Operating parameters optimization for lower emissions in diesel engine with PCCI-DI mode using Taguchi and grey relational analysis

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ABSTRACT

Searching for ultra-low emission engines particularly for automotive applications is still ongoing. Even though LTC combustion mode results a prominent advantages in terms of reducing both NOx and PM and also lowering the consumption of fuel, it mainly faces with the challenge of excess emissions of HC and CO. This study aimed to optimize the operating control factors for low emissions in PCCI-DI engine under LTC mode. Parameters include injection timing, EGR level, dieseline ratio and engine load. Computation of analyzing the grey relation with hybrid of Taguchi was applied. In designing of experiments and conducting tests Taguchi’s L9 matrix was applied. Air-blast of methanol intake port supply and dieseline application instead of diesel was implemented aiming emission reductions. Optimum combinations were found using GRA and ANOVA. Following the optimization work; advanced injection timing of 25° before TDC, 25% EGR, dieseline 90:10 in % and load 75 % (A2B1C3D3) was found optimal combination level for the proposed aim of emission reductions. Key findings of the results following the experiment conducted using this optimal combination includes; reduction of 68.02% NOx and 62.37% in smoke comparing with the base-line conventional diesel combustion mode. Rankings and ANOVA indicated another findings that injection timing being most in influential with a contribution of 69.35% followed by load, dieseline ratio and EGR level respectively. This study confirmed dieseline direct injection with methanol port injection is capable of reducing emissions and better NOx with HC and CO trade-offs in PCCI-DI engines.

1. Introduction

Developing cleaner and efficient engines by researchers and engine manufacturers is unquestionable due to tightening legislation for emissions and increasing demand for fuel economy. These days’ researches are derived into alternative combustion concepts or modes that meet these regulations. Combustion in IC engines are moving towards unexplored combustion concepts where innovative combustion theories are being developed including advanced low temperature combustion following calibration of several engine control parameters. Achieving optimal efficiency and emission behaviors of these future combustion engines requires new approaches or methodologies of fuel use and engine control parameters.

Main forms of achieving low temperature combustion strategy includes; HCCI, PCCI, RCCI, and PPC. These strategies are achieved by modifying engine control parameters and fuel types. Researchers revealed that NOx with soot tradeoffs in the usual combustion could be overcome by PCCI combustion. It applies strategy of lowering the combustion temperature which is mostly used in fuels having comparable characteristics with diesel. Sometimes referred as PPCi and is proposed to obtain better engine load [1]. Drawbacks of HCCI (Homogeneous charge compression ignition) having limited operating range were proposed to be overcome by PCCI by introducing concentration stratification to control combustion level. PCCI helps to fulfill the benefits obtained from gasoline and diesel combustion techniques. It possesses thermal efficiency near to the diesel engines which helps to minimize high NOx and PM together [2]. PCCI resulted lower consumption of fuel and NOx but with greater HC results. Achieving higher lean burning within high compression ratio setting is attained by PCCI. These features help to lower NOx and PM [3, 4, 5].

PCCI operation can be met through appropriate matching of greater EGR level and early ignition. Irrespective of the EGR level by making lower SOI which is below 16° crank angle before TDC (Top dead center) will not enable PCCI to work [6]. Investigators stated that the upcoming
studies to give emphasis for EGR strategy to wider further LTC ranges including PCCI for soot-NOx reductions [7, 8]. Corresponding time of injection with level of EGR were tested using oil from plastic waste. From the investigation applying low level of EGR and earlier time of injection helps for parallel decrease of NOx and that of smoke [9].

In PCCI-DI mode of combustion fuel is delivered to the combustion cylinder through atomisation of fuel on the intake port and injection fuel directly on the cylinder. Additional advantage of this setup is the possibility of dual fuel application and also enhanced combustion features [10]. Its advantage in the reduction of NOx was discussed by investigators through reduction of the effects which brings smog and acid rain on the environment [11]. The arrangement of PCCI and conventional DI of CI mode is investigated on an engine with DME. This type of combustion mode is denoted as PCCI-DI type combustion. NOx reduction of up to 28% was achieved by applying PCCI-DI in Diesel-Diesel approach comparing with the conventional DI approach or mode. The reason for this reduction is proposed in line with the relatively lower temperature of combustion obtained in using PCCI-DI arrangement. LTC combustion mode including PCCI-DI resulted prominent advantages in lowering PM as well as NOx, in addition to lower specific consumption of fuel [12]. Study indicated the considerable increments in NOx during injection advance till 20° BTDC but reductions afterwards [13]. Considering these advantages and the above mentioned features this study used the PCCI operating mode together with the direct injection (DI) approach. PCCI-DI mode is mentioned as a promising technology to reduce NOx emissions but with its problem of increasing CO and HC emissions which needs further investigations [14]. This approach aims to work on the limitations of PCCI engines without significant penalizing of other response parameters.

Experimental design (DOE) helps to do systematic analysis of the control factors which affects the responses. In DOE the essential four stages need to be followed; planning, screening or process characterization, optimization and verification. Determining the optimal or best results from the control factors is the stage or phase of optimization that could be determined through different methods. This study used experimental investigations, design of experiments and a hybrid of Grey centered Taguchi approach that helps in multi response optimization process. Since this experimental study is having multi response functions that Taguchi method alone couldn’t solve these complex interrelationships having multi-objective optimization problems. In this study; injection timing, EGR level, dieseline ratio and engine load were used as a control operating parameters whereas emissions of NOx, HC, CO and smoke are responses.

Studies have been conducted applying the hybrid of Grey centered Taguchi approach to minimize emissions in diesel engines. The optimum response characteristics of PCCI run by ethanol together with mixture of diesel was investigated through applying Grey Taguchi technique [15]. Optimal combination from input parameters applying Grey-Taguchi Method was also found and studied to attain good torque, heat release, power and lower consumption of fuel [16]. In other study also Grey-Taguchi Method was applied for lower production of HC, CO and less consumption of fuel in VCR petrol engine [17]. The number of responses obtained from the Grey-Taguchi method can be converted to a grade of single relational type by evaluating these multiple responses through a gray relational grade. In this study tests were conducted following Taguchi’s L9 orthogonal array that helped the optimization of the multiple control operating parameters of injection timing, EGR level, dieseline ratio and engine load. Parameters like emissions of NOx together with soot on CI engine working through the ignition of methanol and diesel composition were achieved through experimental investigation. Higher HC and CO comparing with the baseline diesel combustion was observed. From the study this new approach of applying the DMCC method together with an oxidation catalyst resulted simultaneous reduction of HC, CO, PM and NOx [18]. Researches indicated the potential of methanol for engines considering its minimum consumption of energy, minimum emissions together with less impact on health [19]. The viable features of methanol for diesel engine application were discussed in a critical review work by elaborating its liquid nature, high octane number and high oxygen contents and also being produced from renewable sources. The review indicated that methanol fumigation reduced emissions of diesel engine without negative influences on diesel engine performance. It concluded that parallel minimization of soot with NOx in CI type engine possessing high efficiency is possible through the application of diesel methanol dual fuel (DMDF) [20]. Methanol for its greater oxygen amount helps for additional oxygen surrounding the diesel for enhanced and effective combustion characteristics. Also the high oxygen and low sulphur contents reduce emissions [21]. Low-cetane fuels have been found suitable for combusions with lower temperature conditions and also to have very less smoke together with better control of NOx outputs. Experimental investigation conducted [22] on SI engine with PFI of the blend of gasoline with methanol at throttle wide open positions showed positive effects on the engine-out regulated emissions. Experimental study was also conducted to obtain the influence of applying methanol as alternative fuel in the operation of engine of the diesel type. It indicated that using methanol together with diesel in varying ratios brought a substantial influence on engine and environment [23].

Other studies using alcohol port injection supply for engines using more than one fuel type is found successful method to minimize UHC together with NOx emissions [24, 25]. Various studies confirmed the benefit of dieseline and this study also investigated dieseline with different ratios together with methanol for PCCI-DI combustion. Premixed combustion in a premixed CI engines showed promising improvements by applying dieseline fuel [26].

Creating the feature of LTC mode on the Experimental setup includes making the fuel injection timing to be done in advance of the combustion begin which permits mixing fuel with air prior to combustion that is for homogeneous mixture formation [27]. Studies indicated that appropriate optimization of injection timing and fuel chemistry in LTC strategies including PCCI can reduce emissions to a satisfactory level. Optimization by taking the control factors and levels; mixture of diesel with that of cyclohexanol, different level of EGR and varying start of injection were carried out in an investigation. The study found out that cyclohexanol with 10 percent ratio with diesel mixture with 21° before top dead center time of injection and level of EGR with 10% was found optimal operational settings in the chosen setup resulting decrease of smoke together with NOx but increment of BSFC [28]. Studies shows that by forming the feature of PCCI through early application of fuel, soot and NOx formation were avoided [29]. Applying low temperature combustion engines in the automotive industry can act as a bridging technology for a fully electric vehicle fleet until the battery technology becomes cheaper, charging infrastructure becomes more accessible and the electric power generation cycle becomes cleaner [30].

This investigation intends in optimizing operating factors i.e. by finding the optimal arrangement of the operating factors for minimizing NOx, HC, CO and smoke, particularly HC and CO which are still the challenges of PCCI and other LTC engines. Another objective is testing methanol port injection which is pre calibrated and adjusted to inject a constant volume of methanol fuel per unit time which is one of the novel strategies in this study. This methanol port injection is air compressor assisted type forming a premixed charge in homogeneous mixture form. This is a technique followed to meet the requirement of PCCI setup. The control parameters include injection timing, EGR level and dieseline fuel ratio (diesel with gasoline) which is direct injected. The other novelty in this investigation is gaining the optimum combination of the control operating parameters resulting optimal minimized emissions in PCCI-DI engine set up. New EGR cooler for this engine set up was also designed and manufactured in a workshop aiming the objectives of the experiment. To attain this objective computation of analyzing the grey relation with hybrid of Taguchi was applied. In designing of experiments and conducting tests Taguchi’s L9 matrix was applied. This work also proved the functionality of the grey-Taguchi method of optimization for lower emission results in PCCI-DI engines. Effects of the control operating
parameters; injection timing, EGR level, dieseline ratio and engine load on this experimental engine set up being explored.

2. Materials and methods

2.1. Experimental setup

Chosen materials and methods helped in optimizing the engine operating control parameters; Injection timing, EGR level and diesel ratio for improved NOX, CO, HC and smoke trade-offs operating in PCCI-DI combustion mode. Figure 1 shows schematic of experimental system. Diesel, gasoline and methanol fuels with quality standards were purchased locally from the reliable sources and suppliers (their property is shown in Table 1) gas stations and chemical stores. Laboratory equipment's from Material engineering department such as a magnetic stirrer for mechanical agitation and an ultra sonicator for ultrasonic vibration mixing of diesel with gasoline were used. Stirrer, reaction flask, light-duty single cylinder diesel engine and compressor were some of the equipment's used for the experiments which are available in the engine laboratory. The experiment was conducted using one cylinder DI diesel type by adapting the intended operational conditions and combustion type. Table 2 designates basic engine specifications and experiment conditions.

The unmodified test engine including the experimental was made initially to run under conventional conditions to have reference or baseline records. The test engine is adapted to work in PCCI-DI mode, by doing suitable changes in injection timing, EGR level, methanol port injection and dieseline direct injection as shown in Figure 2.

For EGR system, 12 in number tubes were used for the cooler design in which the coolant is water. The manufactured cooler being dimensioned as; 12mm inner diameter, 40mm tube length and 1mm thickness of tube. Different issued articles were referred to choose dimensions of the EGR cooler during manufacturing and assembly [31, 32]. For this set up additional container for water is arranged to supply water coolant possessing external warming device making equivalent temperature of water with the actual coolant in a radiator. The study tried to demonstrate the potential of air-blast of methanol intake port supply in parallel with diesel/gasoline mixture direct application on emission reduction in diesel engine by applying dual-fuel combustion strategy.

The methanol port injection is a workshop air compressor assisted type positioned 12cm from the intake valve to form the premixed charge in homogeneous mixture form. Amount of methanol port injection is pre calibrated and pre adjusted to inject a constant volume of methanol per unit time.

1-Single cylinder diesel engine, 2-Asynchronous motor, 3- Cooler for EGR, 4- Valve for EGR, 5- Reservoir for water. 6-Inlet port, 7- Reservoir for diesel/gasoline blended fuel, 8 - reservoir for methanol, 9-Compressor for air, 10- Smoke meter, 1- system control unit.

2.2. Taguchi analysis

Factors and levels chosen for the study considering their impact on emission characteristics are shown in Table 3. L9 orthogonal array being applied in this investigation and results are given in Table 5. The design has 9 rows, 3 levels and 4 columns of operating control parameters.

2.3. Grey relational optimization method

S/N Ratio; Variation of result data comparative to the value of nominal data was measured using signal to noise relation. For this study two categories of S/N ratios were used [15]; the lower being the better uses the following S/N formula (1);

$$S/N = 10 \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} y_{ij}^{-2} \right)$$  \hspace{1cm} (1)

Computing the higher being the better uses the following formula (2);

$$S/N = -10\log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{ij}} \right)$$  \hspace{1cm} (2)

n - number of measurements taken in a trial, yij - i^th response in j^th test.

Level having highest value of S/N indicates the optimum condition of the operating control factors. For this study results of NOX, HC, CO and smoke were treated and computed in S/N ratio for the lower being the better. Normalizing calculations for S/N ratio was done to have an evenly distributed data and up grading the data for the analysis. Normalized
ratio S/N value which is $z_{ij}$ (01) representing $i^{th}$ emission result in $j^{th}$ experiment could be computed:

$$Z_{ij} = \max(\{y_{ij}, i = 1, 2, \ldots , n\} / \max(\{y_{ij}, i = 1, 2, \ldots , n\}) - \min(\{y_{ij}, i = 1, 2, \ldots , n\})$$

(3)

S/N values lower being better

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1, 2, \ldots , n)}{\max(y_{ij}, i = 1, 2, \ldots , n) - \min(y_{ij}, i = 1, 2, \ldots , n)}$$

S/N values higher being better

Calculating the coefficient for the grey relation for the S/N value which is normalized was using the formula;

$$\gamma(y_{o}(k), y_{j}(k)) = \frac{\min + \xi \max}{\Delta_{oj}(k) + \xi \max}$$

(5)

Where,

- $\xi$ denotes a constant between 0 and 1. For this investigation 0.5 is used as $\xi$ value [33].

- Grade for the Grey relation was generated using;

$$\overline{Y}_{j} = \frac{1}{m} \sum_{k=1}^{m} y_{ij}$$

(6)

By considering grades multi response control parameter design was optimized as results shown in Table 7. Results of grades are used to identify the optimal operating parameter aiming to get best results. ANOVA is used to know the input parameters which considerably influence the responses. Determining the optimum combination of the control parameters helps in maximizing response features. Selected optimum level from the operating control factors is used in predicting and also verifying the quality characteristic.

### 2.4. Error and uncertainty analysis

Accuracy of measurements leads in getting genuine study results. In determining the uncertainty obtained in this study, defining the sources of error and calibrating the used measuring apparatus were considered. To minimize errors during measurements three readings were taken and averaged for the analysis. Percentage relative uncertainties for NOx, CO, HC and also smoke being calculated and shown in Table 4.

The exhaust gas analyzer was calibrated with clean ambient air in order to get the mentioned specification standards. Emission results were registered by the element computer controlled TBMC-AGE exhaust gas analyzer. The analyzer needs to make frequently zero the sensors. Once a ZERO has been made the time to the next zero is displayed in minutes assuring there is enough time before beginning the test. The analyzer was

![Figure 2. PCCI-DI diesel engine experimental setup.](image)
calibrated with clean ambient air in order to get the specification standards. Flow sensor is installed to measure the amount of the outlet flow of exhaust gases.

3. Results and discussions

3.1. Experimental observation for L9 orthogonal array

Different combinations of four operating control parameters; advanced injection timing, EGR level, dieseline ratio and load were considered and four output responses; NOx, HC, CO and smoke were obtained. As Table 5 indicates (including results), nine experimental tests were conducted by applying L9 (34) matrix. Impacts of the chosen operating control parameters on emissions were shown on the surface and contour plots (Figures 3, 4, 5 and 6) and Table 5. In this study, results indicated that advancing the time of injection increases NOx as well as smoke but decreases HC and CO results. Increasing EGR level indicated higher HC and CO effects since less amount of oxygen during PCCI condition but it decreases NOx and smoke. In addition, decreasing the gasoline ratio in dieseline; decreases NOx, HC and smoke but increases CO emissions. Decrease in retarded ignition caused by the increased volatility nature from dieseline affected this event. Also the improved ignitability and combustion stability of dieseline in this PCCI-DI combustion could contribute for these results. The decrease in ignition delay helps in forming less over mixed regions that oxidation of fuel is challenging. High engine load resulted better HC and CO outputs however it increased NOx as well as smoke results.

Premixing methanol on intake port in the experiment has an impact on better combustion since improved oxygen amount which positively affected the emission characteristics by forming leaner combustion. Application of dieseline also contributed in lowering emission results from its characteristics of forming homogeneous mixture which improves the combustion efficiency. The air-blast methanol injection helped the PCCI-DI combustion by forming a lean combustion features that helped in achieving lower NOx and smoke and also significant lowering on the increments of HC and CO emissions.

As indicated in Table 6, optimum combination among the control operating factors is obtained by following analysis of grey relational method. During the analysis S/N ratios were calculated for the obtained experimental data, S/N ratios were normalized, coefficients of grey relational including grades of grey relational were computed, and optimum levels combination of the control operating parameters was found.

| NOx | Accuracy ±5% | % Uncertainty |
|-----|--------------|---------------|
| Run No. | Min. - 5% | Max. + 5% | Min. | Max. |
| 1 | 2.68 | 2.78 | 1.83 | 1.83 |
| 2 | 2.06 | 2.14 | 1.90 | 1.90 |
| 3 | 1.56 | 1.60 | 1.27 | 1.27 |
| 4 | 3.88 | 3.96 | 1.02 | 1.02 |
| 5 | 3.09 | 3.21 | 1.90 | 1.90 |
| 6 | 2.01 | 2.05 | 0.98 | 0.98 |
| 7 | 2.66 | 2.72 | 1.12 | 1.12 |
| 8 | 3.62 | 3.74 | 1.63 | 1.63 |
| 9 | 2.50 | 2.56 | 1.19 | 1.19 |

Uncertainty level of NOx: 1.43% ± 1.43%

Likewise results of others are indicated below:

- Uncertainty level of HC: 1.06% ± 1.06%
- Uncertainty level of CO: 1.53% ± 1.53%
- Uncertainty level of smoke: 2% ± 2%

Table 5. Orthogonal array of L9 type test matrix with factors and results.

| Control factors | Exp. No. | A | B | C | D | Results |
|-----------------|----------|---|---|---|---|---------|
| Injection timing (CA BTDC) | | 23 | 25 | 60 | 25 | 2.73 | 0.06 | 153 | 0.05 |
| EGR level (%) | | 23 | 35 | 80 | 50 | 2.10 | 0.05 | 157 | 0.03 |
| Diesel to gasoline ratio (D:G) (% By Volume) | | 23 | 45 | 90 | 75 | 1.58 | 0.08 | 176 | 0.04 |
| Load (%) | | 25 | 25 | 80 | 75 | 3.92 | 0.07 | 154 | 0.42 |
| NOx g/kWh | | 25 | 35 | 90 | 25 | 3.15 | 0.06 | 173 | 0.12 |
| CO g/kWh | | 25 | 45 | 60 | 50 | 2.03 | 0.09 | 158 | 0.06 |
| HC g/kWh | | 30 | 25 | 90 | 50 | 2.69 | 0.03 | 156 | 0.03 |
| Smoke/m | | 30 | 35 | 60 | 75 | 3.68 | 0.04 | 133 | 0.04 |
| 9 | 30 | 45 | 80 | 25 | 2.53 | 0.05 | 139 | 0.02 |

Figure 3. Surface 3D and contour plots for NOx versus injection timing and Load.
Larger values of grade shows improved emission results. Therefore, selection of level is depending on its possession of the largest average response value. As shown in Figure 7; advanced time of injection with $25^\circ$ crank angle before TDC, 25 % EGR level, dieseline ratio of 90:10 in percent and 75 % of load arrangement ($A_2 B_1 C_3 D_3$), is the combination being optimum that achieves minimum emission the engine.

### 3.2. S/N ratio analysis

The S/N response curves are shown from Figures 8, 9, 10 and 11. They also indicate influences of varying levels in each operating factors

| Level | Parameters | A     | B     | C     | D     |
|-------|------------|-------|-------|-------|-------|
| 1     | 0.5350     | 0.5599 | 0.5391 | 0.5364 |
| 2     | 0.6917     | 0.5432 | 0.5598 | 0.5014 |
| 3     | 0.4574     | 0.5350 | 0.5852 | 0.6463 |
| Delta | 0.2342     | 0.0426 | 0.0461 | 0.1450 |
| Rank  | 1          | 4     | 3     | 2     |

* Optimum level of factors
on the responses. Minitab software is applied for S/N ratio calculations, Taguchi design, doing ANOVA and main effects plots.

As shown from Figures 8, 9, 10, and 11; optimum parameter/factor settings for low NO\textsubscript{x} are A\textsubscript{3} (30 CA BTDC), B\textsubscript{1} (25%), C\textsubscript{3} (90:10 %) and D\textsubscript{1} (25%). For low HC; A\textsubscript{1} (23 CA BTDC), B\textsubscript{3} (45%), C\textsubscript{1} (60:40 %) and D\textsubscript{2} (50%) were found optimum parameter settings. For low CO; A\textsubscript{3} (30 CA BTDC), B\textsubscript{1} (25 %), C\textsubscript{3} (90:10 %) and D\textsubscript{3} (75%) were optimum settings. Also for lower smoke; A\textsubscript{3} (30 CA BTDC), B\textsubscript{3} (45 %), C\textsubscript{3} (90:10 %) and D\textsubscript{2} (50%) were found optimum parameter settings. From ANOVA injection timing is found the highest affecting control factor possessing 69.35% contribution followed by load, dieseline ratio and EGR level respectively.
In validating the results found using Taguchi technique experimental verification was conducted using significant factors arranged at optimal conditions. Values from the verification test under the optimal conditions are; advanced time of injection with 25° crank angle before TDC, 25% of EGR level, dieseline ratio of 90:10 in percent and 75 % of load arrangement (A2B1C3D3). Confirmation test results indicated that in optimizing a multi response challenges, grey-Taguchi is a convenient optimizing tool in predicting the injection timing, EGR level, dieseline ratio, and load arrangement for lower emission characteristics in PCCI-DI diesel engines. Outcomes in PCCI-DI optimal combustion mode (optimum combination at A2 B1 C3 D3) resulted reduction of 68.01% in NOx and 62.37% in smoke compared with base-line. Relatively promising lower percentage increments of 27.49% and 33.18% in HC and CO results respectively were found in comparison to the average previous studies on PCCI combustion. Minimized HC and CO percentage increments are promising results comparing with most previous studies having more than 30% increments even more than 100% increments [34, 35].

### 4. Conclusions

In this study operating control parameters; injection timing, EGR level, dieseline ratio and load having three levels were selected for optimization of emission characteristics pertaining to NOx, HC, CO and smoke. In designing of experiments and conducting tests Taguchi’s L9 orthogonal array was applied. Taguchi, relational grey analysis and ANOVA are used in finding optimum combination of the control operating parameters. This study indicated the functionality of the grey-Taguchi method of optimization for lower emission results in PCCI-DI engines. Impacts of injection timing, EGR level, dieseline ratio and engine load on this experimental engine set up were investigated. From the analysis the most influential contributors for the emission productions among the control factors were identified. Methanol port injection together with direct injection of diesel was used on the chosen single cylinder of a diesel type to assess their influences on emission in PCCI-DI diesel engine. A pre calibrated and adjusted port injection of methanol which injects a constant volume of methanol fuel per unit time was successfully implemented on the engine setup. This air compressor assisted type methanol port injection formed a premixed homogeneous mixture. Validity of the results were verified through the confirmation tests. This study showed that a hybrid of Taguchi method and grey relation successfully applied for multi-response optimization in PCCI-DI engine. Generally this work indicated, direct injection of diesel in combination with methanol port injection is capable of emission reductions and better NOx with HC and CO trade-offs in PCCI-DI engines. The following conclusions have been made from the study and computations;

- For reductions of NOx, CO, HC together with smoke; the optimum operational settings of the control parameters/factors for the chosen PCCI-DI engine set up are advanced time of injection with 25° crank angle BTDC, 25 % EGR level, dieseline ratio of 90:10 in percent and 75 % of load arrangement (A2B1C3D3).
- Based on the rankings and ANOVA results, the order of contribution in the emission reduction were injection timing with a contribution of 69.35% % followed by load, dieseline ratio and EGR level respectively.
- From the confirmation test, good agreement between predictions from computation of the grey relation built on Taguchi approach and experimental values are obtained.
- By applying the main elements in analyzing the grey relation, challenges possessing multi-responses were transformed into single response and optimal solution was obtained from the experimental data.
- The study also verified the functionality of the grey-Taguchi hybrid method of optimization to find lower emission results in PCCI-DI engine set ups.
- In this study the modified PCCI-DI operation through port air-blast methanol injection of and dieseline (blend of diesel and gasoline) direct injection being contrasted with base-line combustion. Results indicated that 68.02% decrease in NOx and 62.37% decrease in smoke were obtained. But 27.49 % and 33.18% increments of HC and CO respectively were found. The HC and CO percentage increments are promising results comparing with most previous studies.
- From this investigation, premixing methanol through port injection together with optimization of the engine operational control factors or parameters in PCCI-DI diesel engine helped to minimize emission results particularly comparative CO and HC reductions.
- Challenges in LTC strategy mainly PCCI-DI approach in diesel engine will be solved fully through such further experimental investigations by modifying the engine and fuel.

### Declarations

**Author contribution statement**

Getachew Alemayehu: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ramesh Babu Nallamothu, Deresse Firew: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Rajendiran Gopal: Analyzed and interpreted the data.
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Data included in article supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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