Combustion Mode Switching Characteristics of a Medium-Duty Engine Operated in Compression Ignition/PCCI Combustion Modes

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Introduction

Due to concerns of rapid depletion of fossil fuel reserves, environmental degradation, and global warming, internal combustion (IC) engines with higher efficiency and lower emissions are being expeditiously developed. Diesel engines are becoming increasingly popular for automotive applications due to their inherently superior fuel economy, reliability, durability, lower carbon dioxide (CO₂) emission, and higher specific power output compared to any other power plant in that size range. However, the presence of localized fuel-rich regions and high-temperature regions in the conventional compression ignition (CI) combustion leads to high levels of emissions of oxides of nitrogen (NOₓ) and particulate matter (PM). Massive efforts have been undertaken in last four decades to reduce these pollutants using in-cylinder control measures as well as exhaust gas after-treatment systems; however, these techniques cannot be implemented in all production grade engines due to several operational and system complexities.

In last two decades, the low temperature combustion (LTC) has gained significant attention of the IC engine researchers due to its potential to reduce the PM and NOₓ emissions simultaneously. The absence of localized fuel rich zones results in homogeneous combustion, which leads to lower peak in-cylinder temperature, resulting in ultralow emissions of PM and NOₓ with satisfactory engine performance. Among various LTC derivatives, namely, premixed charge compression ignition (PCCI) combustion, homogeneous charge compression ignition combustion, and partially premixed charge compression ignition combustion, PCCI combustion has been extensively explored because of its superior combustion control potential and practicality for production grade engines [1]. In PCCI combustion, a fraction of fuel is injected very early in the compression stroke (as pilot injection), which results in homogeneous fuel–air mixture formation, however, the remaining fuel is injected in the same way, as is done in conventional CI combustion. Weiskirch and Mueller [2] reported that PCCI combustion characteristics lie in between conventional CI combustion and homogeneous charge compression ignition.

Premixed charge compression ignition (PCCI) combustion is a novel combustion concept, which reduces oxides of nitrogen (NOₓ) and particulate matter (PM) emissions simultaneously. However, PCCI combustion cannot be implemented in commercial engines due to its handicap in operating at high engine loads. This study is focused on the development of hybrid combustion engine in which engine can be operated in both combustion modes, namely, PCCI and compression ignition (CI). Up to medium loads, engine was operated in PCCI combustion and at higher loads, the engine control unit (ECU) automatically switched the engine operation to CI combustion mode. These combustion modes can be automatically switched by varying the fuel injection parameters and exhaust gas recirculation (EGR) by an open ECU. The experiments were carried out at constant engine speed (1500 rpm) and the load was varied from idling to full load (5.5 bar brake mean effective pressure (BMEP)). To investigate the emission and particulate characteristics during different combustion modes and mode switching, continuous sampling of the exhaust gas was done for a 300 s cycle, which was specifically designed for this study. Results showed that PCCI combustion resulted in significantly lower NOₓ and PM emissions compared to the CI combustion. Lower exhaust gas temperature (EGT) in the PCCI combustion mode resulted in slightly inferior engine performance. Slightly higher concentration of unregulated emission species such as sulfur dioxide (SO₂) and formaldehyde (HCHO) in PCCI combustion mode was another important observation from this study. Lower concentration of aromatic compounds in PCCI combustion compared to CI combustion reflected relatively lower toxicity of the exhaust gas. Particulate number-size distribution showed that most particulates emitted in PCCI combustion mode were in the accumulation mode particle (AMP) size range, however, CI combustion emitted relatively smaller sized particles, which were more harmful to the human health. Overall, this study indicated that mode switching has significant potential for application of PCCI combustion mode in production grade engines for automotive sector, which would result in relatively cleaner engine exhaust compared to CI combustion mode engines. [DOI: 10.1115/1.4039741]

Keywords: partially premixed charge compression ignition, mode switching, unregulated emissions, particulate emissions, open ECU

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1. Corresponding author.

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in a NOx emissions peak and extremely high rate of pressure rise during mode switching. Bae et al. [20] studied the fuel injection strategies during combustion mode switching cycles and reported that IMEP of some cycles were significantly higher than steady-state PCCI and CI combustion cycles. Ouyang et al. [21] investigated the effects of different control parameters such as injection timing, FIP, and EGR rate and developed an optimized mode switching strategy based on predefined step-by-step fuel–air coordination. Shi et al. [22] reported that incomplete combustion of fuel during transitional cycles could compensate the IMEP reduction. They suggested that increased fuel injection quantity during early transitional cycles could improve the smoothness of IMEP during mode switching.

The previous studies showed that fuel injection parameters and EGR rate effectively controlled the fuel–air mixture formation and its chemical kinetics in the combustion chamber. Therefore in this study, optimized fuel injection strategy for mode switching between conventional CI and PCCI combustion modes has been developed. Experiments were carried out in a suitably instrumented production grade engine using an open engine control unit (ECU). Measurement of particle number-size distribution and unregulated gaseous emission species are two important and unique aspects of this study, which are not investigated thoroughly in the previous studies.

### Experimental Setup

In this study, PCCI combustion was achieved in a production grade engine using an open ECU. Experiments were carried out to investigate the combustion mode switching characteristics between CI and PCCI combustion modes. The experimental setup consists of three main systems, namely, test engine, emission measurement system, and open ECU. In this study, a two-cylinder, four-stroke, medium-duty transportation direct injection compression ignition engine (Mahindra and Mahindra; 0.9 L 2CY CRDe NA) was used for investigating the mode switching characteristics between CI and PCCI combustion modes. The engine was coupled to an eddy current dynamometer (Dynomerk Controls; EC100). The engine had a common rail direct injection system capable of generating FIP up to 1200 bar. Fuel injection parameters were controlled by an ECU (Bosch; EDC17C55, India), supplied by the original equipment manufacturer (OEM). For PCCI combustion, a fraction of exhaust gas was supplied to the intake manifold through a proportional–integral–derivative controlled EGR valve. A laminar flow element (Meriam, 50MC2-2F) was installed to measure the volumetric air flow rate. Fuel consumption was measured using a graduated burette by determining the time required for consumption of a given volume of fuel. Schematic of the experimental setup is shown in Fig. 1.

Technical specifications of the test engine are given in Table 1. OEM ECU supplied along with the production grade engine performs actions based on predetermined logic (map) stored in its microprocessor. This system does not offer any flexibility for controlling various parameters such as FIP, start of pilot injection, start of main injection (SoMI), fuel injection quantity, and EGR rate for achieving combustion mode switching. Therefore, OEM ECU was replaced with an open ECU (Nira Controls; NIRAI7r), which was duly connected to various sensors and actuators in the engine. Open ECU is a sophisticated electronic engine management system, which is custom-configured for this study. The schematic of the open ECU configuration is shown in Fig. 2. The technical specifications of open ECU are given in Table 2.
fuel quantity was varied depending on engine speed and load. Open ECU controlled the fuel quantity for pilot injection with the help of “injection mass pilot map.” FIP was controlled by a “fuel pressure controller set point map,” which was dependent on two variables, namely, engine speed and fuel mass request. This created the desired set point for the proportional–integral–derivative controller. Fuel injection timings were controlled by two fuel injection timing maps, which took inputs from cycle reference signal and generated pulse output in terms of crank angle degree before the top dead center. EGR rate was controlled with the help of EGR actuator control map, which controlled the opening and closing of the EGR valve through pulse width modulated signals.

To measure the regulated gaseous emissions, a raw exhaust gas emission analyzer (Horiba, EXSA-1500) was used. This analyzer provided the concentrations of regulated gaseous species, namely, HC, CO, NOx, and CO2. Measurement principle and range of raw exhaust gas emission analyzer for each gaseous species is given in Table 3.

Fourier transform infrared (FTIR) emission analyzer (Horiba; MEXA-6000FT-E) was used to measure concentrations of unregulated gaseous species using the FTIR method combined with a multivariate analysis algorithm [24]. For number-size distribution of particulates, an engine exhaust particle sizer (EEPS) (TSI, EEPS-3090) was used, which could measure particle sizes ranging from 5.6 to 560 nm with maximum particle number densities up to $10^5$ particles/cm$^3$ of the exhaust gas at 10 Hz frequency. EEPS spectrometer provided both high temporal resolution and reasonable size resolution using multiple size detectors working in parallel. EEPS spectrometer is therefore an ideal instrument for measuring particulates emitted in the engine exhaust under transient engine operating conditions. Other important details of EEPS spectrometer can be seen in our previous publication [25].

**Experimental Methodology**

Mode switching strategy was based on variations of fuel injection parameters and EGR rate using the open ECU. CI and PCCI combustion modes were optimized, and optimum fuel injection parameters and EGR rates were determined for the entire set of engine loads at fixed speed of 1500 rpm. On these engine operating points, performance and emissions including regulated, unregulated, and particulates were determined. Results of these baseline experiments were used to calibrate the open ECU maps, which in-turn controlled the fuel injection parameters and EGR rate, when such demands were placed on the ECU.

Mode switching experiments were performed at a constant engine speed of 1500 rpm as well. In mode switching experiments, the maximum fuel injection quantity (at 100% throttle) was fixed, which resulted in ~5.5 bar brake mean effective pressure (BMEP) in CI combustion mode. A customized test cycle of 300 s was executed for the mode switching experiments, which included engine idling, CI combustion, PCCI combustion, and mode switching between CI and PCCI combustion modes. In mode switching experiment, low load limit was defined by high IMEP variation and high load limit was defined by knocking combustion [26].

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**Table 1 Technical specifications of the test engine**

<table>
<thead>
<tr>
<th>Manufacturer/Model</th>
<th>Mahindra &amp; Mahindra Ltd. India/0.9 L 2CY CRDe</th>
</tr>
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<tbody>
<tr>
<td>Engine type</td>
<td>Four stroke, naturally aspirated</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>Two</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>18.5</td>
</tr>
<tr>
<td>Injection system</td>
<td>Direct injection</td>
</tr>
<tr>
<td>Bore/stroke</td>
<td>83/84 mm</td>
</tr>
<tr>
<td>Swept volume</td>
<td>999 cc</td>
</tr>
<tr>
<td>Power</td>
<td>20 kW at 3600 rpm</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Water cooled</td>
</tr>
<tr>
<td>Valve train type</td>
<td>Double overhead camshaft (DOHC)</td>
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**Fig. 1** Schematic of the mode switching experimental setup: 1—test engine, 2—eddy current dynamometer, 3—dynamometer controller, 4—laminar flow element, 5—open ECU, 6—ECU interface system, 7—fuel tank, 8—fuel pump, 9—fuel rail, 10—EGR valve, 11—EGR loop, 12—thermodiluter, 13—engine exhaust particle sizer, 14—EEPS data logger, 15—FTIR emission analyzer, and 16—raw exhaust gas emission analyzer

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Strategy of mode switching experiments to achieve both combustion modes is shown in Fig. 3.

In a test-cycle of the mode switching experiment, engine was started in CI combustion mode and the minimum fuel quantity was supplied to each cylinder. Engine was started in CI combustion mode to avoid misfire at low loads, however this led to higher HC emissions. After engine warm-up, mode transition from CI-to-PCCI combustion mode was done by altering the fuel injection parameters. During PCCI combustion, start of pilot injection timing was varied from 30 deg to 35 deg CA bTDC and pilot injection quantity was varied from 5% to 12% of the main injection quantity, depending on the engine load. In PCCI combustion region, FIP was varied from 550 to 750 bar. FIP was decided based on SoMI timing, which was varied from 15 deg to 20 deg CA bTDC. At the starting of PCCI combustion, EGR was 0%, and after complete mode switching from CI-to-PCCI combustion, EGR was maintained at 15% during the entire duration of PCCI combustion. In PCCI combustion mode, engine was loaded up to 55% throttle (BMEP ~2.95 bar). At 55% throttle position, engine showed significantly higher combustion noise due to excessive RoPR. At higher engine loads, relatively faster chemical kinetics of fuel-air mixture led to severe knocking. Earlier SoMI timing used for PCCI combustion resulted in slightly inferior fuel–air mixing due to lower in-cylinder pressure and temperature, leading to higher HC and carbon monoxide (CO) emissions. Beyond 55% throttle, engine was switched back to CI combustion mode by altering fuel injection parameters and deactivating EGR valve gradually. Pilot injection was also deactivated and SoMI was retarded to 6 deg CA bTDC. At higher engine loads, FIP was decreased to 400–450 bar in order to avoid fuel spray impingement on the cylinder walls. Using optimized fuel injection parameters, engine achieved up to 5.5 bar BMEP in CI combustion mode and catered to the rated load.

Results and Discussion

In this study, experimental results were divided into four categories, namely (i) performance characteristics, (ii) regulated emission characteristics, (iii) unregulated emission characteristics, and (iv) particulate characteristics. Engine performance analysis included exhaust gas temperature (EGT) and brake thermal efficiency (BTE) analyses. Regulated emission analysis included CO, NOx, and HC emissions. Unregulated emission analysis included trace species such as benzene (C6H6), Toluene (C7H8), sulfur dioxide (SO2), formaldelyde (HCHO), formic acid (HCOOH), and iso-cyanic acid (HNCO). Particulate characteristics included particle number-size distribution, total particle number (TPN) concentration, nucleation mode particle (NMP) number concentration, and accumulation mode particle (AMP) number concentration. All experiments were repeated thrice and an average of

<table>
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<th>Table 2 Specifications of the open ECU</th>
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<tbody>
<tr>
<td>Make/model</td>
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<tr>
<td>Operating voltage</td>
</tr>
<tr>
<td>Number of connectors</td>
</tr>
<tr>
<td>Number of pins</td>
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<tr>
<td>Type</td>
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<tr>
<td>Analog/Digital inputs</td>
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<tr>
<td>Pulse width modulated outputs</td>
</tr>
<tr>
<td>Relay outputs</td>
</tr>
<tr>
<td>H-bridge</td>
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<td>Injector driver</td>
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<tr>
<td>Communication</td>
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| Table 3 Measurement principle and range of the exhaust gas emission analyzer |
|-------------------------------|-------------------------------|
| Species          | Measurement principle         | Measurement range     |
| CO               | Nondispersive infra-red       | 0–5000 ppm             |
| CO2              | Nondispersive infra-red       | 0–10/20% (v/v)         |
| THC              | Flame ionization detector     | 0–100/1000/5000/10,000/50,000 ppm |
| NOx              | Chemiluminescence detector   | 0–100/500/1000/5000 ppm |

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these results was plotted along with error bars, representing possible experimental errors.

Figure 4 shows the variations in the engine performance characteristics, namely, EGT, BTE, and BMEP with respect to time. All performance parameters were measured once in every 20 s. In this figure, different background colors represented the applicable combustion mode. Figure 4 shows that BMEP was very low (~0.7 bar) at the time of engine starting. During the mode switching from CI-to-PCCI combustion, BMEP was changed gradually in order to avoid sudden changes in fuel injection parameters, which could possibly result in rough engine operation. At the end of the transition period, fuel injection quantity was increased gradually and EGR was employed to operate the engine in PCCI combustion mode up to ~2.9 bar BMEP. At the end of PCCI combustion region (at t = 150 s), termination of pilot injection resulted in slightly inferior fuel–air mixing, leading to reduction in BMEP. To avoid further reduction in BMEP during PCCI-to-CI mode switching, fuel injection quantity was slightly increased at the start of mode switching from PCCI-to-CI combustion. This was similar to the “fuel compensation strategy” adopted by Deng et al. [23]. After achieving CI combustion (t = 200–300 s), BMEP increased gradually due to increase in fuel quantity up to the rated engine load. At lower engine loads, slightly lower BTE (~17%) was observed, which increased gradually with increasing engine load. At lower engine loads, engine misfiring due to low in-cylinder temperature was the main reason for this behavior. During PCCI combustion, application of pilot fuel injection promoted fuel-air mixing, therefore BTE increased rapidly up to ~33%. However in the remaining region of PCCI combustion, BTE remained constant (flat curve between t = 100 and 150 s). This was due to two counter effects, namely (i) increasing in-cylinder temperature at higher engine loads, which increased the BTE, and (ii) increased HC and CO emissions reduced the BTE [27]. Further increase in BTE was observed during mode switching from PCCI-to-CI combustion. This was mainly due to deactivation of EGR, which resulted in slightly higher peak in-cylinder temperature, leading to higher BTE. In CI combustion mode, increasing engine load led to higher BTE. Maximum BTE in CI combustion mode was ~36%. EGT variation with respect to engine load showed significantly lower EGT in PCCI combustion mode compared to CI combustion mode. During mode switching from PCCI-to-CI

Fig. 4 Variations in BTE and EGT with BMEP during different combustion modes and mode switching
mode, a sudden increase of ~100°C in EGT was observed which increased continuously in CI combustion mode with increasing engine load. The presence of diffusion combustion phase in CI combustion mode was the main reason for higher EGT. Termination of EGR during PCCI-to-CI combustion mode switching was another important reason for such a sudden increase in the EGT.

Figure 5 shows the variations in CO, HC, and BMEP with respect to time. Higher CO and HC emissions from PCCI combustion reflected high degree of incomplete combustion, which was mainly due to lower bulk in-cylinder temperatures [28]. Regulated gaseous species (CO and HC) are presented in brake specific values in Fig. 5.

During idling, HC emissions were very high due to milder conditions prevailing in the engine combustion chamber. HC emissions decreased with increasing engine load since the chamber temperature increased. HC emissions increased with increasing engine load during PCCI combustion and reached up to 2 g/kWh. Relatively lower in-cylinder temperature during PCCI combustion was the prime reason for this, which was responsible for incomplete combustion in the absence of diffusion combustion phase. During mode switching from PCCI-to-CI combustion, substantial reduction in HC emissions were observed due to higher bulk in-cylinder temperatures, which promoted fuel oxidation. During CI combustion mode, HC emissions further decreased with increasing engine load. This was another reason for higher EGT during CI combustion mode. CO emission showed significantly different trend during mode switching. The literature shows that CO emission was higher in LTC mode [29,30]. However, mode switching from PCCI-to-CI combustion resulted in higher CO emission from CI combustion compared to PCCI combustion mode. The presence of relatively richer fuel–air mixture at higher engine load may be a possible reason, where lack of oxygen prevented oxidation of CO into CO₂. Peak CO emission concentration in PCCI combustion mode was ~18 g/kWh, however, for CI combustion mode, peak CO concentration went up to ~60 g/kWh.

Figure 6 shows the variations in TPN, NOₓ, and BMEP with respect to time. Particulate characteristics were measured using EEPS. EEPS was continuously operated for 300 s, which helped in measurement of particulate data during mode switching from conventional CI-to-PCCI combustion.

Figure 6 shows significantly lower TPN and NOₓ emissions during PCCI combustion mode compared to CI combustion mode. TPN in CI combustion mode was an order of magnitude higher compared to PCCI combustion mode. In PCCI combustion region, the engine yielded ~4 × 10⁸ particles/cm³ of the exhaust, however, in CI combustion region, the yield was ~1.75 × 10⁹ particles/cm³.
region; PCCI-to-CI region; and CI region. All these regions were
split into five regions in the figure: CI (idle); CI-to-PCCI region; PCCI
combustion mode, which prevented the condensation of gaseous
species onto particulate surfaces and led to relatively smaller par-
iculate emissions during CI combustion mode compared to PCCI
combustion mode.

Significantly lower NOx emissions in PCCI combustion com-
pared to CI combustion region was another advantage of PCCI
combustion mode over the CI combustion mode. In PCCI com-
bustion mode, the maximum NOx concentration was ~150 ppm,
however, it increased up to ~575 ppm in CI combustion mode.
During PCCI combustion, NOx emissions were almost constant;
however, at the end of the PCCI combustion region, NOx emis-
sions increased rapidly (~300 ppm). This was an important crite-
rion for determining the upper load limit of PCCI combustion.
The maximum NOx increase was observed during PCCI-to-CI
combustion mode switching, where retarded SoMI timing, and the
absence of EGR and pilot injection led to heterogeneous fuel–air
mixing, leading to higher in-cylinder temperatures [31]. At the
end of mode switching from PCCI-to-CI combustion, NOx emis-
sions reduced slightly due to thermal stabilization after sudden
increase in peak cylinder temperature, however, NOx emissions
remained almost constant during the CI combustion mode. Al-
though temperature increased during the CI combustion, how-
ever the presence of relatively richer fuel–air mixture led to oxy-
gen deficiency, which might be a possible reason for this trend.
This fact also supports the CO emission trend (Fig. 5).

Figure 7 clearly indicates the variations in particle numbers
emitted from mineral diesel fueled engine during different
combustion modes and mode switching. Smooth variations in par-
cative emissions from CI combustion compared to PCCI combus-
Retarded SoMI timings resulted in lesser time available for
fuel–air mixing and the absence of pilot injection led to relatively
inferior in-cylinder conditions for main fuel injection. Combined
effect of these two factors resulted in localized fuel-rich zones,
which promoted soot nuclei formation and resulted in higher par-
ticulate emissions during CI combustion mode compared to PCCI
combustion mode.

Figure 7 shows the variations of particle number-size distri-
bution with respect to time. Particle number-size distribution was also split
into five regions in the figure: CI (idle); CI-to-PCCI region; PCCI
region; PCCI-to-CI region; and CI region. All these regions were
divided based on BMEP (shown on left vertical surface).

Figure 7 clearly indicates the variations in particle numbers
emitted from mineral diesel fueled engine during different
combustion modes and mode switching. At the time of engine starting, particle number concentration was
very low, which remained almost constant during mode switching
from CI-to-PCCI combustion mode. During PCCI combustion
mode, increasing load resulted in higher particle number concen-
tration. During PCCI combustion mode, peak of particle number-
size distribution shifted toward the accumulation mode (50 nm < Dp < 1000 nm) particles, which indicated that the engine
emitted relatively larger particles during PCCI combustion mode.
The absence of nanoparticles (Dp < 10 nm) during PCCI combus-
tion was another important observation of this study. Concentra-
tion of nanoparticles became significant during mode switching
from PCCI-to-CI combustion mode. This reflected the presence
of fuel-rich zones, which promoted the nuclei formation. During
mode switching from PCCI-to-CI combustion mode, peak of par-
ticle number-size distribution shifted toward smaller particles.
This was mainly due to higher in-cylinder temperature (due to dif-
fusion combustion), which prevented the condensation of gaseous
species onto particulate surfaces and led to relatively smaller par-
ticulate. During CI combustion, increasing engine load shifted the
particle number-size distribution curve upward but toward the
right side. This showed that particle number concentration
increased with increasing engine load and relatively larger par-
ticles were emitted due to higher fuel quantity injected. Nanopar-
ticle concentration was significantly higher in CI combustion
mode compared to PCCI combustion mode, which reflected sig-
ificantly higher health risk potential of CI combustion mode.
Comparison of particle number-size distribution curves of PCCI
combustion mode and CI combustion region clearly showed
wider size distribution of particles emitted in CI combustion
mode. Highest particle number concentration in PCCI combustion
mode was ~2 × 10^7 particles/cm^3 of the exhaust, which increased
up to 1.6 × 10^8 particles/cm^3 of the exhaust in CI combustion
mode, i.e., it increased by an order of magnitude.

Figure 8 shows the variations in concentrations of NMP
(Dp < 50 nm), AMP, and BMEP with respect to time. Figure 8
shows that NMPs were almost constant throughout the test-cycle
(in both combustion modes) except during the mode switching
period from PCCI-to-CI combustion mode. This was mainly due
to reduction in FIP, which led to slightly inferior fuel–air mixing
and resulted in the formation of higher number of NMPs [32]. The

![Fig. 7 Variations in particle number-size distributions with respect to time and BMEP for different combustion modes and mode switching](image-url)
effect of inferior fuel-atomization was also observed in AMP concentration, which increased rapidly during PCCI-to-CI combustion mode switching. Few researchers also reported this behavior and suggested that solid carbonaceous particles also exist in CI combustion mode due to fuel-air mixture inhomogeneity [33]. After mode switching from PCCI-to-CI combustion, AMP concentration further increased due to combined effect of the two factors, namely, heterogeneous fuel-air mixing and higher fuel quantity. These trends showed that the differences in TPN concentrations emitted during CI combustion mode was mainly due to dominance of AMPS in the exhaust gas.

Figures 9–11 show the variations in different unregulated gaseous species emitted from different combustion modes and mode switching. These unregulated gaseous species were measured using FTIR emission analyzer, which was capable of continuous measurement of 31 unregulated hydrocarbon species quite precisely. During mode switching, six gaseous emission species were observed to be present in significant quantities, which were classified as harmful to the human health.

Figure 9 shows the variations in benzene ($C_6H_6$), toluene ($C_7H_8$), and BMEP with respect to time. These species were a part of emission group of benzene, toluene, ethyl-benzene, and xylene (BTEX), however, ethyl-benzene and xylene were not detected. The presence of unsaturated hydrocarbons in mineral diesel acts as precursor, which is responsible for the formation of aromatic species such as benzene and toluene. Benzene is a known carcinogen; therefore its emission and human exposure is undesirable [34–36].

Figure 9 shows that benzene concentration was almost constant in PCCI combustion mode and it increased drastically in CI combustion mode. In IC engines, benzene forms mainly due to incomplete combustion of higher chain length hydrocarbons present in fuel and lubricants. In the presence of high in-cylinder temperature and pressure, fuel oxidizes completely; however, pyrolysis of fraction of lubricating oil results in higher concentration of benzene in the CI combustion region. These results are similar to the results reported by Bermúdez et al. [37], who suggested that aromatic species such as benzene form due to fuel pyrolysis at higher temperature and pressure conditions prevailing in the engine combustion chamber. Insufficient oxygen availability was another factor, which partially oxidized the fuel carbon into several unburnt hydrocarbon products, including benzene. In PCCI combustion mode, maximum benzene concentration reached up to $\sim$3 ppm, and in CI combustion mode, it reached up to $\sim$8 ppm. Results of FTIR analysis show that minor
concentration (~2–4 ppm) of toluene was also present in the engine exhaust. Toluene has a cyclic structure (similar to benzene) with one methyl group attached to benzene ring and its properties are nearly same as that of benzene. However, the toxicity of toluene is relatively lower than benzene. Toluene is also a product of incomplete combustion (pyrolysis of heavier fractions of mineral diesel and lubricating oil). The present study showed slightly random behavior of toluene emission in different combustion modes and mode switching. During PCCI combustion and PCCI-to-CI mode switching, toluene concentration was slightly higher, which decreased in CI combustion mode. This was due to relatively lower in-cylinder temperature in the PCCI combustion mode, which promoted incomplete combustion of fuel and lubricating oil. The toluene emission levels were within permissible limit because current standard for a permissible exposure limit for toluene vapors stands at 100 ppm [38].

Figure 10 shows the variations in HCHO and HCOOH with BMEP during different combustion modes and mode switching.

Figure 10 shows that variations in HCOOH were not significant. In entire operating region, HCOOH was almost constant (~0.5 ppm), therefore, HCOOH emission was not discussed any further. However, HCHO emissions were significant in both combustion modes. HCHO was a result of partial combustion and pyrolysis of fuel and lubricating oil in the engine combustion chamber. HCHO emission was higher in PCCI combustion mode and it reduced with increasing engine load in the CI combustion mode. In PCCI combustion mode, in-cylinder temperature was relatively lower, which led to relatively lower evaporation and higher degree of incomplete combustion of fuel droplets. CI combustion showed slightly lower HCHO emission due to higher incylinder temperatures; however lack of oxygen during relatively richer fuel–air mixture conditions restricted HCHO oxidation. HCHO was produced in CI combustion mode and was destroyed in the later stages of combustion. In PCCI combustion mode, relatively shorter combustion duration was another important factor.

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for higher HCHO emissions, whereas lesser time availability reduced the oxidation of HCHO [39]. Highest HCHO emission levels reached up to 20 ppm during mode switching from PCCI-to-CI combustion mode, which reduced to ~16 ppm during CI combustion mode.

Figure 11 shows the variations in SO2, HNCO, and BMEP with respect to time. Figure 11 shows that SO2 emissions were less than 6 ppm in both combustion modes. The presence of sulfur in mineral diesel led to formation of SO2 during combustion. In CI combustion mode, SO2 concentration was relatively lower than the PCCI combustion mode. This was mainly due to formation of sulfur trioxide (SO3), which resulted in formation of sulfuric acid (H2SO4) in the presence of moisture. The presence of sulfuric acid vapors in the exhaust acts as a site for condensation of volatile materials, which promotes particulate formation with higher adsorbed organic content. Therefore, conversion of SO2 into particulates led to higher particulate concentration in CI combustion mode and subsequently lower SO2 in the gas phase in the engine exhaust. HNCO emission was another important aspect of this study. The literature states that HNCO forms in higher quantities when NO, CO, and H2/NH3 react over precious metal catalysts. Recent studies have shown that IC engines are also one of the main sources of HNCO emissions in the atmosphere [40,41].

HNCO has been known to be a highly toxic gaseous substance and is a potential health risk due to its dissociation at physiological pH. Roberts et al. [42] reported that inhalation of even very low concentrations of HNCO (~ 1 ppbv) may be sufficient to commence carbamylation reactions in the human body. In the present study, it was observed that HNCO emission increased with increasing engine load during PCCI combustion mode, however, CI combustion mode showed slightly lower HNCO emission. Brady et al. [41] reported that lower in-cylinder temperature (during cold-start) might be a possible reason of HNCO formation in the engines. Maximum HNCO concentration reached up to ~23 ppm during PCCI combustion mode and reduced to ~18 ppm during the CI combustion mode.

Conclusions

In this study, experiments were performed to achieve combustion mode switching between conventional CI and PCCI combustion modes in a production grade engine. For mode switching, open ECU maps were generated for controlling different engine operating parameters, depending on the engine load. Results showed significant differences in the performance and emission characteristics during mode switching between CI-to-PCCI combustion modes in a customized test-cycle of 300 s. BTE was relatively lower at lower engine loads and it increased at higher engine load. CI combustion showed slightly improved BTE compared to PCCI combustion. EGT variations with respect to engine load showed significantly lower EGT in PCCI combustion mode compared to CI combustion mode. Regulated emission results showed significantly lower NOx emissions in PCCI combustion mode, however, HC emissions were higher compared to CI combustion mode. Higher CO emission during mode switching from PCCI-to-CI combustion mode was an important observation of this study. Particulate emission results revealed significantly lower TPN during PCCI combustion mode compared to CI combustion mode. The presence of nanoparticles in the exhaust from CI combustion mode showed its significantly higher health risk potential. Unregulated emission results showed that the concentrations of HCHO, SO2, C2H8, and HNCO increased with increasing engine load during PCCI combustion mode, however, it reduced slightly in the CI combustion mode.

Based on overall experimental analysis and results, it can be concluded that mode switching technique has significant potential for commercial application of PCCI combustion in a production grade engine. This study indicated that it is suitable to employ PCCI combustion at lower-to-medium engine loads and conventional CI combustion at higher engine loads by employing mode switching technology and thus reaping the complete benefits of LTC for commercial applications such as in automotive sector.

References


