 2.

Eq. (1) is used to calculate heat release rate (HRR) using pressure volume data.

\[
Q = \frac{\gamma}{\gamma - 1} \frac{P}{V} \frac{dV}{d\gamma} + \frac{1}{\gamma - 1} \frac{V}{P} \frac{dP}{d\gamma}
\]

where \(\gamma\) represents the ratio of specific heats

Exhaust gas emissions such as HC, CO and NOx are measured by AVL gas analyzer in ppm. AVL smoke meter measures the smoke opacity in %. The brake specific emissions are calculated in g/kWh using the measured values as in Eq. (2)

\[
NO_x(g/kWh) = NO_x(ppm) \times 10^{-6} \times \frac{\text{Mol.wtofNO}_x}{\text{Mol.wtofair}} \times \frac{(ma + mf)}{BP}
\]

\[
NO_x(g/kWh) = NO_x(ppm) \times 10^{-6} \times \frac{\text{Mol.wtofNO}_x}{\text{Mol.wtofair}} \times \frac{(ma + mf)}{BP}
\]

\[(2)\]

Table 2

<table>
<thead>
<tr>
<th>Engine specifications.</th>
</tr>
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<tbody>
<tr>
<td>Make and model</td>
</tr>
<tr>
<td>Engine type</td>
</tr>
<tr>
<td>Bore dia. (mm)</td>
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<tr>
<td>Stroke length (mm)</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Injection timing and pressure</td>
</tr>
<tr>
<td>No. of nozzle holes</td>
</tr>
</tbody>
</table>

Fig. 2 shows the experimental set up with provision for exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) device.

2.3. In-cylinder geometry modification

Many investigations were done so far by researchers on engine modifications such as thermal coating of piston, nozzle diameter variation, injection pressure, injection timing etc. In this study, the piston shape is modified to a different configuration i.e. toroidal type. The required shape was achieved by removing material in surface grinding process. The profile has a high swirl and double curve pattern. The cavity produced by the piston modification determines the quality of air fuel mixing and squish motion. Fig. 3 shows the photograph of developed piston shape and its geometrical details.

2.4. EGR set up

Cold EGR method is used in this work, as it helps in reducing the cylinder temperature and increase the charge density. The exhaust gases were directed to enter through the inlet manifold. The rate of recirculation was fixed as 5% based on optimization carried out by the authors [20]. Control valve regulate the flow rate of exhaust gases by Eq. (3).

\[
\%\text{ofEGR} = \frac{(CO_2)_{\text{inlet}}}{(CO_2)_{\text{exhaust}}} \times 100
\]

Cold EGR method is used in this work, as it helps in reducing the cylinder temperature and increase the charge density. The exhaust gases were directed to enter through the inlet manifold. The rate of recirculation was fixed as 5% based on optimization carried out by the authors [20]. Control valve regulate the flow rate of exhaust gases by Eq. (3).

Tap water is circulated in the passage around the exhaust gases and temperature of gases is brought down to 35 °C. The specific conditions of EGR run are given in Table 3.

2.5. SCR device

SCR technology is involved in this research work as it is an effective technology in reducing NOx emissions [24]. A honeycomb ceramic substrate was purchased from China and the catalyst (Copper zeolite) was coated on it and dried simultaneously using a blower. The coated substrate was placed in an incinerator for 30 min. The volume of catalyst was calculated by weighing the substrate before and after coating. The catalyst coated ceramic was kept enclosed inside a chamber with a converging-diverging
The SCR circuit consists of an aqueous urea tank, pump, injector, decomposition pipe, mixers and connecting pipelines. The specification of SCR device is shown in Table 3. For every one mole of urea undergoing chemical reaction, two moles of ammonia gas are produced and this ammonia gas reacts with oxides of nitrogen to produce N₂ as shown in Eq. (4).

\[
4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
\]  

(4)

The SCR set up is shown in Fig. 4. The injection is positioned at a distance of 210 mm from the exhaust valve. Porous type mixers at 850 mm distance from SCR inlet are located. These mixers enable complete mixing of generated ammonia gas with engine exhaust gas.

2.6. Test procedure

For this study, the engine speed was maintained at 1500 rpm and loads varying from 0.98 kW to 5.2 kW. The engine readings were noted after steady state was reached and ensured that there were no fluctuations. For all the load conditions, parameters like air flow, fuel flow rate, pressure at crank angle, emissions like HC, CO, NOx and smoke were noted. Average value of readings helped to minimize the errors. Initially, the engine was warmed up with diesel fuel. Later GSME was used to run the engine followed by ZnO added GSME fuel. The engine was fitted with toroidal piston shape, 5% EGR rate and SCR device with mixers and nano particle blended with biodiesel was run on it.

2.7. Uncertainty

Uncertainty relates to discrepancy in measured and calculated values. This analysis helps to reduce experimental errors, random errors and instrumental errors. Different parameters measured and calculated such as BP, BTE, HC, CO etc. contribute to total uncertainty. Table 4 shows the uncertainty of instruments used in the experiment. A specimen calculation for determining the uncertainty in BP is shown below in Eq. (5)

\[
BP = \frac{2\pi N \times R \times W}{60}
\]

\[
Un_{BP} = \sqrt{\left(\frac{\partial BP}{\partial N} \Delta N\right)^2 + \left(\frac{\partial BP}{\partial R} \Delta R\right)^2 + \left(\frac{\partial BP}{\partial W} \Delta W\right)^2} = 0.0124\text{kW}
\]

The cumulative error is derived as follows:

\[
\text{Totalerr.} = \sqrt{\left(Un_{N}\right)^2 + \left(Un_{R}\right)^2 + \left(Un_{W}\right)^2 + \left(Un_{BP}\right)^2 + \left(Un_{\text{mech.}}\right)^2}
\]

Table 3

<table>
<thead>
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<th>Description</th>
<th>Value</th>
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<td>EGR type</td>
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<td>Orifice diameter</td>
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<tr>
<td>SCR catalyst dia.</td>
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</tr>
<tr>
<td>Cell density</td>
<td>400 cpsi</td>
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<tr>
<td>Reducing agent</td>
<td>Aqueous urea</td>
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<tr>
<td>Molecular formula</td>
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</table>

Table 4

<table>
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<th>Measured quantity</th>
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<tr>
<td>NOx</td>
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</tr>
<tr>
<td>HC</td>
<td>0–20,000 ppm</td>
<td>±20 ppm</td>
</tr>
<tr>
<td>CO</td>
<td>0–10%</td>
<td>±0.02%</td>
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<tr>
<td>Smoke opacity</td>
<td>0–100%</td>
<td>±1%</td>
</tr>
<tr>
<td>Engine speed</td>
<td>0–2000 rpm</td>
<td>±10 rpm</td>
</tr>
<tr>
<td>Cylinder pressure</td>
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<td>±0.5 bar</td>
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</tbody>
</table>
3. Results and discussion

Performance, emission and combustion parameters are plotted for base fuel diesel and GSME. For better understanding, GSME case 1 represents GSME + 5% ZnO nano fluid. GSME case 2 represents GSME + 5% ZnO nano fluid + toroidal shaped piston. GSME case 3 represents GSME + 5% ZnO nano fluid + toroidal shaped piston + 5% EGR and GSME case 4 represents GSME + 5% ZnO nano fluid + toroidal shaped piston + 5% EGR + SCR.

3.1. NOx emissions

Fig. 5 shows the change in NOx for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, NOx for diesel and GSME are 7.7 g/kWh and 9.2 g/kWh respectively. The excess oxygen atoms in GSME lead to higher temperature during combustion, thus producing more NOx emissions. Irrespective of the air fuel ratios, at low loads NOx emission in terms of ppm are lesser due to low adiabatic temperature and residence time [32]. More quantity of fuel participates in the premixed phase. When zinc oxide particles were added to it, their catalytic effect and higher thermal conductivity absorbs the excess heat and reduces adiabatic flame temperature. This reduces NOx emitting levels to 8.2 g/kWh. The toroidal shape geometry does not induce much change in NOx emissions and the level is maintained at 8.07 g/kWh. EGR and SCR set up reduce NOx by the diluents (H2O and CO2) and catalytic reactions. The recirculation gases reduce the thermal effect and produces NOx of 5.5 g/kWh for 5% EGR. Likewise, SCR device initiates the hydrolysis reaction for NOx reduction. The more time rested by the exhaust gas in the catalyst bed, more the NOx reduction efficiency (see Fig. 6).

Henceforth, NOx emissions are reduced from 5.5 g/kWh to 2.05 g/kWh. The collective impact of various strategies used in this work has led to reduction in NOx emission by 76.9%.

3.2. HC emissions

At full load condition, HC emissions for diesel and GSME are 0.53 g/kWh and 0.4 g/kWh respectively. HC emissions reduce with rise in load for both the base fuels. Hydrocarbons are burnt effectively under the high combustion temperature. Zinc oxide particles and toroidal piston shape further promotes complete combustion, thereby reducing HC emissions to 0.35 g/kWh and 0.33 g/kWh. The activation temperature of carbon atoms is brought down and the hydrocarbons get oxidized. 5% EGR rate was not beneficial for oxidation of hydrocarbon molecules as the cylinder temperature was reduced by oxygen dilution. SCR inclusion did not affect much the HC emission, as their impact was more on NOx emissions. Hence, a HC emission of 0.42 g/kWh was observed after fuel modification and after treatment methods.

3.3. CO emissions

Fig. 7 shows the change in CO for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, CO emissions for diesel and GSME are 4.8 g/kWh and 4.3 g/kWh respectively.

The main reasons leading to CO emissions are deficient oxygen and rich mixture inside the combustion zone. The nano blended sample produced lesser CO emission compared to GSME fuel. This is explained by the 18% additional oxygen molecules in zinc oxide nano particles. CO formation is also attributed to the transformation of CH2O and HCO radicals [33]. CO emissions at full load were reduced to 4.19 g/kWh. Toroidal piston shape prevented the flame from spreading into the squish region, thereby further reducing CO emissions to 4.4 g/kWh as the diluents absorbed the heat by their specific heat capacity. The catalyst bed reaction enabled NOx reduction and failed to impact on CO emissions. Other after treatment devices like DOC and DPF would be helpful to reduce CO emissions.

3.4. Smoke emission

Fig. 8 shows the change in smoke for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, smoke emissions for diesel and GSME are 48% and 46% respectively. Evolution of soot molecules occurs at rich mixture in the cylinder. Increased combustion rates were noticed for GSME due to the oxygen existence in the fuel. Opacity reduced by 8.6% after adding zinc oxide particles. The spray momentum got upraised and formed hydroxide radicals, which in turn induces oxidation of soot particles. Toroidal piston shape developed more kinetic energy and augmented swirl consumes the usable oxygen, thereby reducing smoke to 38%. However, EGR and SCR techniques were
not supportive in smoke reduction. There was a high rise in soot precursors and they interrupted the rate of soot oxidation. Smoke emissions rise to 55.1% due to EGR inclusion. SCR device further rise the opacity to 57.6%, as the oxygen atoms were partially absorbed by conversion of NO into NO₂. Hence, more soot particles were produced as an impact of SCR reactions. The smoke at final experiments was 23% higher than GSME at half load.

3.5. Brake thermal efficiency (BTE)

Fig. 9 shows the change in BTE for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, BTE of diesel and GSME are 32.2% and 28.8%. The loss in BTE for biodiesel is realized due to high viscosity and density of fuel. Zinc oxide nano particles help to enhance the combustion process, as they possess additional oxygen content in them. A marginal rise of BTE to 29.3% is noticed for GS ZnO fuel. Modifying the piston shape to toroidal shape, further improves the BTE to 30.5%. The increased swirl motion inside the combustion zone, burns the fuel effectively, thereby producing high useful work. The EGR inclusion at 5% rate leads to some loss of available energy as the exhaust gases absorbs it and reduces the peak temperature. BTE slightly reduces to 29.4%. The SCR reactions in the device, creates back pressure flow and interruption on smooth combustion. Therefore, a loss in useful work is realized for unit quantity of fuel supplied. BTE lowers from 29.4% to 28.8%. Brake specific fuel consumption (BSFC)

Fig. 10 shows the change in BSFC for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, BSFC for diesel and GSME are 278 g/kWh and 325 g/kWh. The lower calorific value of GSME attributes the more fuel consumption to produce same brake power. BSFC decreases from 325 g/kWh to 313 g/kWh by the addition of nano particles to the biodiesel. The nano particles explode at micro levels and the reaction rate is incremented due to their oxygen levels. Piston shape alteration further decreases BSFC to 290.5 g/kWh due to better air fuel mixing. The swirl and induced tumble motion help for
effective utilization of supplied fuel. 5% EGR rate inclusion dilutes the intake air and the combustion mixture, thereby rising BSFC to 312 g/kWh. Excess quantum of fuel was required to sustain the combustion quality. Addition of SCR device, further increased BSFC to 319 g/kWh, due to back pressure effects. 3.7 Exhaust gas temperature (EGT)

Fig. 11 shows the change in EGT for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, EGT for diesel and GSME are 336 °C and 410 °C respectively. As the combustion process continued for a longer crank angle in GSME combustion, the exhaust gases had higher temperature. This is also illustrated in BTE graph (Fig. 9). Zinc oxide nano particles when added to GSME, contributed to good amount of shaft work. This clarifies the fact that less heat was carried away by the exhaust gases. The toroidal shaped piston improves the air fuel momentum and mixing process causing a drop in EGT to 357 °C. The combustion mixture is diluted due to EGR. The specific heat values of CO₂ and H₂O are higher and they tend to reduce the adiabatic flame temperature. Thus, EGT reduces from 357 °C to 339 °C.

SCR reactions utilize the heat of exhaust gases for decomposition and thermolysis of urea. This reduces EGT from 339 °C to 278 °C.

3.6. In-cylinder pressure

Fig. 12 shows the change in cylinder pressure for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR at full load. Lower viscosity and better volatility of fuel enables good quantity of fuel to be burnt in the premixed combustion stage, thereby raising the cylinder pressure. The peak value of pressure for diesel and GSME are 76.01 bar and 60.4 bar respectively. The physical and chemical properties of biodiesel were unfavorable, leading to inferior air fuel mixture. Addition of nano particles improves the chemical properties of biodiesel. Their additional oxygen content supports combustion process and promotes secondary atomization. The maximum pressure is raised from 60.5 bar to 65.2 bar. The in-cylinder pressure value of biodiesel is further rise to 73.02 bar by the combined effect of piston shape and nano particle suspension. The peak pressure was attained closer to TDC compared to the hemispherical piston shape. EGR and SCR technology has reduced the peak pressure to 72.1 bar and 64.2 bar. As the inlet charge temperature varied and combustion efficiency deteriorated with diluents gases (CO₂ and H₂O), peak pressure faced a fall with EGR. The back-pressure flow creates problem for the engine to compress the burnt gases, thereby requiring extra mechanical work. This affects the engine performance and reduced combustion efficiency. Hence, peak pressure is reduced to 67.2 bar by inclusion of SCR device.

3.7. Heat release rate

Fig. 13 shows the change in HRR for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, HRR for diesel and GSME are 62.3 J/°CA and 54.8 J/°CA respectively. Maximum heat release for biodiesel occurs at crank angle prior to diesel. This is connected with the shorter ignition delay of the fuel. ZnO blended GSME produces maximum HRR of 59.6 J/°CA, which is the end effect of increased fuel momentum and better air fuel mixture. The occurrence of maximum HRR is
advanced by 1°CA from TDC. Toroidal shaped piston prepares more quantity of fuel to be burnt in the premixed phase. Therefore, HRR is higher (63.1 J/°CA) than hemispherical shaped piston. Including EGR circuit in the test has retarded the HHRRmax position and its value was reduced to 58.6 J/°CA. As the re-circulated gases cause thermal effect dilution, the back flow of exhaust gases creates disturbance in combustion process, thereby reducing HRR value to 51.1 J/°CA.

3.8. Ignition delay and combustion duration

Figs. 14 and 15 shows the change in ignition delay and combustion duration for SCR fitted engine with GS ZnO coupled with toroidal piston and 5% EGR. At full load condition, ignition delay for diesel and GSME are 10°CA and 9°CA respectively. Nano particle additives and toroidal shape guides in air fuel mixing and better fuel momentum. This leads to instantaneous combustion and hence ignition delay is reduced to 6°CA. EGR and SCR technique creates hindrance in air fuel mixing and vaporization due to dilution and back pressure effects, hence increasing ignition delay to 7°CA. Variation in combustion duration is attributed to the nature of combustion process.

When more quantity of heat is released, the combustion duration is less stating that combustion process is enhanced and competed earlier. Combustion duration of diesel and GSME are 42°CA and 47°CA. The higher viscosity and poor volatility have extended the combustion duration for GSME. Adding nano particles and modifying the piston shape has increased the flame speed and combustion duration is reduced to 46°CA and 44°CA. EGR and SCR techniques increases combustion duration to 45°CA and 47°CA due to re-burning of the mixture and shrunk heat release.

4. Conclusions

The present study focused on methods to utilize the winery industry waste and convert it into biodiesel for conventional CI engines. This was achieved by a sequence of methodologies like fuel make up, engine design.

1. Physical and chemical properties of GSME satisfied ASTM standards. To further enhance the fuel nature, GSME was blended with zinc oxide particles in nano form. Cetane index was improved by 7.2%.

2. BTE increased from 28.9% to 29.3% due to zinc oxide additives. Toroidal piston shape modified the BTE by 4%. EGR and SCR technique caused a slight decrease in BTE compared to GSME fuel.

3. NOx emissions were 22.08% greater than diesel. The catalytic effect and thermal conductive properties of zinc oxide particles reduced the adiabatic flame temperature and in turn decreased NOx emissions to 8.2 g/kWh. Piston shape adjustment, EGR and SCR device further reduced NOx emissions by 76.9%.

4. HC emissions were reduced at all phases of work due to increased oxygen molecules in the nano blend and air fuel enhanced mixing. HC emissions for GSME + ZnO + toroidal shape was 0.34 g/kWh which is 15% lesser than GSME. EGR and SCR technique elevated HC emissions by 23.5% due to diluents and thermal effects.

5. CO emissions for GSME was 10.4% lesser compared to diesel. Additional oxygen content still reduced CO emissions. CO emissions for GSME + ZnO + toroidal shape was 4.01 g/kWh. EGR and SCR technique were not favorable for reducing CO emissions. This augmented CO emissions by 12.51%.

6. Smoke emissions faced a decrease of 17.5% for GSME + ZnO + toroidal shape compared to GSME. EGR at 15% and SCR elevated opacity levels by 49.8% due to reduction in flame temperature.

7. Maximum cylinder pressure for GSME with fuel and engine design changes was 64.1 bar which is 5.9% higher compared to GSME. The HRR was highest at 63.01 J/°CA for GSME + ZnO + toroidal shape and started to lower with introduction of EGR and SCR techniques.

Considering the above data, the different strategies suggested like addition of nano particles, piston shape make up, EGR technique and SCR device can be helpful in reducing all regulated emissions keeping the BTE within acceptable limits. GSME proves to be a promising source of energy and also resolves the disposal problems faced by wine manufacturing industries all around the globe.

5. Scope for future work

Carbon based nano particles can be blended with GSME and their effects on performance, combustion and emission characteristics could be studied. This is expected to produce a minimal effect...
on the environment. SCR coated with DPF catalyst can replace the existing SCR, so as to improve the NOx reduction efficiency. Various sources of ammonia other than aqueous urea solution could be used and their ammonia gas productivity be analyzed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References


[7] B. Deng, Q. Li, Y. Chen, M. Li, A. Liu, J. Ran, Y. Xu, X. Liu, J. Fu, R. Feng, The effect of DPF coated with DPF catalyst can replace the existing SCR, so as to improve the NOx reduction efficiency. Various sources of ammonia other than aqueous urea solution could be used and their ammonia gas productivity be analyzed.

