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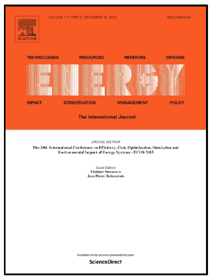

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<u>Research Highlights</u>

- Advancing SoMI and SoPI timings improved PCCI combustion
- Retarded SoMI timings resulted in higher NOx and PM emissions
- Increasing EGR reduced NOx and PM mass emissions simultaneously
- Increasing EGR rate effectively controlled the HRR of PCCI combustion
- Too high EGR resulted in higher HC and CO emissions

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Abstract

In this study, an advanced combustion concept 'premixed charge compression ignition' (PCCI) has been explored for diesel engines. PCCI combustion is a single-stage combustion process, in which a large fraction of fuel burns in premixed combustion phase resulting in relatively lower in-cylinder temperatures compared to compression ignition (CI) engine combustion. However at high loads, PCCI combustion results in severe knocking and higher oxides of nitrogen (NOx) emissions. This limits the applicability of this combustion concept to medium loads. This limitation of PCCI combustion can be resolved by altering in-cylinder pressure-temperature history at the time of fuel injection. This can be also be resolved by deploying suitable split fuel injection strategy and exhaust gas recirculation (EGR), which control combustion events such as start of combustion (SoC) and combustion phasing, leading to lower knocking and NOx emissions. To investigate the effects of various split injection strategy and EGR on PCCI combustion, engine experiments were conducted at different start of main injection (SoMI) timings (12, 16, 20 and 24° bTDC), start of pilot injection (SoPI) timings (30, 35 and 40° bTDC) and EGR rates (0, 15 and 30%). This study also included detailed particulate characterization such as particulate number-size distribution using an engine exhaust particle sizer (EEPS) and particulate bound trace metal analysis by inductively coupled plasma-optical emission spectrophotometry (ICP-OES). PCCI combustion was found to be superior at 35° bTDC SoPI timing and 15% EGR. At retarded SoPI timing (30° bTDC), PCCI combustion resulted in slightly higher NOx and particulate emissions, however at too advanced SoPI timing (40° bTDC), PCCI combustion showed relatively inferior engine performance. Application of EGR improved PCCI combustion and emission characteristics, however at high EGR, PCCI combustion resulted in inferior engine performance due to reduction in bulk in-cylinder temperatures. Overall, this study showed that PCCI combustion stability, knocking and NOx emissions can be optimized by selecting suitable combination of SoMI and SoPI timings, and EGR rate.

Keywords: Partially premixed charge compression ignition; Heat release rate; Exhaust gas recirculation; Split injection; Knocking.

1. Introduction

Rapid technological and economic advances in last few decades have culminated in rapid depletion of petroleum resources. In transport sector, compression ignition (CI) engines are being widely used currently, especially in light-duty and heavy-duty vehicles because of their higher thermal efficiency, greater reliability and superior fuel economy compared to gasoline engines. However CI engines suffer from major drawbacks of high oxides of nitrogen (NOx) and particulate matter (PM) emissions, which limit their applications due to prevailing stringent emission norms globally. Trade-off between PM and NOx is the main challenge faced by CI engines. The PM-NOx dilemma in CI engines was first addressed by Akihama et al. [1]. They suggested that application of exhaust gas recirculation (EGR) might be one of the possible solutions for this problem and experimentally studied the effects of ultra-high EGR on diesel combustion for simultaneous reduction in both NOx and PM. Too high EGR deteriorates the combustion characteristics and subsequently the engine performance; therefore different researchers coupled EGR with advanced combustion techniques such as homogeneous charge compression ignition (HCCI). HCCI emerged in the late 1970's, when Onishi et al. [2] experimentally demonstrated this novel combustion concept in a two-stroke engine. This concept was further explored by Thring [3], and HCCI combustion was implemented in a four-stroke engine. After these pioneering research efforts, several other researchers including Christensen et al. [4], Stanglmaier et al. [5] and Maurya et al. [6] successfully demonstrated HCCI combustion concept in spark ignition (SI) engines. In 1990's, efforts were made to examine and deploy this concept in diesel engines. Singh et al. [7] reported combustion characteristics of diesel HCCI engine. Even though HCCI concept proved to be effective in reducing NOx emissions from diesel engines, there were significant unresolved issues related to start of combustion (SoC), combustion phasing and, high hydrocarbons (HC) and carbon monoxide (CO) emissions [8]. These challenges motivated researchers to develop a new low temperature combustion (LTC) strategy, known as premixed charge compression ignition (PCCI) combustion. In PCCI combustion, fuel is injected at an intermediate timing between that of HCCI and conventional CI combustion. Advanced start of injection (SoI) timing results in a partially premixed fuel-air mixture due to relatively lesser time available compared to HCCI combustion. Therefore, PCCI combustion can be considered as a 'premixed combustion phase dominated CI combustion'. Due to low volatility of mineral diesel, diesel fuelled PCCI combustion investigations mainly focused on high pressure direct fuel injection strategies employing EGR [1, 9-12]. Higher fuel injection pressures and enhanced swirl ratios promoted fuel-air mixing however sufficient premixing time between end of injection (EoI) and SoC was necessary for achieving efficient PCCI combustion [13].

Initially, single stage direct injection of fuel was employed to achieve PCCI combustion wherein early direct injection during the compression stroke promoted fuel-air mixing due to presence of higher in-cylinder temperature and longer charge premixing time. However too advanced SoI timings resulted in fuel spray impingement on the walls resulting in cylinder wall wetting, leading to incomplete combustion and subsequently reduced thermal efficiency as well as higher HC emissions [14-15]. In PCCI combustion, fuel-air mixture homogeneity was also significantly affected by in-cylinder conditions (pressure-temperature history). For controlling the in-cylinder conditions at the time of main injection, researchers employed split fuel injection. Hashizume et al. [14] proposed a concept of 'multiple stage diesel combustion' (MULDIC), in which two-stage fuel injection was implemented to achieve the LTC. Using MULDIC, they achieved significant reduction in NOx and soot emissions simultaneously, however fuel economy was inferior compared to conventional CI combustion. Neely et al. [15] investigated effect of pilot injections (up to 3) to achieve PCCI combustion in light and heavy-duty vehicles. In case of single pilot injection, they observed considerable reduction in NOx emissions however higher CO emission. This CO penalty was reduced by implementing multiple pilot injections. Effect of split injection strategy on NOx formation was explored by Horibe et al. [16] and Torregrosa et al. [17]. They reported that higher thermal efficiency and lower NOx emissions at moderate engine loads could be achieved by single pilot injection however excessive rate of pressure rise (RoPR) limited the operating window of the PCCI combustion. In order to control the RoPR of PCCI combustion, researchers suggested using EGR. Higher level of EGR was used to achieve longer ignition delay (to improve fuel-air mixing) and lower in-cylinder temperature (to reduce NOx emissions) simultaneously [18]. However very high level of EGR increased HC and CO emissions and reduced the thermal efficiency. Kook et al. [19] and Kanda et al. [20] conducted experiments using different dilution rates (EGR) to attain PCCI combustion. High heat capacity of diluting gas lowered the adiabatic flame temperature, which prevented NOx formation. These researchers reported that NOx and soot luminosity had direct correlation with the adiabatic flame temperature and it decreased with increasing EGR rate. Manente et al. [21] examined the physical and chemical concepts of EGR on engine-out emissions in a PCCI engine. They reported that increasing EGR did not affect engine efficiency however it decreased CO and HC emissions significantly. Detailed study of injection parameters and fuel spray impingement on emission characteristics of mineral diesel fuelled PCCI engines was performed by Kiplimo et al. [22]. They observed that an increase in fuel injection pressure (FIP) led to lower HC, PM and NOx emissions with no change in CO emission. EGR stratification was a novel approach demonstrated by Andre et al. [23] and it was used to control rapid heat release and combustion noise in a LTC engine. Jacobs et al. [24] and Hardy et al. [25] investigated lean PCCI combustion for controlling NOx and PM emissions simultaneously. Lean PCCI combustion was achieved by employing high EGR rates, higher FIP and SoI timings close to TDC. This strategy reduced NOx and PM emissions because in-cylinder conditions were not favorable for formation of soot particles in the combustion chamber in case of LTC. None of these studies discussed effects of fuel injection parameters and EGR on particulate composition.

Many researchers showed that particulate emitted by PCCI combustion were significantly lower therefore detailed particulates characterization remained a rather ignored area by the researchers. However hypothesis of generating negligible particulate from LTC was contradicted by Price et al. [26]. This was supported by experimental studies of Kittelson and Franklin [27]. Agarwal et al. [28] also undertook comprehensive experimental investigations to characterize exhaust particulate from a mineral diesel fuelled LTC engine. It was amply demonstrated without any doubt that the relative air-fuel ratio (λ) and EGR were the major governing factors that affect particulate emissions from the LTC engine. Further, the effect of intake air pressure and oxygen content of the inlet air on particulate size-number distribution was investigated by Desantes et al. [29]. They reported that a slight increase in inlet air oxygen content caused significant reduction in CO, HC, and PM mass and particulate number emissions. Khalek et al. [30] observed the influence of inlet air dilution (EGR) on particulate emissions from a mineral diesel fuelled HCCI engine. They reported that dilution air temperature, dilution ratio and relative humidity were quite important for the formation of nucleation mode particulate ($D_p < 50$ nm). However accumulation mode particulate formation was less dependent on dilution conditions. Idicheria et al. [31] examined soot formation in PCCI combustion at very high EGR rates and reported that an increase in ambient temperature resulted in higher soot formation in presence of high EGR rate compared to no EGR case. Researchers also reported that particulate composition was different in case of LTC compared to CI combustion [28], due to different combustion characteristics of LTC. Among composition of particulate, trace metals, polycyclic aromatic hydrocarbons (PAHs) and benzene soluble organic fraction (BSOF) content are important. Springer [32] carried out experiments to evaluate particulate bound trace metals from light-duty and heavy-duty diesel engines. He reported that presence of trace metals like calcium, sodium, phosphorus, zinc, silicon, etc., were strongly affected by in-cylinder conditions during combustion. Agarwal et al. [28] also investigated particulate bound trace metals from mineral diesel fuelled LTC engine. They reported that most of trace metals mainly originated from incomplete combustion of fuel (trace metals in fuel), wear of engine components and pyrolysis of lubricating oil (from organo-metallic additives). However detailed analysis of particulate such as trace metals emitted from PCCI engines has not been thoroughly investigated.

All these studies indicated that fuel injection timing, strategy and charge dilution affect combustion, performance, emissions and particulate characteristics of a LTC engine. These studies were carried out by considering variations in each parameter separately. However combined effect of these parameters was not explored. This study evaluates the effects of split injection and EGR on combustion, performance, emissions and particulate characteristics simultaneously. The experiments were carried out in a single cylinder research engine operated in PCCI combustion mode. Detailed particulate characterization including particulate number-size distribution and particulate bound trace metal analysis was done. These are the innovative aspects of this experimental investigation, which were not been explored by previous studies given in open literature. To support the particulate characterization results, detailed analysis of combustion, performance and emission characteristics of PCCI combustion has been also carried out as well. Effects of SoPI and SoMI timings and EGR on NOx-PM trade-off is another important aspect of this study.

2. Experimental Setup

In this experimental study, a single cylinder direct injection compression ignition (DICI) research engine (AVL List GmbH; 5402) was used to perform PCCI experiments. This test engine was a single cylinder version of a four-cylinder automotive high-speed direct injection (HSDI) diesel engine and was equipped with a modern common rail direct injection (CRDI) system. The mechanical dynamics of the engine was made similar to a multi-cylinder engine using first order force balancers. A transient (AC) dynamometer (Wittur Electric Drives GmbH, 2SB-3) was used to control the engine speed and torque. The engine was equipped with a fuel measurement unit, a fuel conditioning unit, a chiller unit, a coolant conditioning system and a lubricating oil conditioning system for carrying out all investigations under controlled experimental conditions. During entire experiment, the lubricating oil and fuel temperatures were maintained at 90° and 25°C respectively. For combustion analysis, a water-cooled piezoelectric pressure transducer (AVL, QC34C) was installed in the engine cylinder head. Rotation of the crankshaft was monitored using an optical encoder (AVL, 365C). Cylinder pressure-crank angle data was acquired and analyzed by a high speed combustion data acquisition system (AVL, IndiMicro). Schematic of the experimental setup is shown in Figure 1 and the technical specifications of the engine are given in Table 1.

Figure 1: Schematic of the experimental setup

Table 1: Technical specifications of the test engine

Engine management system (EMS) of this engine had flexibility to control and measure fuel injection parameters in manual mode of operation. Flexible fuel injection system of EMS was capable of employing 4 injections in a cycle, including 2 pilots, 1 main and 1 post injection. An open loop fuel injection control strategy was loaded in the ETAS system to control fuel injection parameters independently. This control system consisted of an electronic control unit (ECU), a communication interface (ETAS, ETK 7.1) and an INCA software program. The injection parameters for each injection event could be modified and logged independently through the INCA software, which was used to communicate with the ETAS system.

To control PCCI combustion, a fraction of exhaust gas (coming directly from the engine) was recirculated back into the intake manifold. For controlling the EGR, a control valve was installed in the EGR loop. EGR rate was measured by reduction in mass flow rate of fresh intake air since reduction in mass flow rate of fresh air was directly proportional to the EGR. Quantity of fuel supplied to the engine was measured using a Coriolis force based fuel metering unit (AVL, 733s). This system performs continuous measurement of weight of a measuring vessel, through which fuel is supplied to the engine. To measure gaseous emission concentrations, a raw exhaust emission analyzer (Horiba, ESXA-1500) was used. This equipment comprised of a CO/ CO_2 analyzer (NDIR detector: MCA-220UA), O_2 analyzer (Paramagnetic pressure detector: MCA-220UA), HC analyzer (Hot flame ionization detector: FIA-225UA) and NO_x analyzer (Chemiluminescense detector: CLA-220UA). Opacity of exhaust was measured by a smoke opacimeter (AVL; 437). Particulate emission characterization was done using an engine exhaust particle sizer™ (EEPS) (TSI Inc.; 3090), which was capable of measuring particle sizes ranging from 5.6 - 560 nm and particle concentrations up to 10^8 particles/ cm^3 of exhaust gas. For particulate composition analysis, a partial flow dilution tunnel was used to collect the particulate emitted by the engine on a preconditioned filter paper. Particulate loaded filters were analyzed for trace metals using inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Thermo Fischer Scientific, iCAP DUO 6300 ICP Spectrophotometer).

3. Results and Discussion

Objectives of this study were to select a suitable split injection strategy and optimum EGR rate, which could deliver lower NOx and PM emission and control the engine knocking. To attain this objectives, PCCI experiments were performed at varying SoPI timings (30, 35 and 40° bTDC), SoMI timings (12, 16, 20 and 24° bTDC) and EGR rates (0, 15 and 30%). During entire set of experiments, FIP and engine speed were maintained constant at 700 bar and 1500 rpm respectively and mineral diesel was used as test fuel. Results obtained from the experiments were divided into five categories namely: combustion, performance, emissions, particulate characteristics and particulate bound trace metals and the main outcome of this study was summarized as statistical plots between PM and NOx emissions.

3.1 Combustion Characteristics

Parameters such as in-cylinder pressure history, heat release rate (HRR), SoC, etc., are very effective tools for analyzing the engine combustion characteristics. In this study, pressure-crank angle data was acquired by a high speed data acquisition system. To eliminate cycle-to-cycle combustion variability, average data set of 250 consecutive engine cycles was used for detailed combustion analysis.

Figure 2: Variations in cylinder pressure and HRR w.r.t. crank angle at different SoPI and SoMI timings

Figure 2 shows the variation in cylinder pressure and HRR at different SoPI and SoMI timings. At each SoPI timing, SoMI timings sweep was taken from 12 to 24° bTDC. During experiment, 15% EGR rate was maintained. Results obtained showed that advancing SoMI timing improved PCCI combustion due to longer time availability for fuel-air mixing. At advanced SoMI timings (20 and 24° bTDC), peak in-cylinder pressure (P_{max}) and peak HRR increased and shifted towards bTDC. This indicated higher premixed combustion tendency at advanced SoMI timings. At advanced SoMI timings, main combustion duration also reduced (reduced HRR curve width) due to faster fuel-air chemical kinetics. These trends are similar to those reported by Zhao et al. [33]. Advancing SoPI timings affected PCCI combustion in two ways: (i) advanced SoPI timings provided longer time for in-cylinder conditioning, which resulted in homogeneous fuel-air mixture and improved PCCI combustion, and (ii) too advanced SoPI timings led to inferior fuel-air mixing due to lower in-cylinder temperature and pressure. In presence of lower in-cylinder temperature, fuel vaporization decreased.

However lower in-cylinder pressure deteriorated fuel spray characteristics (relatively bigger fuel droplets leading to longer spray tip penetration and smaller spray area), which ultimately affected fuel-air mixing characteristics [34]. Dominantion of these two factors can be clearly seen from the trends for in-cylinder pressure. At 30° bTDC SoPI timings, less time avalilability for in-cylinder conditioning resulted in slightly lower P_{max}, higher HRR and higher RoPR (steeper in-cylinder pressure curves). At 40° BTDC SoPI timing, slightly inferior in-cylinder conditions dominated over the time availability factor, resulting in lower P_{max}, HRR and RoPR (flatter in-cylinder pressure curves). Ganesh et al. [35] performed similar experiments and observed similar combustion characteristics. Amongst all SoPI timings, 35° bTDC showed trade-off between the above two factors, which resulted in slightly higher (~2-3 bar) P_{max} compared to 30 and 40° bTDC. With advancing SoPI timings, slightly advanced SoC was another important observation. This indicated that SoPI timing controlled the chemical kinetics of the fuel-air therefore it can be used to control PCCI combustion.

Figure 3 shows the variation in cylinder pressure and HRR at different EGR rates and SoMI timings. At each EGR rate, SoMI timings were varied from 12 to 24° bTDC. During these experiments, SoPI timing was maintained constant at 35° bTDC. Variations in combustion characteristics at different SoMI timigs were similar to those observed in case of varying SoPI timings, however effects of varying SoMI timings were greater at higher EGR rates. This was mainly due to relatively lesser fuel quantity and lower in-cylinder temperatures at higher EGR rates.

Figure 3: Variation in cylinder pressure and HRR w.r.t. crank angle for different SoMI timings and EGR rates

Results obtained showed that P_{max} and maximum HRR decreased with increasing EGR rate. Exhaust gas consists of primarily inert species therefore increasing EGR rate reduced the oxygen content of intake air, resulting in relatively lower chemical kinetics of fuel-air mixtures. Presence of gaseous species with high heat capacity such as CO_2, water vapor, etc., in exhaust gas led to absorption of combustion generated heat thus lowering the P_{max} and HRR. This is the main reason for lower NOx formation at higher EGR rates. Retarded SoC with increasing EGR rate was another important observation of this study. With increasing EGR rate, presence of inert species in the exhaust gas led to longer ignition delay and subsequently retarded the SoC timings. Effect of EGR rate on combustion stability and knocking characteristics can also be observed from the trends of cylinder pressure and HRR. At 0% EGR rate, HRR was too high, which led to noisy combustion. With increasing EGR rate, combustion knock reduced. However at very high EGR rate (~30%), combustion became too slow, which deteriorated the PCCI engine performance and resulted in higher HC emissions. Amongst all the three EGR rates, 15% EGR rate was found to be the most suitable for PCCI combustion because it exhibited a trade-off between combustion and performance characteristics.

Figure 4: SoC, combustion phasing and combustion duration w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates

Figure 4 (a) shows variation in SoC, combustion phasing and combustion duration at different SoMI and SoPI timings. These parameters were calculated from mass fraction burned (MFB) analysis. MFB was calculated by Rossweiler and Withrow method [36] as given below:

$$(\Delta p_c) = p_i - p_{i-1}\left(\frac{V_{i-1}}{V_i}\right)^{\gamma}$$

Here Δp_c is the increase in cylinder pressure due to combustion and γ is the polytropic exponent. Using this relation, MFB can be computed as:

$$\frac{m_{b(i)}}{m_{b(total)}} = \frac{\sum_{j=0}^{i} \Delta(p_c)_j}{\sum_{j=0}^{N} \Delta(p_c)_j}$$

Here it is assumed that sample 0 is between inlet valve closing and SoC and sample N is after the completion of combustion.

In the current study, crank angle position corresponding to 10% MFB (CA_{10}) was considered as SoC. In PCCI combustion, combustion started well before TDC (~2-10° bTDC) due to advanced SoMI timings and faster chemical kinetics of fuel-air mixture. Advancing SoMI timing from 12 to 24° bTDC also resulted in advanced SoC. This trend was also visible from cylinder pressure and HRR curves. Advancing SoPI timings resulted in slightly advanced SoC. This was attributed to improved fuel-air mixing due to longer time availability. The difference between SoC timings at different SoPI timings increased at advanced SoMI timings. This showed that advanced SoPI timing was more effective at advanced SoMI timings (~20-24° bTDC) compared to retarded SoMI timings (~12-16° bTDC). 30 and 35° bTDC SoPI timings resulted in almost similar SoC, however 40° bTDC SoPI timing resulted in slightly advanced SoC. This showed that chemical kinetics of fuel-air mixture was not significantly affected by fuel-air premixing, but was significantly affected by in-cylinder conditions. This could be clearly observed from the combustion phasing results. Crank angle position corresponding to 50% MFB (CA_{50}) was taken as combustion phasing. Combustion phasing affected PCCI combustion efficiency, which decreased for too advanced as well as too retarded combustion phasing. Advanced combustion phasing led to higher HRR which resulted in excessive knocking. However late combustion phasing led to inferior combustion, which resulted in higher HC and CO emissions. Combustion phasing also followed similar trend at different SoMI and SoPI timings as that of SoC. However differences between combustion phasing at different SoPI timings were relatively lower compared to that of SoC. In PCCI combustion, combustion phasing was significantly advanced compared to CI combustion [37]. This was attributed to dominance of premixed combustion phase, which resulted in relatively faster combustion compared to CI combustion. Combustion duration is defined as the crank angle difference between 10 and 90% MFB (CA_{90} - CA_{10}). In PCCI combustion, variation in combustion duration shows the rapidness of combustion. Results obtained showed that combustion duration of PCCI combustion (~10-20 CAD) was significantly shorter compared to CI combustion (~30-40 CAD). This was mainly due to absence of diffusion combustion phase (slower combustion) in PCCI mode. With advanced SoMI timings, combustion duration slightly decreased. This trend also validated previous observation of relatively faster chemical kinetics of fuel-air mixture at advanced SoMI timings. Combustion duration slightly decreased at advanced SoPI timings though the difference was not significant. At all SoPI timings, combustion duration varied from ~12-17 CAD.

Figure 4 (b) shows the variation in SoC, combustion phasing and combustion duration at different SoMI timings and EGR rates. In the experiment, SoPI timing was maintained constant at 35° bTDC. At 0% EGR rate, SoC was significantly advanced compared to 15 and 30% EGR rates. This was mainly due to presence of relatively higher fuel quantity, which enhanced chemical kinetics of fuel-air mixtures, resulting in advanced SoC. Combustion phasing also varied similar to SoC. Increasing EGR rate led to relatively advanced combustion phasing. These observations showed that EGR affected both, the fuel-air mixing (hence SoC), as well as the chemical kinetics of fuel-air mixture (i.e. combustion phasing). At 30% EGR rate, combustion phasing retarded due to slower chemical kinetics of fuel-air mixture. At higher EGR rates, presence of inert gaseous species reduced the reaction kinetics of fuel-air mixture and reduced the in-cylinder temperature further, thus retarding the combustion phasing. With increasing EGR rate, combustion duration slightly increased, however the difference in combustion duration at different EGR rates was negligible. Combustion duration in PCCI combustion was controlled by two factors: (i) with increasing EGR rate, slower fuel-air chemical kinetics increased the combustion duration, and (ii) presence of lower fuel quantity decreased the combustion duration. Due to these two counter effects of EGR, combustion duration remained almost constant for different EGR rates. The results obtained by Hardy et al. [25] were also similar to these findings. Figure 5 shows the variation in knocking integral (KI), knock peak (KP) and combustion noise at different SoPI timings and EGR rates.

KI is the integral of superimposed, rectified knock oscillations and KP reflects absolute maxima of the rectified knock oscillations superimposed on the in-cylinder pressure traces. To calculate these parameters, in-cylinder pressure signal was filtered through a high pass filter and then rectified. Parameters such as KI or KP of the superimposed oscillations were determined from these signals. Cylinder noise levels were calculated from the cylinder pressure signals.

Figure 5 (a) shows the variations in KI, KP and combustion noise w.r.t. SoMI and SoPI timings. In PCCI combustion, KI has been shown to be very low compared to CI or HCCI combustion [38] and this was attributed to presence of pilot fuel injection, which improves fuel-air mixing due to higher in-cylinder temperatures. In this study, application of EGR further improved the PCCI knocking characteristics due to relatively slower chemical kinetics of fuel-air mixtures. With advancing SoMI timing, KI slightly decreased with almost negligible variations. Advancing SoPI timing didn't affect KI significantly.

Figure 5: Variation in knock integral, knock peak and combustion noise w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates

Similar to KI, KP was also low for PCCI combustion. Advancing SoMI or SOPI timings also did not affect KP significantly, though it decreased slightly. This was attributed to improved fuel-air mixing. Advancing SoMI timing resulted in slightly higher cylinder noise, however variation of SoPI timing didn't affect combustion noise. These results showed that variations in SoI timings didn't affect knocking characteristics. Knocking characteristics of PCCI combustion at different SoPI and SoMI timings showed that 35° bTDC resulted in slightly stable combustion compared to relatively advanced (30° bTDC) or retarded (40° bTDC) SoPI timings. This was mainly due to trade-off between in-cylinder conditions and time availability for fuel-air mixing, which directly influenced combustion phasing.

Figure 5 (b) shows the variations in KI, KP and combustion noise at different SoMI timings and EGR rates. KI slightly decreased with advancing SoMI timings. Increasing EGR reduced KI, which reflected smoother combustion at higher EGR rates. This observation was further validated by KP results. As EGR rate increased from 0 to 30%, KP decreased from ~8 to ~2 bar. This was mainly due to dilution effect of EGR, which directly controlled the chemical kinetics of fuel-air mixture. At higher EGR rates, lower in-cylinder temperatures also suppressed knocking. Cylinder noise was also significantly affected by EGR. With increasing EGR rates from 0 to 30%, combustion noise continuously decreased from ~98 to ~92 dB. Comparison of PCCI combustion results at different EGR rates indicated that EGR played an important role in PCCI combustion thus showing its potential for noise and knock reduction. However too high EGR adversely affected the performance of PCCI engines and resulted in higher HC and CO emissions.

3.2 Performance Characteristics

To investigate the effects of split injection and EGR on PCCI engine performance, experiments were carried out at varying SoPI timings and EGR rates. In this study, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) were measured and plotted w.r.t. SoMI timings. At each experimental condition, performance parameters were measured three times and average was presented with error bars.

Figure 6: Variations in BTE, BSFC and EGT w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates

Figure 6 (a) shows the variations in PCCI engine performance parameters at varying SoPI and SoMI timings. Results obtained show that BTE decreased with advancing SoMI timings. This was mainly due to dominant premixed combustion phase, which led to relatively higher negative piston work, resulting in lower BTE. Advancing SoPI timing from 30 to 35° bTDC resulted in slightly higher BTE, but further advancing SoPI timing (up to 40° bTDC) decreased BTE drastically. With retarded SoPI timing (30° bTDC), lesser time availability for fuel-air mixing led to inferior combustion. However with advanced SoPI timing (40° bTDC), lower peak cylinder pressure and temperature both dominated, resulting in inferior combustion. BSFC followed similar behavior at different SoMI and SoPI timings, with lowest BSFC attained at intermediate SoPI (35° bTDC) and retarded SOMI (12° bTDC) timing. EGT was measured very close to the exhaust port. EGT gives qualitative information of in-cylinder combustion. In PCCI combustion, EGT was observed to be significantly lower (~100°C) compared to CI combustion [39] and was attributed to absence of diffusion combustion. Application of EGR was another important reason for lower EGT in PCCI combustion mode. In this study, EGT slightly reduced with advanced SoMI and SoPI timings. This was due to longer time availability, which improved fuel-air mixing and promoted premixed combustion. Negligible diffusion combustion with slightly lower EGT was observed. Amongst the three SoPI timings, 35° bTDC showed minimum EGT (~225°C).

Figure 6 (b) shows variation in engine performance parameters at different SoMI timings and EGR rates. BTE decreased with increasing EGR rate. This was mainly due to two reasons: (i) lower fuel quantity at higher EGR rates, which retarded the chemical kinetics of fuel-air mixture, resulting in slightly inferior combustion, and (ii) lower in-cylinder temperature due to presence of higher heat capacity exhaust gas, which encouraged incomplete combustion. These factors resulted in higher CO and HC emissions and adversely affected PCCI engine performance. BSFC followed a similar trend. BSFC continuously increased with increasing EGR rate. Effect of EGR was also seen by variations in EGT. EGT drastically decreased (by up to 75°C) with increasing EGR rate. This is the main advantage of PCCI combustion because lower EGT represents absence of diffusion combustion phase because thermal NOx formation takes place during diffusion combustion phase. Engine performance results showed that increasing EGR rate slightly decreased the PCCI engine performance however significant reduction in EGT occurred at 15% EGR rate. This shows a trade-off between reduction in BTE and EGT, therefore it can be considered as optimized EGR rate for PCCI combustion in the present experiment.

3.3 Emission Characteristics

To compare the PCCI mode engine emission characteristics, CO, HC, NOx and smoke opacity were measured at different SoPI timings (30, 35 and 40º bTDC) and EGR rates (0, 15 and 30%). CO, HC and NOx emissions are presented as brake specific mass emissions (g/kWh) and smoke opacity is measured in absolute units.

Figure 7: Variations in mass emissions of CO, HC, NOx and smoke opacity w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates

Figure 7(a) shows variations in CO, HC and NOx emissions, and smoke opacity w.r.t. SoMI timings at different SoPI timings. In IC engines, CO and HC are formed mainly due to incomplete combustion. Other researchers have also reported slightly higher CO and HC emissions from PCCI combustion mode [23-25]. CO is an intermediate combustion product, primarily formed due to incomplete oxidation of CO to CO_2, under relatively lower in-cylinder temperature conditions. Advanced SoMI timings lead to relatively lower CO emissions. Relatively advanced combustion phasing at advanced SoMI timings was the main reason for this behavior. Results showed that CO emission increased slightly in case of advancing the SoPI timing from 30 to 35° bTDC. At advanced SoPI timings, improved fuel-air premixing prevented diffusion combustion, leading to relatively lower in-cylinder temperature. With further advancing SoPI timing from 35 to 40° bTDC, CO emission slightly decreased. This was attributed to slightly inferior in-cylinder conditions, which promoted diffusion combustion therefore lower CO emissions. Similar to CO emissions, HC emissions were also observed to be higher in PCCI combustion mode. In IC engines, HC formation takes place due to three reasons: (i) incomplete combustion (shorter combustion duration), (ii) trapped fuel droplets in crevice volume (early injection at higher FIPs), and (iii) in-cylinder wall quenching (lower in-cylinder temperature). Results obtained show that HC emissions increased with advancing SOMI and SoPI timings. Advancing SoI timings result in homogeneous fuel-air mixture, which promotes premixed combustion. This leads to lower in-cylinder temperature and forms HCs due to incomplete combustion and wall quenching. With advanced SoI timings, relatively larger fraction of fuel enters into the crevice volume resulting in higher HC emissions. Fuel spray impingement at advanced SoI timings may be another reason for higher HC emissions, wherein fuel spray comes in contact with cold in-cylinder walls and combustion is quenched. Higher HC emissions also affect combustion efficiency adversely, which in turn reduce overall thermal efficiency. Ultra-low NOx emission is the main advantage of PCCI combustion. NOx formation mainly occurs in diffusion combustion phase, where in-cylinder temperatures are too high. In PCCI combustion, absence of a prominent diffusion combustion phase is the prime reason for lower NOx formation. NOx emissions increased slightly with advanced SoMI timings. Amongst all three SoPI timings, lowest NOx was obtained for 35° bTDC. This was the main reasons for selecting 35° bTDC as the optimum SoPI timing in further experiments. Smoke opacity reflects qualitative pollutant level in the exhaust gas. Lower smoke opacity is another advantage of PCCI combustion. Results showed that smoke opacity decreased with advancing SoMI timings. Improved fuel-air mixing due to longer time availability was the main reason. Advancing SoPI timing first reduced smoke opacity, however too advanced SoPI timing resulted in slightly higher smoke opacity. Higher smoke opacity at 40° bTDC SoPI timing can be correlated to higher HC emissions. Higher HC emissions promoted more soot nuclei formation, which resulted in higher smoke opacity. Lowest smoke opacity at 35° bTDC SoPI timing makes it the most favorable condition for PCCI combustion mode.

Figure 7(b) shows the variation in CO, HC and NOx emissions, and smoke opacity at varying SoMI timings and EGR rates. Results obtained showed that CO and HC emissions increased with increasing EGR rates. At higher EGR rate, in-cylinder temperature became too low, which reduced oxidation of CO to CO_2, leading to higher CO emissions. At 30% EGR rate, availability of oxygen further reduced, resulting in increased CO emission. CO emission can also be related to the retarded combustion phasing, which resulted in slower chemical kinetics of fuel-air mixture, inhibiting CO to CO_2 conversion. With increasing EGR rate, in-cylinder temperature became too low to oxidize the fuel completely which increased the unburned HC emissions. Combustion temperature near the cylinder walls was even lower due to higher heat losses. Therefore at locations in the vicinity of cylinder walls, combustion was either quenched or did not occur at all, which further increased the HC emissions. NOx formation was found to be sensitive to EGR. With increasing EGR rate, NOx emissions reduced continuously. These observations were in agreement with that of variations in EGT (Figure 6(b)). Increasing EGR rate from 0 to 15% resulted in ~60% reduction in NOx emissions. Further increase in EGR rate led to even lower NOx emissions, but it also caused inferior and erratic engine performance. Therefore 15% EGR rate was considered as a reasonable trade-off between the engine performance and the emission characteristics. Smoke opacity slightly increased with increasing EGR rate, which led to lower in-cylinder temperatures. At higher EGR rate, lower in-cylinder temperatures promoted soot formation and enhanced smoke opacity. Overall emission results reflected that increasing EGR rate resulted in slightly higher CO, and HC emissions and smoke opacity, and these increments were relatively lower at 15% EGR rate compared to 30% EGR rate. Therefore 15% EGR was used for optimizing PCCI engine performance and emission characteristics.

3.4 Particulate Characteristics

To compare the characteristics of particulate emitted by diesel fuelled PCCI engine, two parameters used were: (i) Particulate number-size and (ii) Particulate surface area-size distributions. Particulate number-size distribution was determined after thermal stabilization of the engine. Particulate sampling was done for one minute at a sampling frequency of 1 Hz. Average of these 60 data points were analyzed and presented along with standard deviation as the error bars, in the following figures. Figure 8 shows the number-size and surface area-size distributions of particulate at varying SoPI and SoMI timings, and 15% EGR rate.

Figure 8: (a) Number-size and (b) Surface area-size distributions of particulate at varying SoPI and SoMI timings, and 15% EGR rate

Variations in particulate number-size distributions with SoPI and SoMI timings can be correlated with two parameters, namely (i) in-cylinder conditions (temperature and pressure), and (ii) time availability (for fuel-air mixing). Trends clearly indicated that particulate number concentration at a given size decreased with advancing SoMI timings. This was mainly due to relatively longer time available for fuel-air mixing, which resulted in formation of more homogeneous mixture. PCCI combustion at advanced SoMI timings shifted peak particulate number-size distribution towards larger particulate. This showed higher adsorption of condensed exhaust species on primary particles. With advanced SoPI timing, particle number concentration first decreased (from 30 to 35° bTDC) and then increased (from 35 to 40° bTDC). Advancing SoPI timing from 30 to 35° bTDC decreased particulate number concentration, however peak of particulate number size-distribution shifted towards larger particles. Effect of variation of SoMI timing was also relatively more significant at 35° bTDC, which resulted in slightly lower in-cylinder temperature due to improved fuel-air pre-mixing. Lower in-cylinder temperature enhanced particulate agglomeration, leading to larger particles in relatively lower concentration. At 30° bTDC SoPI timing, less time difference between pilot injection and the main injection dominated over superior in-cylinder conditions, which resulted in slightly inferior fuel-air mixing, leading to higher particulate number concentration. However at 40° bTDC SoPI timing, relatively inferior in-cylinder conditions dominated over longer time availability, leading to inhomogeneous fuel-air mixing resulting in emission of higher number of particles. Due to presence of inferior in-cylinder conditions, soot nuclei formation increased, resulting in higher particulate number concentration, however longer time availability affected particulate size. Too advanced SoPI timing (40° bTDC) improved fuel-air pre-mixing and size of peak particulate number concentration decreased in comparison to intermediate SoPI timing (35° bTDC). At 35° bTDC SoPI timing, particulate size distribution was relatively wider in comparison to other SoPI timings. This indicated trade-off between fuel-air pre-mixing time and in-cylinder conditions. In the experiment, 30° bTDC SoPI showed maximum particle concentration ($6x10^7$ particles/cm^3 exhaust gas) and 35° bTDC SoPI showed minimum particle concentration ($3x10^7$ particles/ cm^3 exhaust gas). Particulate surface area-size distribution affects the toxicity of particulate because higher surface area of particulate increases probability of surface adsorption of toxic gaseous species and PAHs. Particle surface area was calculated by assuming them to be spherical.

$$dS = dN.(D_p)^2$$

Here dS is the area concentration of the size range with mean diameter D_p and dN is the number concentration of particles with mean diameter D_p. Higher number concentration of smaller particles results in higher surface area in comparison to surface area of lower number of larger particles. Smaller particles have the ability to penetrate deeper in the respiratory system, which enhances the possibility of them causing several diseases [40]. Smaller particles also have longer retention time in the environment due to their lower settling velocity. This increases their possibility to be inhaled in the human body. Therefore smaller particles tend to become more hazardous for human health as opposed to larger particles.

From figure 8(b), it can be observed that particle surface area distribution decreased with advancing SoMI timing. This trend was common at all SoPI timings. With advancing SoPI timings, particulate surface area decreased continuously with trend slightly different from that of particle number-size distribution. Advancing SoPI timing improved fuel-air pre-mixing, leading to lower particulate concentration. At too advanced SoPI timing, particle number concentration increased slightly, however particulate size distribution decreased. These two counter effects resulted in lower particulate surface area. At too advanced SoPI timings (40° bTDC), wider particle surface area-size distributions also showed the contribution of larger particles to the total particulate surface area. This showed that contribution of larger particles ($D_p > 200$ nm) to the total particulate surface area was almost equal to the contribution of small particles ($D_p < 200$ nm). Due to longer time availability for fuel-air premixing, variation of SoMI timing was slightly less effective at advanced SoPI timings. Overall, the results at different SoPI timings suggested that intermediate SoPI timing was suitable for

PCCI combustion because it resulted in larger particulates in lower number concentration, which are less harmful to the human health.

Figure 9 (a) shows particle number-size distribution at varying EGR rates and SoMI timings.

Figure 9: (a) Number-size and (b) surface area-size distributions of particulate at varying EGR rates and SoMI timings

Similar to SoPI results, advancing SoMI timing resulted in lower particulate number concentration however reduction at advanced SoMI timings was higher at 0 and 30% EGR rates compared to 15% EGR rate. Figure 9(a) showed that the particle number concentration first decreased with increasing EGR rate (up to 15%) and then increased drastically with further increasing EGR rate up to 30%. There were two factors responsible for this observation. First was the shifting of combustion phasing, which improved combustion efficiency leading to lower number of soot nuclei formation. Second factor was the dilution effect, which reduced in-cylinder temperature and increased particulate formation near the cylinder walls (due to presence of fuel-rich pockets formed during combustion quenching and spray impingement). When EGR rate increased up to 15%, the first factor dominated, resulting in lesser particulate number emissions. However at 30% EGR rate, second factor dominated, resulting in significantly higher particulate number emissions. With increasing EGR rate, peak of particle number-size distribution also shifted towards larger particles. This was mainly due to lower in-cylinder temperatures at higher EGR rate, which promoted condensation of volatile organic species. These condensates were adsorbed on to the primary particulate surface, resulting in larger particles. Figure 9(b) shows that the particulate surface area-size distribution followed similar trend as that of particulate number-size distribution. With increasing EGR rate, particulate surface area increased due to formation of larger particulate. At 30% EGR rate, peak of particulate surface area significantly increased compared to 0 and 15% EGR rates. This was mainly due to higher number concentrations of relatively smaller particles. Amongst all three EGR conditions, 15% EGR rate was found to be most suitable for PCCI combustion mode because of its lower particulate number as well as surface area distributions.

Overall analysis of particulate emitted from PCCI combustion mode was carried out in terms of nucleation mode particles (NMP) (D_p < 50 nm) and accumulation mode particles (AMP) (50 nm< D_p < 1000 nm) concentrations; total particle number (TPN) concentration and count mean diameter (CMD) (Figure 10). These parameters were calculated from particulate number-size distributions. Figure 10(a) shows the analysis of particulate emitted from PCCI combustion at different SoPI and SoMI timings. With advanced SoMI timings, NMP concentration remained almost constant at 30° and 40° bTDC SoMI timings, however it slightly decreased at 35° bTDC timing. This showed that the formation of NMP was affected by two factors: (i) in-cylinder conditions, and (ii) fuel-air pre-mixing time. At too advanced or retarded SoPI timings, one factor always dominated, resulting in higher NMP. At intermediate SoPI timing, trade-off among these two factors showed the effect of variations in SoMI timing, which increased the fuel-air pre-mixing and resulted in lower NMP concentration. Amongst all three SoPI timings, 35° bTDC resulted in lowest NMP concentration. At all SoPI timings, NMP concentration was > $1x10^8$ particles/cm^3 of exhaust gas, which was significantly lower than HCCI combustion and conventional CI combustion modes [38]. With advanced SoMI timing, AMP concentration slightly decreased due to improved fuel-air pre-mixing. AMP concentration also followed similar trend as that of NMP. However AMP concentration (~$4x10^8$ particles/cm^3 of exhaust gas) was higher than NMP concentration (~$1x10^8$ particles/cm^3 of exhaust gas).

Figure 10: Number of Nucleation mode particles, number of accumulation mode particles, total particulate number, and count mean diameter of particulate for varying SoMI timings at different (a) SoPI timings and (b) EGR rates

Figure 10(a) shows that 30 and 35° bTDC SoPI timings showed the highest TPN concentration (~5x10^8 to 6x10^8 particles/cm^3 of the exhaust gas) and the lowest TPN concentration (~3x10^8 to 4x10^8 particles/cm^3 of exhaust gas) respectively. For all SoPI timings, advancing SoMI timings resulted in relatively lower TPN concentration. At 24° bTDC SoMI timing, reduction in TPN concentration was slightly lower due to inferior in-cylinder conditions. Advancing SoPI timing also resulted in lower TPN concentration, however too advanced SoPI timing led to slightly higher TPN concentration due to inferior fuel vaporization in presence of lower in-cylinder temperatures. Average size of particulate emitted at different SoPI and SoMI timings were presented by CMD. CMD showed the number averaged diameter of particulate. Results showed that particulate emitted at 35° bTDC SoPI timing had the highest CMD and particles emitted from 30° bTDC SoPI timing had the lowest CMD. At 12° SoMI timing, CMD of particulate at different SoPI timings was almost same. This was attributed to longer time difference between SoPI and SoMI timings, which decreased with advancing SoMI timings. At 35 and 40° SoPI timing, CMD increased with advancing SoMI timings, however CMD was almost constant at 30° bTDC SoPI timing. CMD varied mainly due to variations in particle number as well as particle size.

Figure 10(b) shows the variations in NMP, AMP and TPN concentrations, and CMD of particulate emitted from PCCI combustion at different SoMI timings and EGR rates. NMP concentration remained almost same at different EGR rates. With increasing EGR rates, AMP concentration increased due to reduction in peak cylinder temperature and chemical kinetics of fuel-air mixtures. These two factors promoted formation of higher number of soot nuclei as well as particulate agglomeration. At 15% EGR rate, AMP concentration remained almost constant, however at 30% EGR rate, AMP concentration increased drastically. At 15% EGR rate, particulate number concentration decreased due to slightly improved combustion phasing. At 30% EGR rate, too retarded combustion phasing resulted in emission of large number of particulate. TPN trends showed that 30% EGR rate resulted in maximum TPN concentration (~7×10^8 particles/cm^3 of exhaust gas) and 15% EGR rate resulted in minimum total particle concentration (~3×10^8 particles/cm^3 of exhaust gas). Advancement of SoMI timing led to lower TPN concentration. Variations in CMD of particulate showed that 30% EGR rate resulted in formation of larger particles compared to 0% and 15% EGR rates. Increasing EGR rate enhanced condensation of volatile species due to lower in-cylinder temperatures. These condensates were adsorbed on to primary particulates, which increased the particulate size, leading to higher CMD.

Particulate analysis showed that 35° bTDC SoPI timing was most suitable for PCCI combustion mode. At 35° bTDC SoPI timing, TPN concentration was lowest with the highest CMD, which reduced their potential harmful effects. Comparison of particulate emission characteristics at different EGR rates showed slight reduction in particulate number concentration at 15% EGR rate and significantly higher particulate number concentration at 30% EGR rate. Therefore 15% EGR rate was suitable for PCCI combustion.

3.5 Particulate Bound Trace Metals

For detailed particulate analysis, particulate samples were analyzed for trace metals. The experiments were carried out in two stages. In the first stage, effect of SoPI timings was investigated by analyzing three particulate samples collected at SoPI timings of 30, 35 and 40° bTDC. In the second stage, effect of EGR was investigated by analyzing three particulate samples collected at EGR rates of 0, 15 and 30%. During these experiments, all other parameters such as SoMI and FIP were maintained constant at 16° and 700 bar respectively. In trace metal analysis, total of 34 trace metals were detected in the particulate samples, however only 20 trace metals, which could be detected with <90% accuracy level are discussed here. These trace metals were further classified into five groups based on their origin, their health effects and for convenience of presentation (figure 11).

Figure 11: Particulate bound trace metals at different (a) SoPI timings and (b) EGR rates

Figure 11 shows particulate bound trace metals emitted from the engine at different SoPI timings and EGR rates during PCCI combustion mode. First group contained traces of Al, Cu, Fe and Zn, which are harmful for human health due to their reactive oxygen species (ROS) generation potential, and can lead to onset of cancer. Main source of these trace metals are the wear debris of engine components. These wear debris are picked up by the lubricating oil, which is recirculated in an engine in order to reduce friction between piston rings and cylinder liner interface. During combustion, pyrolysis of lubricating oil also contributes to these trace metals in the particulate. Zinc containing compounds are commonly used as additives in lubricating oils and greases. During combustion, these compounds undergo thermo-oxidative decomposition in presence of oxygen to form zinc poly phosphate, which gets converted into ZnO and emitted as trace metal. At advanced SoPI timings, improved fuel-air mixing resulted in lower particulate emissions with consequently lower trace metal content. Increasing EGR rate showed significant reduction in concentration of these trace metals in the particulate. At higher EGR rate, lower in-cylinder temperatures reduced pyrolysis of lubricating oil, leading to lower emissions of these trace metals, which is different from HCCI combustion trace metals emission characteristics [28]. Results showed that the concentration of Al and Fe traces decreased with advancing SoPI timings, however Cu and Zn trace concentrations slightly increased at 35° bTDC SoPI timing. In this group, Al concentration was relatively higher (~8 to 10 ppm/mg of PM) compared to other trace metals. Second group of trace metals included Ca, K, Na and Mg. Pyrolysis of lubricating oil was the main source of these metals. These trace metals are a part of different organo-metallic additives added to the lubricating oil in order to improve its lubricity, corrosion resistance, etc. Concentrations of these trace metals were slightly higher in PCCI combustion mode. These trace metals do not affect human health therefore these trace metals were not much discussed in previous studies [28, 41]. Advancing SoPI timings didn't show significant variation in concentration of these trace metals. Results showed that trace concentrations of Ca, Na and Mg decreased with increasing EGR rate since lower in-cylinder temperatures reduced pyrolysis of lubricating oil. The third group of trace metals included Ni, Cr, Cd and As, which primarily originate from wear of metallic engine components and lubricating oil additives. These metals are not harmful in their pure form however they easily combine with other species to form highly toxic compounds. Lower concentration of Ni, Cd and As was due to relatively lower in-cylinder temperature during PCCI combustion mode. Nickel is used as an additive in the lubricating oil in very small concentration as Nickel ethoxy-ethyl-xanthate for improving lubrication quality. Upon combustion, these compounds dissociate to release nickel, which reacts with sulphur and forms a carcinogenic compound NiS [42]. Concentration of Ni emitted from PCCI engine was significantly lower compared to HCCI engine, which was mainly due to lower particulate emission (Figure 8) [28]. In the experiments, Cr was found to be in relatively higher concentration and its trace concentration decreased with advanced SoPI timing and increasing EGR rate. This trend is different from gasoline fuelled HCCI combustion in which Cr concentration slightly increased with increasing EGR rate [41]. Fourth group of trace metals included Pb, Mo, Sr and Ba, which primarily originate from fuel, lubricating oil and sometimes from wear of engine components such as gaskets, piston rings, etc. Pb, Mo, Sr and Ba are also harmful for human health. These trace metals didn't show any specific trend in variation with SoPI timings. Pb, Mo and Sr concentrations decreased with increasing EGR rate. Lower in-cylinder temperatures at higher EGR rates were the main reason for this trend, which reduced the deterioration of softer engine components such as gaskets and seals. However Pb, Sr and Ba were lowest for 15% EGR rate. Last group of trace metals included Mn, Bi, In and V, which are generally used in engine components to enhance their properties. Therefore wear of engine components was the main source of these metal traces. Concentration of these trace metals were found to be very low, which didn't show any specific trend at different SoPI timing and EGR rate.

Comparison of trace metals emitted from PCCI combustion and HCCI combustion shows one important finding that concentration of harmful trace metals were significantly lower in PCCI combustion mode [28]. This was attributed to lower particulate emissions from PCCI combustion mode. Therefore this study clearly indicates that optimized PCCI combustion is beneficial for particulate reduction compared to HCCI combustion.

3.5 Statistical Analysis

To compare different split injection stratgeies and EGR rates, statistical analysis of PM mass and NOx emissions was plotted. This analysis gave a direct comparison of effectiveness of combustion at different fuel injection strategies and EGR rates. Height of rectangle showed particulate mass and width of the rectangle represented NOx emission. Area of the rectangle represented the combined emission of PM and NOx. Overall objective of this study was to reduce the area under the curve.

Figure 12: NOx-PM mass analysis at varying (a) SoPI timings and (b) EGR rates in PCCI combustion mode

Figure 12 (a) shows the variation of brake specific NOx (BSNOx) with PM mass emissions at different SoMI and SoPI timings. In all cases, it was observed that advancing SoMI timings resulted in higher NOx but lower PM emissions. This was attributed to longer time availability for fuel-air mixing, which resulted in superior combustion and led to slightly higher NOx emission. For a particular SoMI timing, advancement in SoPI timing from 30 to 35° bTDC resulted in simultaneous reduction in PM and NOx. However further advancement in SoPI timing led to lower PM (due to more time available for fuel-air pre-mixing) but higher NOx emissions. Due to slightly inferior cylinder conditions, performance and combustion also degraded at 40° bTDC compared to 35° bTDC. PM and NOx emission showed an interesting behavior with the EGR rate (Figure 12(b)). An increment in EGR rate from 0 to 15% simultaneously reduced NOx and PM emissions. NOx emissions reduced primarily due to lower in-cylinder temperatures. An increase in EGR rate led to slower chemical kinetics of fuel-air mixtures, which resulted in slightly retarded combustion phasing. Retarded combustion phasing increased overall combustion duration, which provided sufficient time for soot oxidation, led to relatively lower PM emission. However 30% EGR led to very low combustion temperature, which reduced NOx emissions significantly. However incomplete combustion resulted in drastically higher PM emissions. Poor engine performance and higher PM emission at 30% EGR made it unsuitable for PCCI combustion mode. Therefore, 15% EGR rate and 35° bTDC SoPI timing were found to be the most suitable conditions for PCCI combustion mode in a medium-duty diesel engine.

Conclusions

This experimental study was carried out to investigate suitable split injection parameters and EGR rate for optimized PCCI combustion. The experiments were carried out at different SoMI timings (12 to 24° bTDC), SoPI timings (30 to 40° bTDC) and EGR rates (0, 15 and 30%). During the experiment, FIP was maintained constant at 700 bar. Results showed that advancing SoMI and SoPI timings improved PCCI combustion, but too advanced SoPI timings resulted in slightly inferior performance and emission characteristics. Advancing SoPI from 30 to 35° bTDC improved chemical kinetics of fuel-air mixture and led to slightly higher P_{max} and highest HRR. At 40° SoPI timing, combustion degraded slightly due to inferior combustion chamber conditions. SoPI timing didn't show any significant effect of the SoC and combustion phasing. Advancing SoPI timing reduced knocking and resulted in lower knock peak and combustion noise. BTE improved slightly at SoPI timing of 35° bTDC however it drastically reduced at SoPI timing of 40° bTDC. EGT also showed that intermediate SoPI timing was suitable for PCCI combustion. NOx, and smoke opacity were slightly lower at SoPI timing of 35° bTDC. Particulate number concentration was the minimum and average particulate size was the maximum at this condition as well. Particulate bound trace metals didn't show any significant variation with changing SoPI timings. Statistical analysis showed that advanced SoPI timing reduced PM mass and NOx emissions simultaneously, however too advanced SoPI timing led to slightly higher NOx emissions. Increasing EGR rate effectively controlled the HRR during PCCI combustion mode, but very high EGR rate resulted in ultra-dilution of the combustible charge. This led to very low peak in-cylinder temperature, resulting in very low BTE and higher HC and CO emissions. Increasing EGR rate reduced the knocking and combustion noise though. With higher EGR rate, NOx emission decreased but PM mass emission increased significantly. Trace metal analysis revealed that PCCI combustion emitted relatively lower trace metals compared to HCCI combustion and concentration of most of the reported trace metals decreased with increasing EGR rate. Overall effectiveness of EGR on PCCI combustion mode was indicated by the statistical analysis. With increasing EGR rate, NOx and PM mass emission decreased simultaneously however too high an EGR rate led to significantly higher PM mass emission. Therefore, it can be concluded that optimum SoI timings and EGR rate can effectively control and enhance engine performance and reduce emissions further in the PCCI combustion mode.

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References

1. Akihama, K., Takatori, Y., Inagaki, K., Sasaki, S., Dean, A. M. (2001). Mechanism of the smokeless rich diesel combustion by reducing temperature. SAE Technical Paper 2001-01-0655.
2. Onishi, S., Jo, S. H., Shoda, K., Do Jo, P., Kato, S. (1979). Active thermo-atmosphere combustion (ATAC)-a new combustion process for internal combustion engines. SAE Technical Paper 790501.
3. Thring, R. H. (1989). Homogeneous-charge compression-ignition (HCCI) engines. SAE Technical paper 892068.
4. Christensen, M., Johansson, B., Einewall, P. (1997). Homogeneous charge compression ignition (HCCI) using isooctane, ethanol and natural gas-a comparison with spark ignition operation. SAE Technical Paper 972874.

5. Stanglmaier, R. H., Roberts, C. E. (1999). Homogeneous charge compression ignition (HCCI): benefits, compromises, and future engine applications. SAE Technical Paper 1999-01-3682.
6. Maurya, R. K., Agarwal, A. K. (2011). Experimental investigation on the effect of intake air temperature and air–fuel ratio on cycle-to-cycle variations of HCCI combustion and performance parameters. Applied Energy, 88(4), 1153-1163.
7. Singh, A. P., Agarwal, A. K. (2012). Combustion characteristics of diesel HCCI engine: an experimental investigation using external mixture formation technique. Applied Energy, 99, 116-125.
8. Singh, A. P., Agarwal, A. K. (2012). An experimental investigation of combustion, emissions and performance of a diesel fuelled HCCI engine. SAE Technical Paper 2012-28-0005.
9. Akagawa, H., Miyamoto, T., Harada, A., Sasaki, S., Shimazaki, N., and Hashizume, T. (1999). Approaches to solve problems of the premixed lean diesel combustion. SAE Technical Paper 1999-01-0183.
10. Hasegawa, R. and Yanagihara, H. (2003). HCCI combustion in DI diesel engine. SAE Technical Paper 2003-01-0745.
11. Kimura, S., Aoki, O., Ogawa, H., Muranaka, S., and Enomoto, Y. (1999). New combustion concept for ultra-clean and high-efficiency small DI diesel engines. SAE Technical Paper 1999-01-3681.
12. Shimazaki, N., Tsurushima, T., and Nishimura, T. (2003). Dual-mode combustion concept with premixed diesel combustion by direct injection near top dead center. SAE Technical Paper 2003-01-0742.
13. Agarwal, A. K., Dhar, A., Srivastava, D. K., Maurya, R. K., Singh, A. P. (2014). Effect of fuel injection pressure on diesel particulate size and number distribution in a CRDI single cylinder research engine. Fuel, 107, 84-89.

14. Hashizume, T., Miyamoto, T., Akagawa, H., et al. (1998). Combustion and emission characteristics of multiple stage diesel combustion. SAE Technical Paper 980505.
15. Neely, G. D., Sasaki, S., & Leet, J. A. (2004). Experimental investigation of PCCI-DI combustion on emissions in a light-duty diesel engine. SAE transactions, 113(4), 197-207.
16. Horibe, N., Harada, S., Ishiyama, T., & Shioji, M. (2009). Improvement of premixed charge compression ignition-based combustion by two-stage injection. International Journal of Engine Research, 10(2), 71-80.
17. Torregrosa, A. J., Broatch, A., García, A., & Mónico, L. F. (2013). Sensitivity of combustion noise and NOx and soot emissions to pilot injection in PCCI Diesel engines. Applied Energy, 104, 149-157.
18. Al-Qurashi, K., Boehman, A. L. (2008). Impact of exhaust gas recirculation (EGR) on the oxidative reactivity of diesel engine soot. Combustion and Flame, 155, 675−695.
19. Kook, S., Bae, C., Miles, P., Choi, D., & Pickett, L. M. (2005). The influence of charge dilution and injection timing on low-temperature diesel combustion and emissions. SAE Technical Paper, 2, 005-01.
20. Kanda, T., Hakozaki, T., Uchimoto, T., Hatano, J., Kitayama, N., & Sono, H. (2005). PCCI operation with early injection of conventional diesel fuel. SAE transactions, 114(3), 584-593.
21. Manente, V., Johansson, B., Tunestal, P. (2010). Characterization of partially premixed combustion with ethanol: EGR sweeps, low and maximum loads. J. Eng. Gas Turbines Power, 132, 082802.
22. Kiplimo, R., Tomita, E., Kawahara, N., & Yokobe, S. (2012). Effects of spray impingement, injection parameters, and EGR on the combustion and emission characteristics of a PCCI diesel engine. Applied Thermal Engineering, 37, 165-175.

23. André, M., Walter, B., Bruneaux, G., Foucher, F., & Mounaïm-Rousselle, C. (2012). Exhaust gas recirculation stratification to control diesel homogeneous charge compression ignition combustion. International Journal of Engine Research, 1468087412438338.

24. Jacobs, T., Bohac, S., Assanis, D. N., & Szymkowicz, P. G. (2005). Lean and rich premixed compression ignition combustion in a light-duty diesel engine. SAE Paper 2005-01-0166.

25. Hardy, W. L., & Reitz, R. D. (2006). A study of the effects of high EGR, high equivalence ratio, and mixing time on emissions levels in a heavy-duty diesel engine for PCCI combustion SAE Technical Paper 2006-01-0026.

26. Price, P., Stone, R., Misztal, J., Xu, H., Wyszynski, M., Wilson, T., & Qiao, J. (2007). Particulate emissions from a gasoline homogeneous charge compression ignition engine. SAE Technical Paper 2007-01-0209.

27. Kittelson, D. B., & Franklin, L. (2010). Nanoparticle emissions from an ethanol fueled HCCI engine. In Center for Diesel Research Department of Mechanical Engineering University of Minnesota, Presented at Cambridge particle meeting.

28. Agarwal, A. K., Singh, A. P., Lukose, J., & Gupta, T. (2013). Characterization of exhaust particulates from diesel fueled homogenous charge compression ignition combustion engine. Journal of Aerosol Science, 58, 71-85.

29. Desantes, J., Benajes, J., García-Oliver, J. M., & Kolodziej, C. P. (2013). Effects of Intake Pressure on Particle Size and Number Emissions from Premixed Diesel Low Temperature Combustion. International Journal of Engine Research, 1468087412469514.

30. Abdul-Khalek, I., Kittleson, D., and Brear, F. (1999). The influence of dilution conditions on diesel exhaust particle size distribution measurements. SAE Technical Paper 1999-01-1142, 1999.

31. Idicheria, C. A., & Pickett, L. M. (2005). Soot formation in diesel combustion under high-EGR conditions Sandia National Laboratories SAND2005-2879C.

32. Springer, K. J., 1997. Characterization of Sulfate, Odor, Smoke, POM and Particulates from Light Duty and Heavy-duty Diesel Engines, Part IX. Prepared by South West Research Institute.

33. Zhao, Y., Wang, Y., Li, D., Lei, X., & Liu, S. (2014). Combustion and emission characteristics of a DME (dimethyl ether)-diesel dual fuel premixed charge compression ignition engine with EGR (exhaust gas recirculation). Energy, 72, 608-617.

34. Suh, H. K., Roh, H. G., Lee, C. S. (2008). Spray and combustion characteristics of biodiesel⁄diesel blended fuel in a direct injection common-rail diesel engine. Journal of Engineering for Gas Turbines and Power, 130, 032807.

35. Ganesh, V., Deshpande, S., & Sreedhara, S. (2015). Numerical investigation of late injection strategy to achieve premixed charge compression ignition mode of operation. International Journal of Engine Research. doi: 10.1177/1468087415585466

36. Rassweiler, G., Withrow, L. (1938). Motion Pictures of Engine Flames Correlated with Pressure Cars. SAE Technical Paper 380139.

37. Singh, G., Singh, A. P., & Agarwal, A. K. (2014). Experimental investigations of combustion, performance and emission characterization of biodiesel fuelled HCCI engine using external mixture formation technique. Sustainable Energy Technologies and Assessments, 6, 116-128.

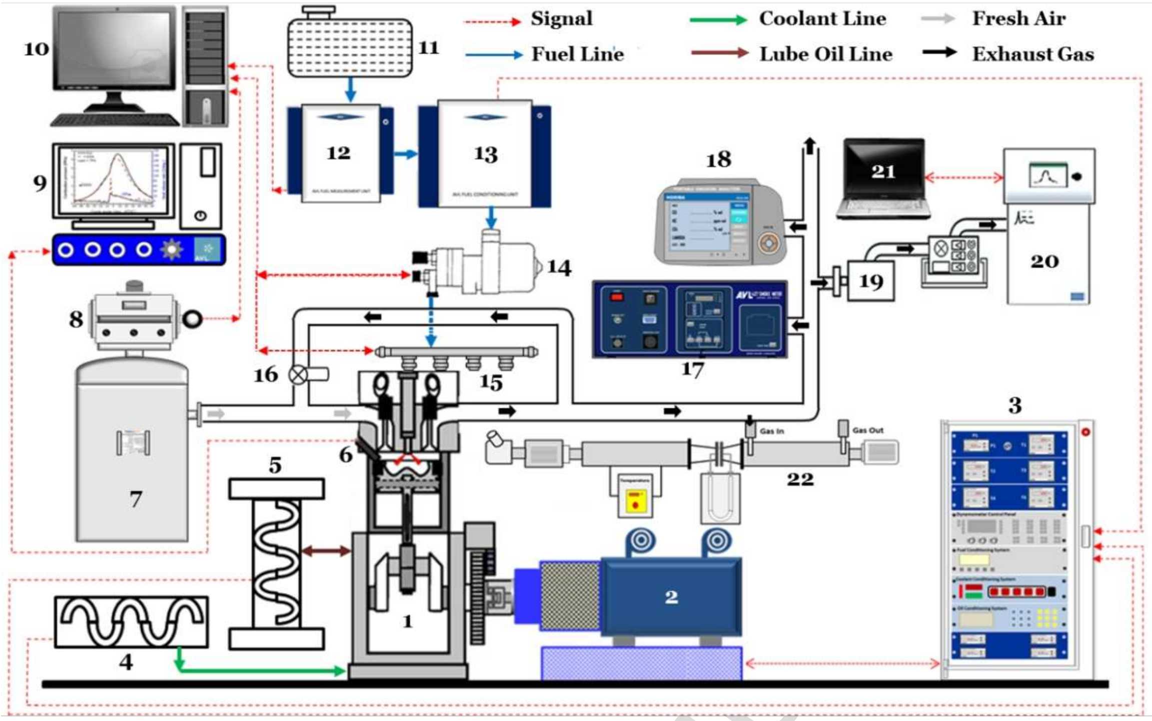
38. Singh, A. P., Agarwal, A. K. (2016). Diesoline, Diesohol and Diesosene Fuelled HCCI Engine Development. Journal of Energy Resources Technology, 138(5), 052212.

39. Agarwal, A. K., Srivastava, D. K., Dhar, A., Maurya, R. K., Shukla, P. C., Singh A. P. (2013). Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine. Fuel; 111, 374-83.

40. McClellan, R.O. (1987). Health effects of exposure to diesel exhaust particles. Annual review of Pharmacology and Toxicology, 27, 279-300.

41. Agarwal A. K., Lukose J., Singh A. P., Gupta T. (2015). Engine exhaust particulate characterization of gasoline homogeneous charge compression ignition engine. Aerosol and Air Quality Research; 15 (2), 504-516.

42. Sunderman Jr, F. W. (1978). Carcinogenic effects of metals. Fed. Proc.; (United States) 37, no. 1.



1- Single cylinder research engine, 2- Transient dynamometer, 3- Dynamometer controller, 4- Coolant conditioning system, 5- Lubricating oil conditioning system, 6- Pressure transducer, 7- Intake air surge tank, 8- Air-flow rate measurement system, 9- Combustion data acquisition system, 10- ECU interface system, 11- Fuel tank, 12- Fuel measurement system, 13- Fuel conditioning system, 14- High pressure fuel pump, 15- Common rail, 16- EGR valve, 17- Smoke opacimeter, 18- Exhaust gas emission analyzer, 19- Thermo diluter, 20- Engine exhaust particle sizer, 21- EEPS data logger, 22- Partial flow dilution tunnel

Figure 1: Schematic of the experimental setup

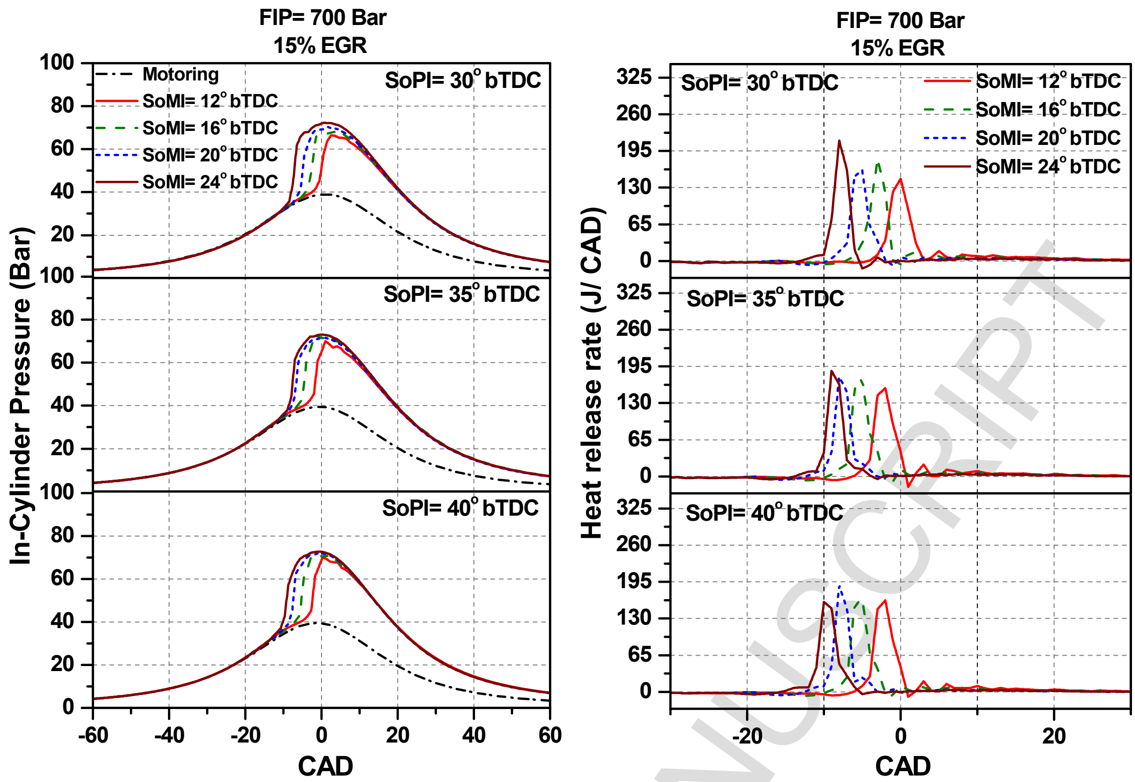
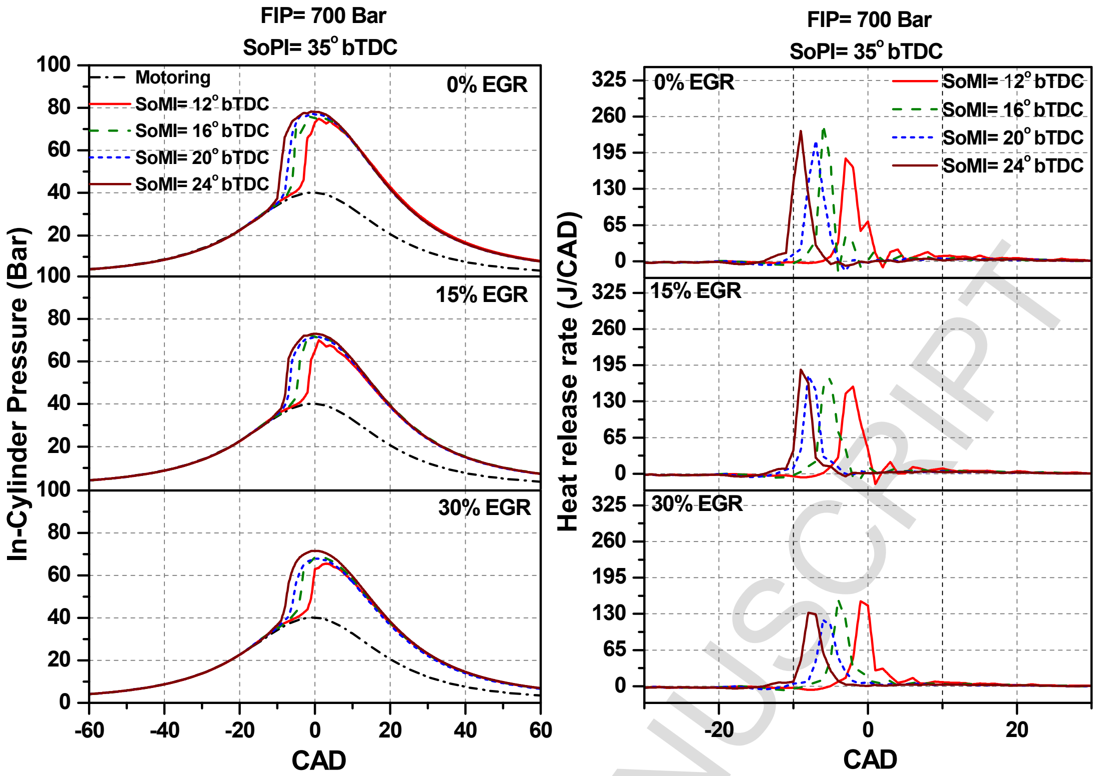


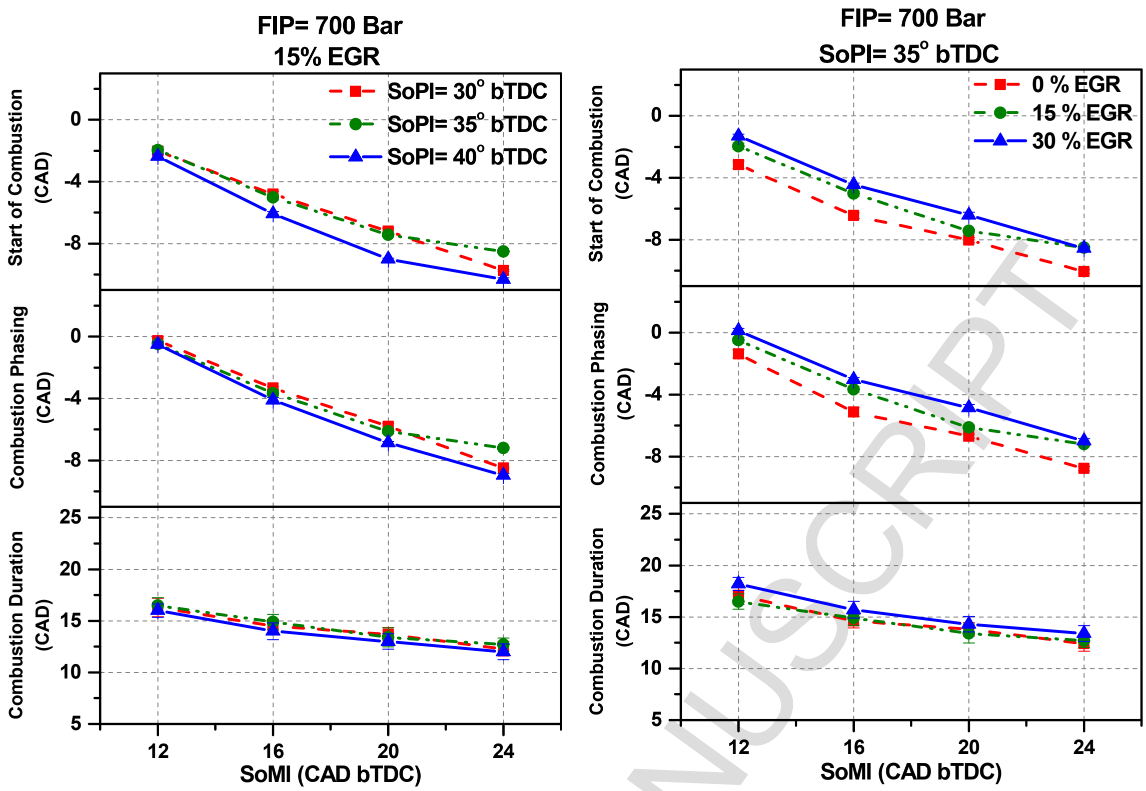
Figure 2: Variations in cylinder pressure and HRR w.r.t. crank angle at different SoPI and SoMI timings

979 

980 Figure 3: Variation in cylinder pressure and HRR w.r.t. crank angle for different SoMI

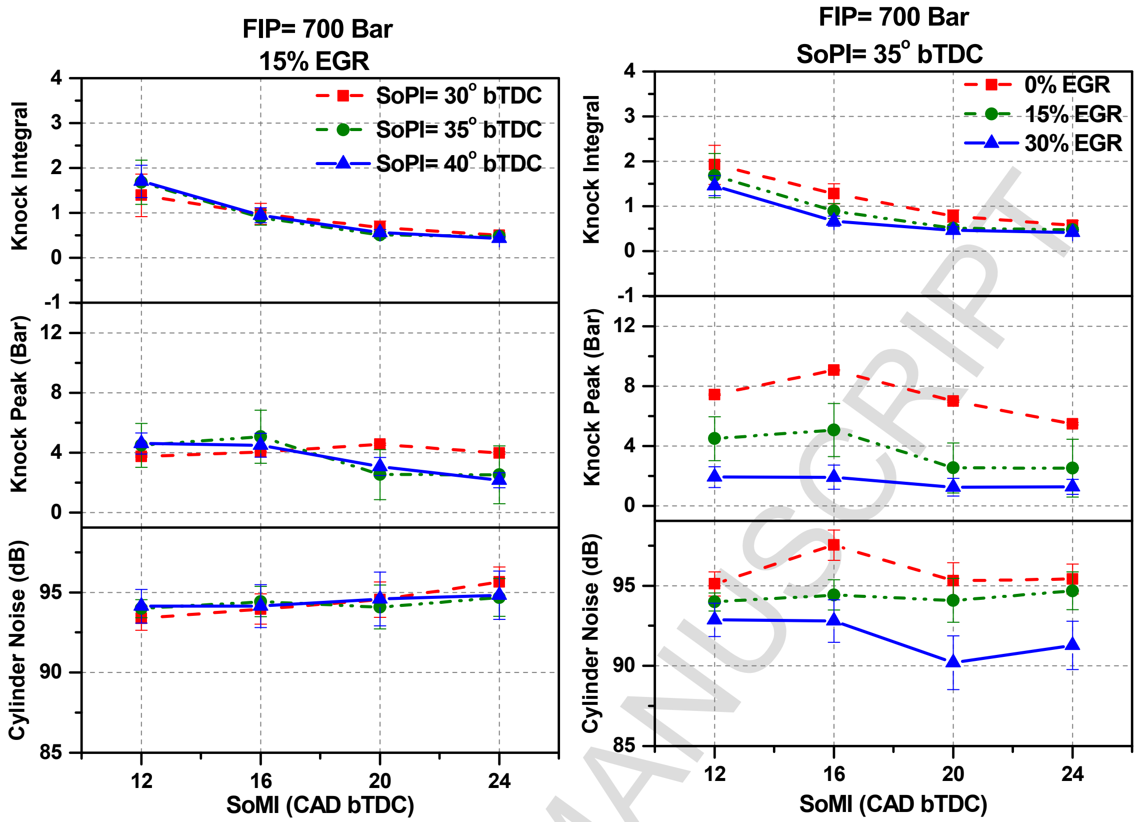
981 timings and EGR rates

982



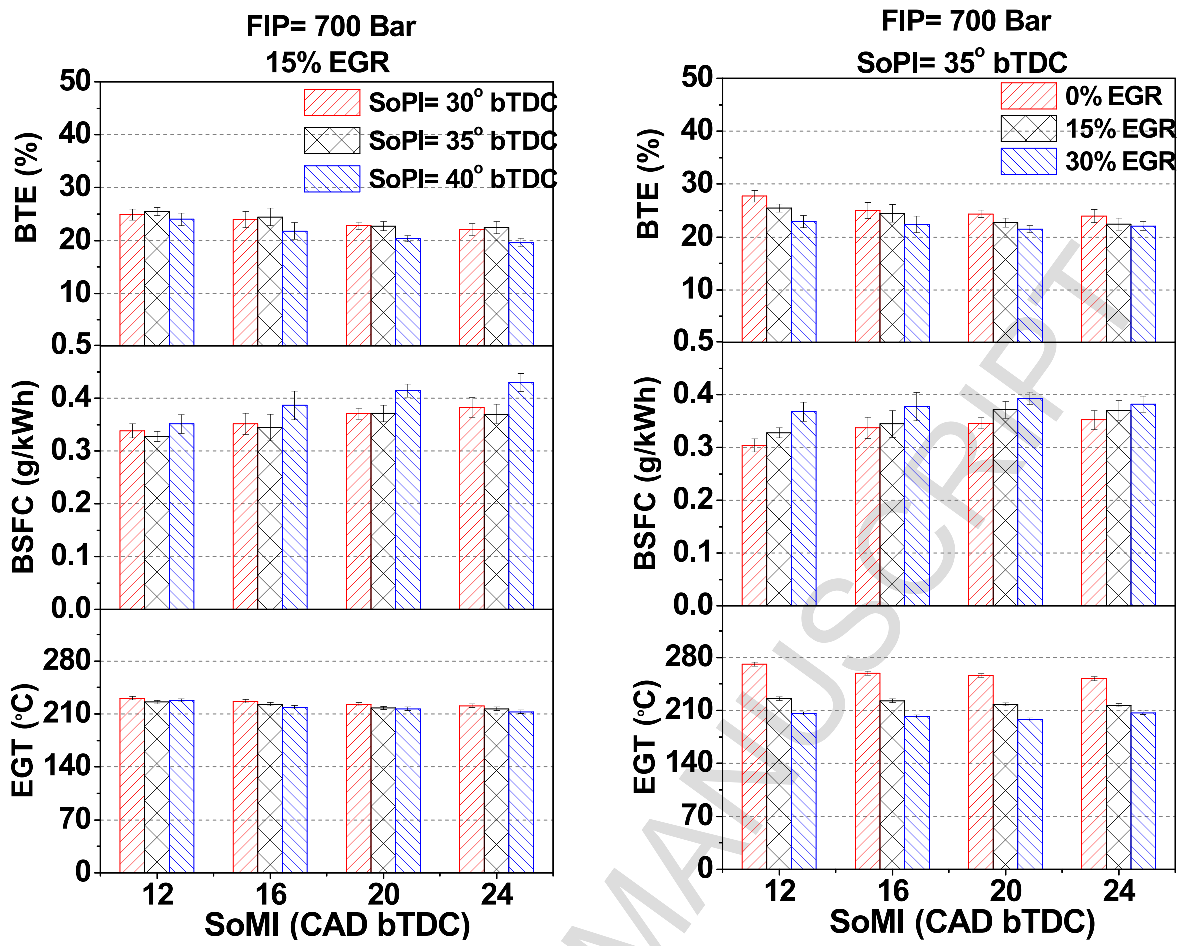
(a) (b)

Figure 4: SoC, combustion phasing and combustion duration w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates



(a) (b)

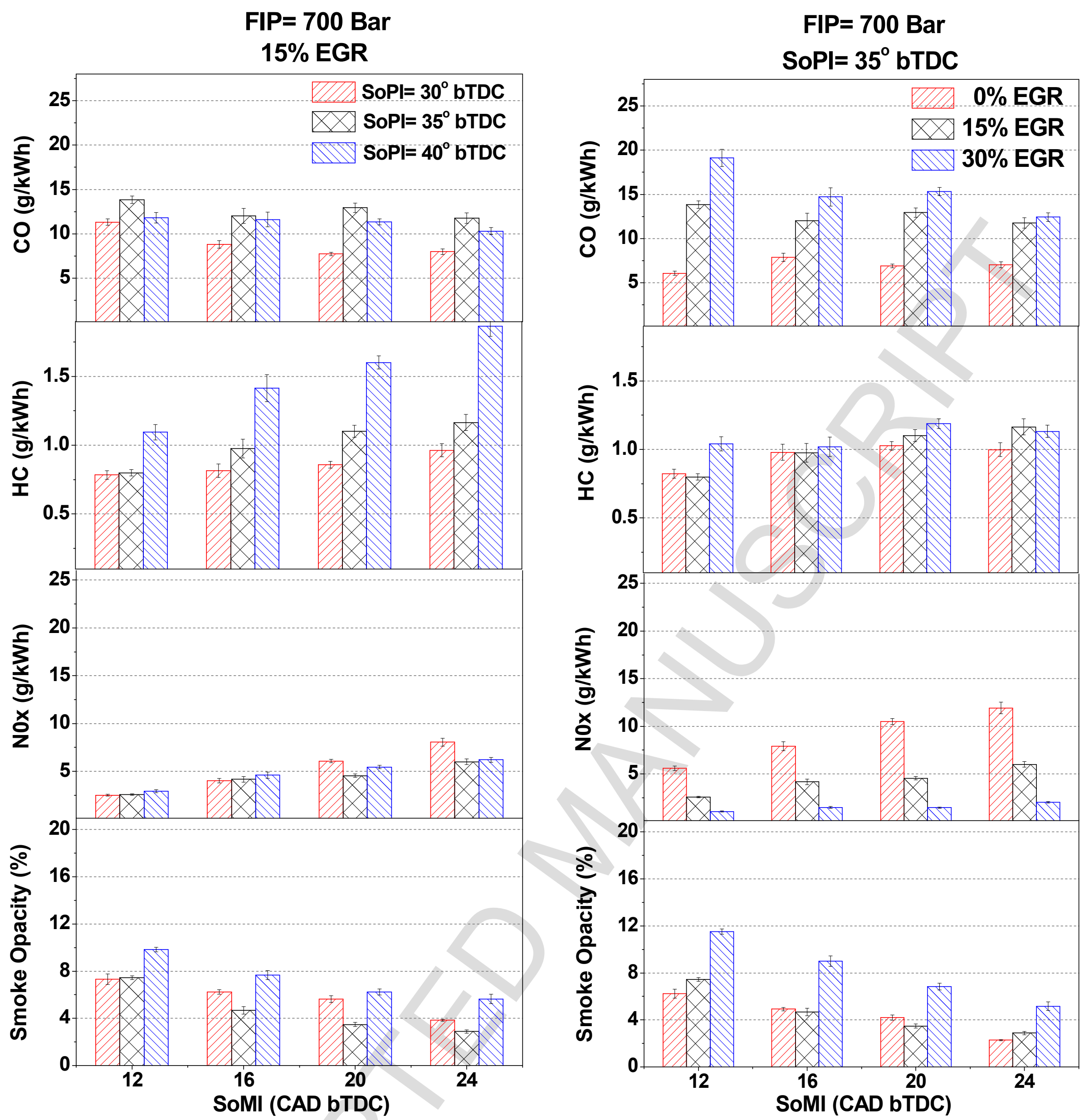
Figure 5: Variation in knock integral, knock peak and combustion noise w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates

993 

994 (a) (b)

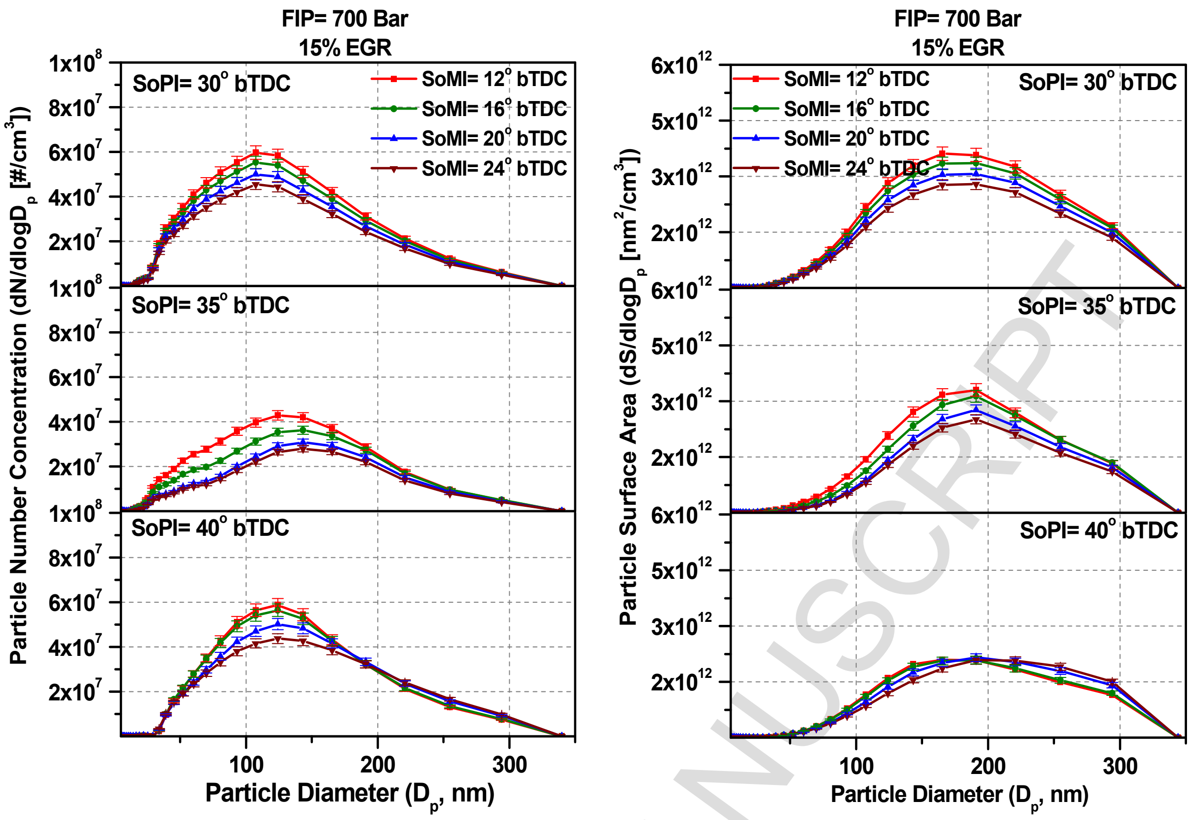
995 Figure 6: Variations in BTE, BSFC and EGT w.r.t. SoMI timings at different (a) SoPI

996 timings and (b) EGR rates



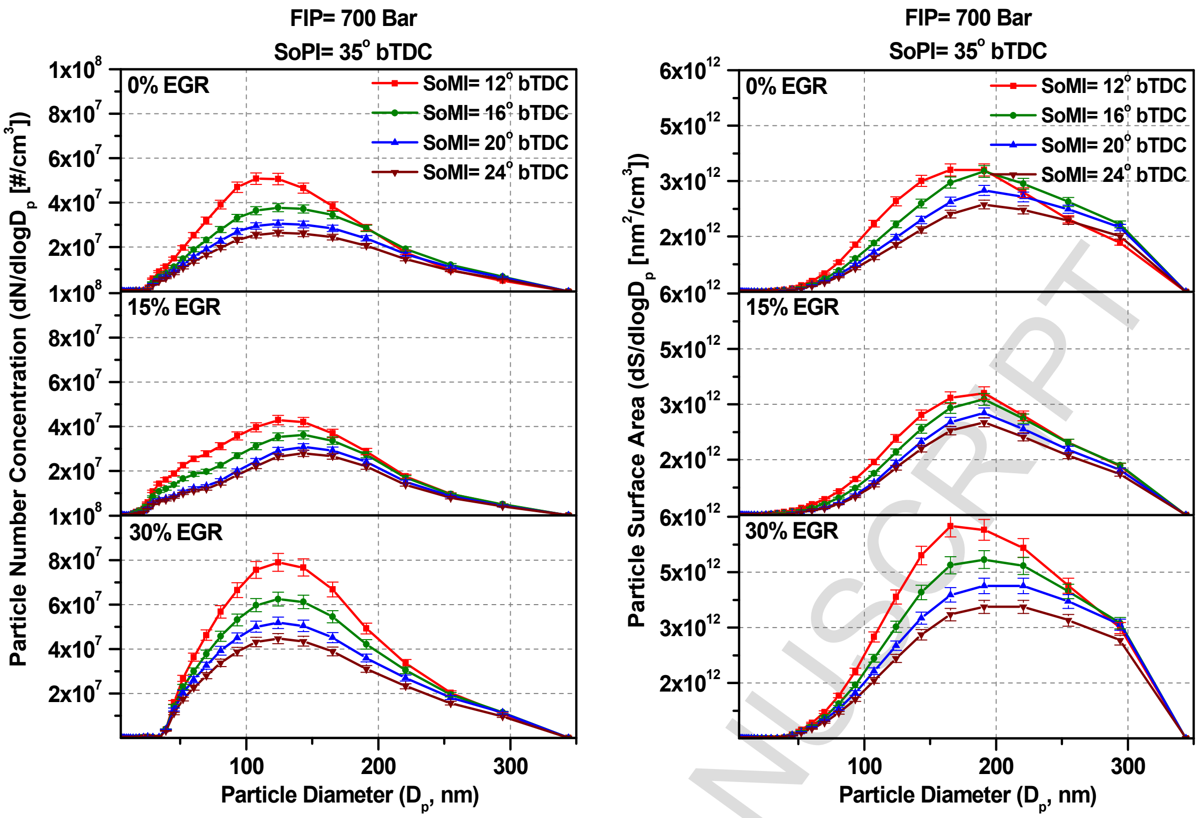
(a) (b)

Figure 7: Variations in mass emissions of CO, HC, NOx and smoke opacity w.r.t. SoMI timings at different (a) SoPI timings and (b) EGR rates



(a) (b)

Figure 8: (a) Number-size and (b) Surface area-size distributions of particulate at varying SoPI and SoMI timings, and 15% EGR rate



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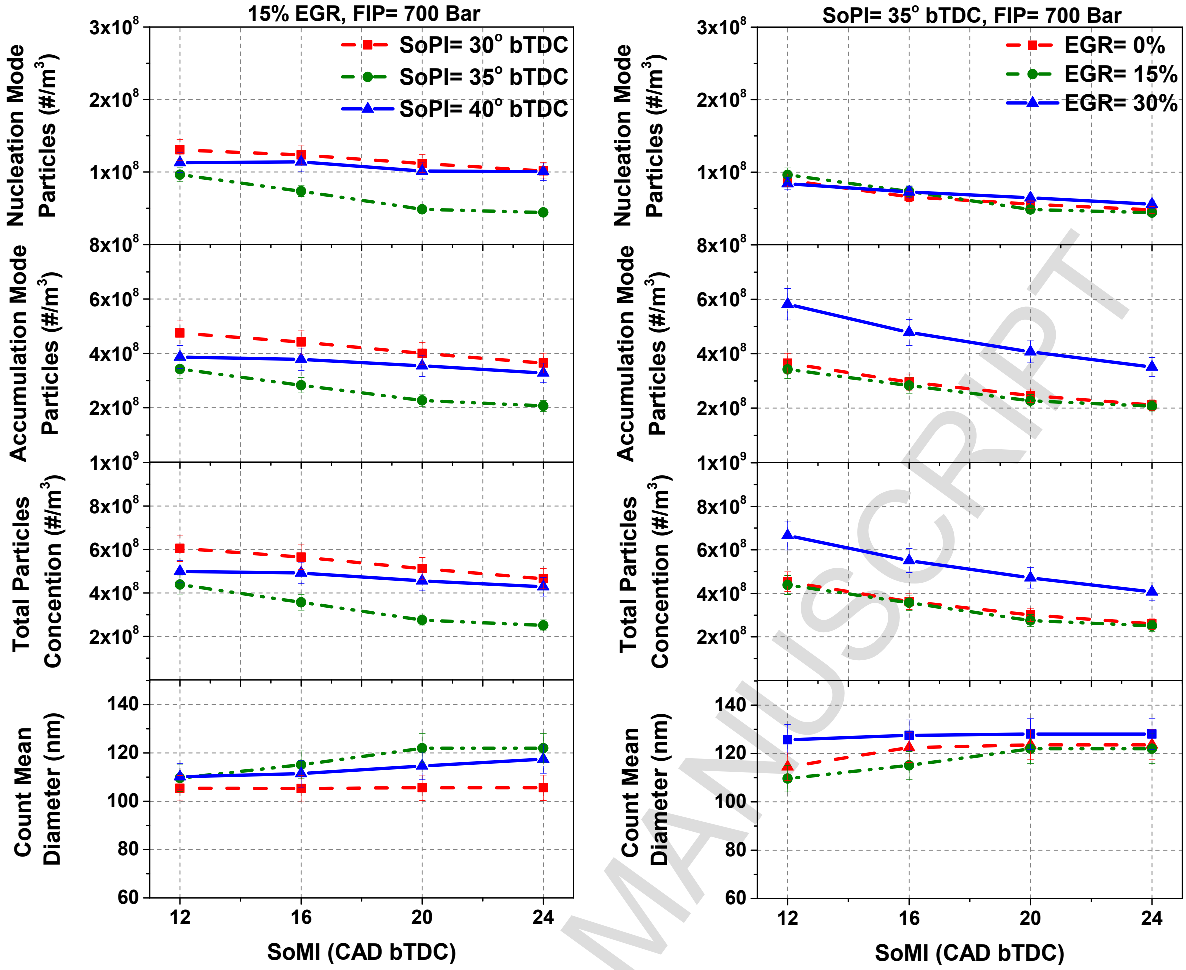
1006 (a) (b)

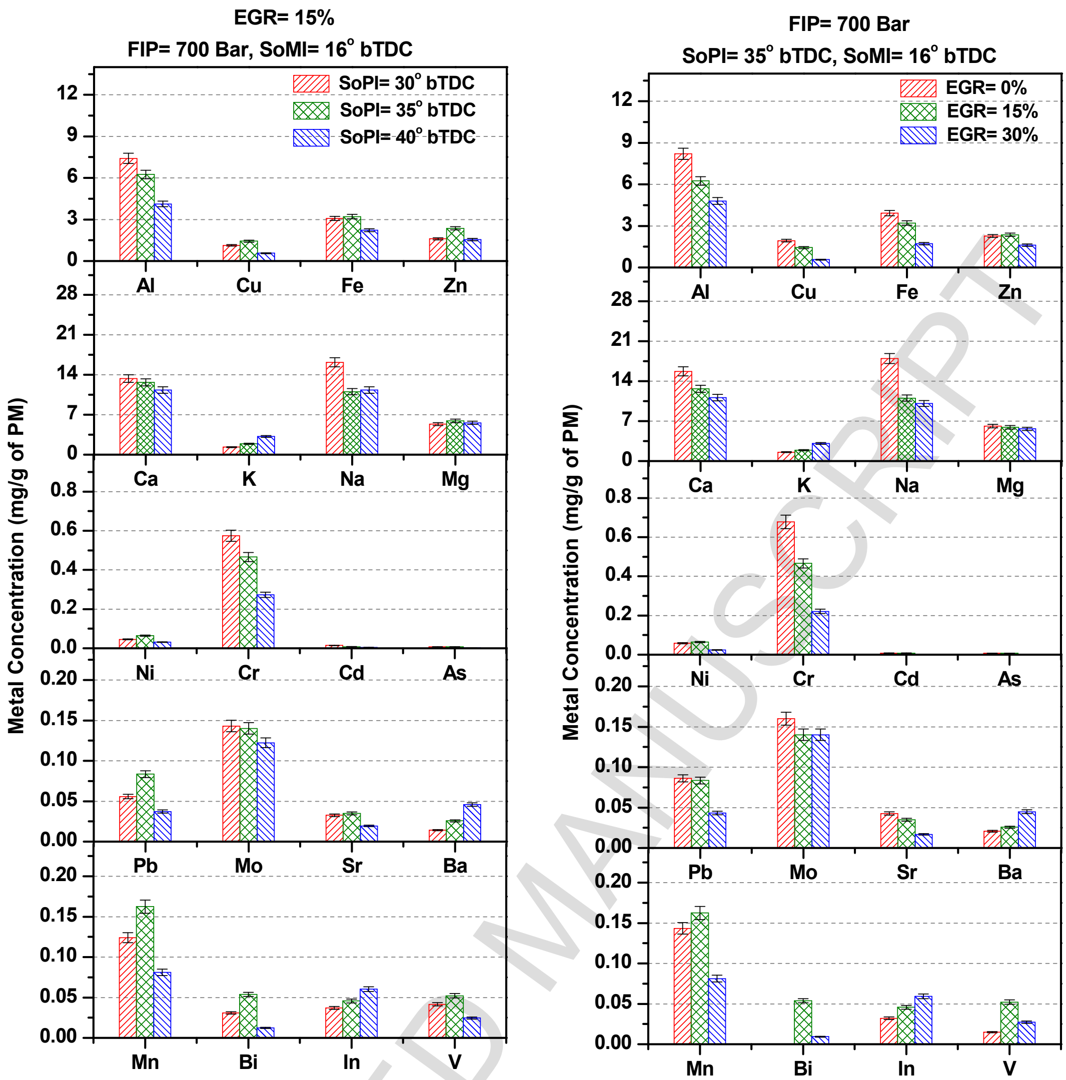
1007 Figure 9: (a) Number-size and (b) surface area-size distributions of particulate at

1008 varying EGR rates and SoMI timings

1009 

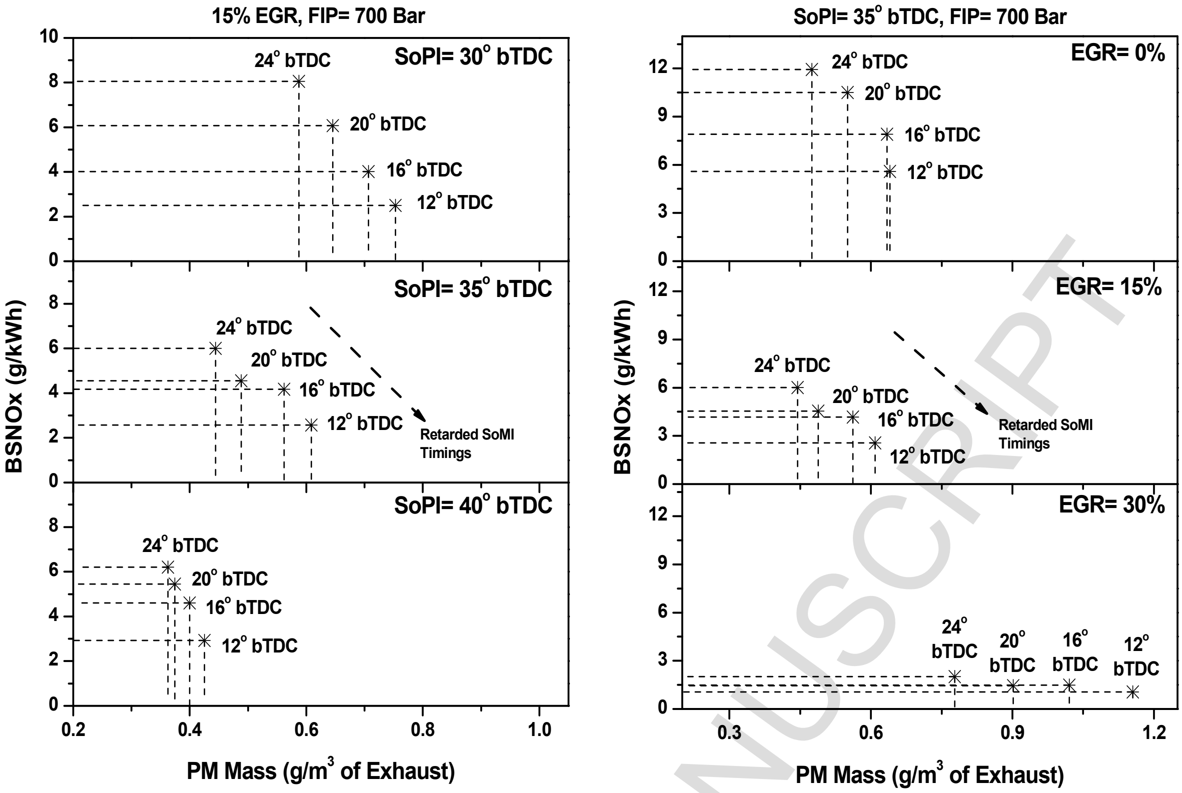
1010 (a) (b)

1011 Figure 10: Number of Nucleation mode particles, number of accumulation mode
1012 particles, total particulate number, and count mean diameter of particulate for varying
1013 SoMI timings at different (a) SoPI timings and (b) EGR rates



(a) (b)

Figure 11: Particulate bound trace metals at different (a) SoPI timings and (b) EGR rates



(a) (b)

Figure 12: NOx-PM mass analysis at varying (a) SoPI timings and (b) EGR rates in PCCI combustion mode

Table 1: Technical specifications of the test engine

Engine Parameters	Specifications
Engine make/ model	AVL/ 5402
Number of cylinder/ s	1
Cylinder bore/ stroke	85 mm/ 90 mm
Swept volume	510.7 cc
Compression ratio	17.5
Inlet ports	Tangential & swirl ports
Maximum power	6.25 kW
Rated speed	4200 rpm
High pressure system	Common rail direct injection BOSCH CP4.1
Engine management system	AVL-RPEMS + BOSCH ETK7
Valves per cylinder	4 (2 inlet, 2 exhaust)
Valve train type	DOHC cam follower
Liner type/ base	Wet