Scientia Iranica (2025) **32**(11): 7387

Sharif University of Technology
Scientia Iranica
Transactions on Mechanical Engineering
https://scientiairanica.sharif.edu

Review of advanced combustion technology using low temperature combustion in automobile industries

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Received 11 December 2022; Received in revised form 13 May 2023; Accepted 21 January 2024

Keywords

Internal Combustion engine (IC);
Low Temperature Combustion (LTC);
Nitrogen Oxides (NO_x);
Particulate Matter (PM);
Reactivity Controlled Compression Ignition (RCCI).

Abstract

An overview has been presented related to the advances in Internal Combustion engines (IC) for future solutions of the automotive industry. This review discusses as many current research areas as possible. This evaluation will be of great assistance to students, researchers, and enterprises working on the subject of IC engines. Moreover, there are numerous technological options for delivering environmentally friendly vehicles with low carbon emissions. This paper also examines the methods available as well as the use of technology road-mapping to plan for future manufacturer adoption. The Low Temperature Combustion (LTC) technique is among the most sophisticated combustion technologies. Various LTC techniques like Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI) have been discussed in detail. The results of the evaluation of LTC against conventional engines were provided in order to demonstrate both the strengths and shortcomings of each. The goal of this review article is to show new combustion approaches and how they may be utilized to increase the engine's thermal efficiency while lowering Nitrogen Oxide (NO_x) and Particulate Matter (PM) emissions.

1. Introduction

Vehicle discharges have risen to become the world's most significant source of air contamination, owing to tremendous economic growth [1]. The automotive industry is confronting tremendous difficulties in developing efficiency and outflows from Internal Combustion engines (IC) [2]. The depletion of petroleum supplies is a serious issue that has to be addressed by the international community using cutting-edge technology [3]. Excessive use of petroleum products contributes to global warming and the rapid exhaustion of petroleum resources [4]. New environmental restrictions have compelled the hunt for new sorts of technologies to address the problems caused by IC engine emissions [5]. Several environmental challenges have arisen as a result of the vehicle sector's market expansion, such as carbon emissions, global warming, greenhouse gas emissions, atmospheric air pollution, and climatic changes [6]. In order to prevent knock-like combustion, Bastawissi et al. [7] examined the Homogeneous Charge Compression Ignition (HCCI) engine under various load conditions by varying the amount of dimethyl ether and Hydrogen (H_2) fuels injected in to the inlet air. Another benefit is that they mixed fuels such as Di-Methyl Ether (DME) and H_2 with Compressed Natural Gas (CNG) to ensure stable operation.

Automobile engines and fuels are encountering difficulties in reducing emissions, improving air quality in local cities, and improving fuel efficiency, which decreases

To cite this article:
M.S. Kumaravel, T. Surulivel Rajan, N. Alagumurthi, P. Thangavel, K. Raja "Review of advanced combustion technology using low temperature combustion in automobile industries", *Scientia Iranica* (2025) **32**(11): 7387. https://doi.org/10.24200/sci.2024.61586.7387

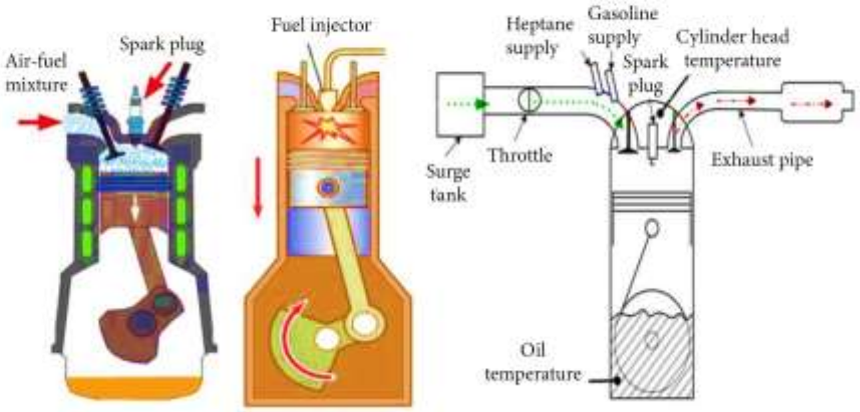

Figure 1. (a) SI engine; (b) CI engine; and (c) HCCI Engine [16].

CO_2 emissions to mitigate global warming [8]. To optimise combustion engines' tolerance to a wide variety of fuels, engine researchers must develop technologies designed to maximize engine efficiency and reduce exhaust emissions [9]. Therefore, it is important to create new technologies to protect the environment for present and future generations. The Low Temperature Combustion (LTC) is a type of advanced IC engine combustion that has sparked a lot of interest in recent years [10]. The automobile industry's difficulties can be mitigated by using LTC to improve existing engine technology [11]. LTC-based engines can achieve high thermal efficiency while emitting low levels of Nitrogen Oxides (NO_x) and Particulate Matter (PM) [12].

As LTC has a lower combustion temperature, it consumes less energy and has better thermal performance. LTC improves the environment by reducing emissions by eliminating NO_x and PM levels. LTC-based engines adopt different types of fuels with enhanced performance. It uses low-quality fuels in IC engines and has overall better combustion characteristics. This review article's major goal is to determine how cutting-edge LTC technology is being used to effectively lower NO_x and PM emissions while simultaneously enhancing thermal efficiency. The goal of this study is to assess LTC engines and their combustion features by looking at the most recent research. This review article discusses the most recent sophisticated technology as well as enhancements to older LTC engines.

2. HCCI engine

HCCI combustion is used to describe the novel LTC concept. Riyadi et al. [13] used a promising technique called the HCCI engine, which uses premixed combustion to produce a homogeneous, lean mixture that will ignite on its own. Controlling its combustion phasing, however, is still a difficult task. Additionally, HCCI engines emit considerable amounts of Unburned Hydro-Carbon (UHC) and Carbon monoxide (CO). The working principle of the LTC engine is illustrated in Figure 1. The LTC engines have the potential to produce the highest Brake Thermal Efficiency (BTE) with the least expenditure [14]. Elkelawy [15] studied "the fuel cavitation inside the injector nozzle parameters (such as injection pressure and fuel system temperature where fuel premixed ratio, NO_x, CO_2, and UHC emissions are measured) in order to develop a methodology for the HCCI combustion mode using diesel aerosol/air mixtures." The injection pressure of fuel and the temperature of the fuel system have been optimised to provide an appropriate fuel premixed ratio and the optimal fuel/air mixture for a wide range of engine operating conditions based on engine efficiency as well as engine emission characteristics. The optimal fuel injection pressure is about in the range of 150 to 200 bars, and the temperature of the fuel system is about in the range of 175 to 200°C.

Chaudhari and Deshmukh [17] designed premixed LTC engines for clean combustion and efficiency gains. For the initiation of combustion in the LTC engine, they controlled crucial variables such as inlet air pressure, temperature, pressure, and compression ratio. Wang et al. [18] looked at the possibility of a diesel-fueled LTC engine with excellent thermal efficiency while emitting minimal NO_x and PM at low loads. They achieved a thermal efficiency of 50% with a minimum fuel consumption of 168.6 g/kWh and an Exhaust Gas Recirculation (EGR) rate of 56% at a speed of 1900 r/min. The combustion mode of HCCI is a viable future technology for the development of 1900 r/min. The combustion mode of HCCI is a visible future technology for the development of IC engines due to its great thermal efficiency.

Although HCCI engines have improved thermal efficiency, their limited stable working range is widely regarded as their most significant disadvantage. Recent research has suggested that HCCI engines and their combustion characteristics can be improved with the use of nanoparticles as fuel additives [19]. In order to achieve stable HCCI combustion in the engine cylinder, Elkelawy et al. [20] studied "the detailed oxidation mechanism of natural gas in HCCI". According to their findings, "Cycle simulations utilising H_2 as an additive to the natural gas have identified the key factors influencing the engine's combustion efficiency and emission characteristics, and they also suggested the limits of potential improvement in comparison to traditional natural gas-HCCI engine technologies." El-Din Mohammad et al. [21] used DME, which will be crucial in regulating the auto-ignition time of the HCCI engine combustion, particularly at low intake charge temperatures. H_2 may assist in increasing the working range of CNG fuel in HCCI engines and drastically reducing their regulated emissions. The viscosity of the mixed gasoline reduces with an increase in DME, while the vapour pressure in the fuel system slightly rises. A suitable higher fuel vapour pressure may have beneficial impacts on the formation of a homogenous mixture for an HCCI engine. Yu et al. [22]

concluded that while both hydrocarbon and carbon monoxide emissions are relatively high, with the exception of high load situations, an HCCI engine running on DME50 is smokeless and emits nearly zero NO_x [22]. Phase change materials are used for latent heat storage applications [23]. The addition of nanoparticles enhances the phase change material's thermal conductivity property [24]. So, it is used as a better choice for thermal energy management and heat transfer application [25]. Aluminium, Steel, and its alloy containers are used as encapsulations for phase change materials [26].

Wang et al. [27] focused on the characterization of the HCCI engine's combustion characteristics by using natural gas as fuel at different conditions. They desired to overcome the challenges of regulating the combustion process in HCCI engines. They carried out sensitivity analyses of Start of Combustion (SOC) to in-take temperature and excessive air ratio at different speeds. Their result suggested that SOC can be controlled by regulating the pressure and temperature in the cylinder through the addition of EGR, the addition of water, and modifying the inlet temperature at moderate speed. Elkelawy et al. [28] analysed a promising low-temperature technique, the HCCI diesel engine, employing ethanol as a fuel additive to boost the amount of oxygen needed for combustion in fuel-biodiesel blends. Diesel-biodiesel-ethanol blends have higher Specific Fuel Consumption (SFC) than diesel fuel. The higher SFC is a result of the biodiesel blend's lower energy content and reduced calorific value. Increasing the brake power of pure diesel and oxygenated fuel mixtures enhanced the thermal efficiency of the brakes. There was improvement in the BTE for various three different biodiesel mixtures because of their higher volatility, high viscosity, and lower calorific value. Solmaz et al. [29] used B20 fuel devoid of the Multi-Walled Carbon Nanotube (MWCNT) addition. The characteristics of B20 were improved by the addition of MWCNT. Their research showed that the inclusion of the MWCNT additive boosted thermal efficiency (33.16%) and enhanced HCCI engine performance by utilising 100 ppm preservative B20 fuel.

3. Premixed Charge Compression Ignition (PCCI) engine

Singh and Agarwal [30] concluded that the achievement of superior thermal efficiency has always been challenging in HCCI engines [30]. Jeon and Bae [31] promoted research to look for and discover superior technologies. Premixed Charge Compression Ignition (PCCI) combustion is more sophisticated than Homogeneous Charge Compression Ignition (HCCI) combustion. Elkelawy et al. [32] examined diesel engines with Partially Premixed Lean Charge Compression Ignition (PPLCCI) combustion that are capable of reducing NO_x and PM emission output while maintaining improved engine BTE.

Jain et al. [33] reported on the combustion stability of the PCCI engine by analysing the fuel injection parameter. Reducing knocking and minimising the emissions of NO_x have been the main objectives of the PCCI engine. Combustion stability was achieved in the PCCI engine by maintaining the pressure of fuel injection at about 700 bar. This was possible owing to excellent fuel atomization at a higher Fuel Injection Pressure (FIP). Lower CO and UHC emissions can be achieved in PCCI engines [34]. Oxyhydrogen gas was used by Bhave et al. [35] to supplement the fuel in the PCCI engine, and they contrasted PCCI mode with and without the addition of oxyhydrogen gas. Their findings demonstrated that peak pressure and thermal efficiency were all enhanced by the addition of oxyhydrogen gas. They also revealed that their analysis found very little NO_x emissions, or less than 10 ppm.

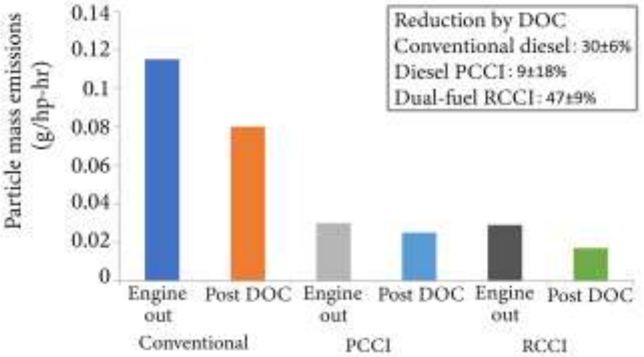

Figure 2. PCCI Combustion for improved Diesel engine emissions [37].

Strict emission norms have forced all investigations to find advanced technology with low emissions. Srihari et al. [36] examined the effect of diethyl ether in biodiesel blends in PCCI-Direct Injection (PCCI-DI) engines. They used biodiesel produced from cotton seal, and their emissions were lower in UHC, CO, and NO_x values. They also noticed an increase in BTE in the PCCI-DI engine. Alemayehu et al. [37] focused on better emission properties in PCCI engines. A conventional IC engine with an unacceptable emission range was compared with the newly developed PCCI engine. The PCCI engine produced the minimum amount of oxides of nitrogen and PM. They employed EGR adjustment at various loads to help the PCCI engine achieve the best performance. In the PCCI engine, they were also to create improved thermal efficiency with the least amount of negative emission impacts. Figure 2 shows better combustion effects in the PCCI engine. Single-fuelled and dual-fuelled single-cylinder engine performance characteristics were compared by Shim et al. [38].

The PCCI engine's combustion performance and engine emission characteristics running on ethanol diesel mixes were examined by Elzahaby et al. [39]. In research, a single-zone model is used to forecast how the PCCI engine will operate at various premixed ratios of ethanol-diesel fuel mixtures. The results demonstrated that chemical kinetic behaviour in PCCI combustion is highly capable of controlling the ignition of the engine and the combustion process by employing the premixed ratio of the ethanol/diesel mixture. They reported that dual-fuel PCCI combustion could reduce CO_2 emissions and achieve higher thermal efficiency than standard diesel combustion.

Muruga Nachippanan et al. [40] investigated the effectiveness of a PCCI engine running on Tamanu biodiesel combined with MWCNT. They discovered that the physiochemical characteristics of Tamanu biodiesel were enhanced by the use of nanoparticles. The optimal characteristics of Tamanu biodiesel were enhanced by the use of nanoparticles. The optimum choice, according to the results, is to add 100 ppm of MWCNT to Tamanu biodiesel in PCCI mode.

Ramachandran et al. [41] examined “the ideal mixture of biodiesel with nanoparticles in a 5.2 kW CI engine for various amounts (B10, B20, B30, and B40). About 20% of the fuel provided is guaranteed to be vaporised for premixing by the PCCI function. Finally, the ideal amount of desired dependent and independent variables was determined by using Response Surface Methodology (RSM) to investigate the interactions between the independent variables of the PCCI engine”. The engine was used to test and validate the project blend ratio for B25. The results showed a rise in BTE to 31.42% and a decrease in Brake Specific Energy Consumption (BSEC) to 9.82 MJ/kWh, as well as a decrease in NO_x to 691 ppm [42].

Charitha et al. [43] developed a “Reactivity-Controlled Compression Ignition (RCCI) combustion engine” by modifying the intake of a diesel engine. They studied the difference between Conventional Diesel Combustion (CDC) engines and RCCI engines and investigated their engine performance and emission characteristics. With the addition of Cotton Seed Biodiesel (CSBD), they noticed a decrease in NO_x and particulate emissions, at decreasing CSBD%, CO_2 emissions and UHC were reduced. Any further increase in CSBD was reported to result in increased CO_2 and UHC emissions. The findings revealed that the 10%-20% CSBD, which has a 22% average reduction in NO_x and an average reduction of 30% in smoke emissions, is effective. By combining waste cooking oil and fossil diesel fuel, Elkelawy et al. [44] investigated the performance of the engine, its emission characteristics, and the combustion characteristics of the PCCI engine with different fuel injection strategies. According to their findings, the in-cylinder pressure peaks have been somewhat reduced, the apparent heat release has been decreased, and the average BTE has increased by about 10.57% compared to conventional direct injection at premixed ratio 3. Furthermore, average CO emissions were reduced by 0.241%, and average NO_x emissions were reduced by 408.8 ppm.

Yang et al. [45] used “Low Pressure Dual-fuel Direct Injection” (LPDDI) to compare and explore combustion performance and emission parameters in an RCCI engine running on diesel and CH_4 injections, which have a substantial impact on the combustion chamber. This study found that the initial diesel injection time of 250° CA After Top Dead Center (ATDC) and the newest CH_4 injection time of 112°CA ATDC yielded the best combustion performance.

Sajjad et al. [46] developed a deep learning method combined with explainable artificial intelligence to assess the heat transfer from the liquid-to-vapour phase shift in nanoporous surface coatings. Paykani et al. [47], found that compared to either Spark Ignition combustion (SI) or Compression Ignition (CI), SI is substantially quicker. By altering both CI and SI engines, the HCCI combustion mode improves thermal efficiency while retaining low emissions. With this technology, a broad range of fuels, fuel mixtures, and renewable fuels may be employed [48]. By swapping either traditional diesel or spark-ignited combustion engines, significant reductions in NOx emissions can be accomplished [49]. In addition to lowering particular fuel usage, LTC technology offers notable advantages in the sharp decrease of NOx and PM [50]. Dimitriou et al. [51] concluded that higher EGR rates raise the temperature of the intake charge, which improves H_2 combustion and fuel efficiency. There was a reduction in NO_x of 90 – 98% compared to that of normal diesel combustion [52]. Figure 3 shows the various ranges of PM emission in advanced LTC technology with reference to the conventional engine. Ghaffarzadeh et al. [53] showed that a dual–fuel RCCI engine’s performance and emission characteristics are significantly influenced by the timing of the beginning of liquid fuel direct injection.

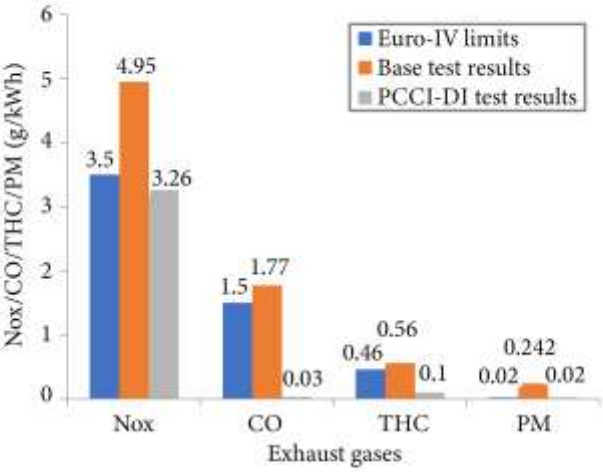

Figure 3. Performance of PM values in different ITC technology [47].

4. Emission characteristics

Emission characteristics were studied by Alagumalai [54] and suggested that induction of ethanol (10% and 20%) in the intake manifold and injecting waste cooking oil biodiesel directly inside the cylinder reduced NO_x emissions by 60% and smoke emissions by 29%. However, UHC and CO emissions increased in their investigation. An evaluation of RCCI-mode combustion engines using gasoline and mineral diesel in single-cylinder research engine was performed by Singh et al. [55]. “They found that adding low-reactivity gasoline to the RCCI engine made it run better performance. Also, RCCI mode combustion engine delivered low NO_x and PM emissions compared to the baseline CI mode combustion” [56]. However, both UHC and CO emissions from RCCI mode increased slightly when compared with the CI mode combustion. As far as emission, RCCI mode combustion has greater potential for the utilisation of alternative fuels with enhanced engine performance and the possible reduction of NO_x and PM emissions compared to CI and PCCI [57]. Elkelawy et al. [58] examined “The RCCI combustion engine requires a very low EGR rate because the rate of combustion is controlled by varying the mixture’s reactivity by employing two fuels with considerably different reactivities. RCCI operation with cooled EGR resulted in a decrease in pressure rise rate, cyclic variation, and NO_x emission but an increase in THC emission. At low loads, internal EGR’s lower intake air pressure achieved generally higher net indicated efficiencies and lower combustion losses than conventional RCCI. Utilising a higher EGR percentage has greater advantages for extending maximum load and reducing particulate and NO_x emissions, while the combustion and indicated thermal combustion efficiencies decrease.” Eldon et al. [59] analysed “The conversion of a CI diesel engine to dual-fuel RCCI combustion. The effects of various energy shares of carbon-free NH_3 and carbon-neutral microalgae biodiesel were investigated. The outcomes are compared with conventional

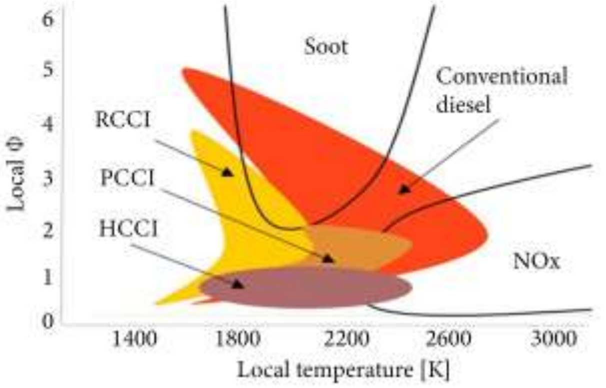

Figure 4. Emission of NOx in different combustion mode [60].

mode running at 80% load. Operating an NH_3 dual fuel RCCI raises the ID, which causes a longer CD and lower CP". The emission of NO_x and PM in different combustion modes is presented in Figure 4.

Studies revealed that emissions of PM and NO_x affect the environment and humans [60], and Reşitoğlu et al. [61] analysed the emission control methods of pollutant exhaust gases. Boningari and Smirniotis [62] revealed the study impact of NO_x in the environment and health issues related to these gases, and hence it is vital to eliminate these emissions with the help of the latest advanced combustion technology [63]. Ranasinghe et al. [64] reviewed the use of advanced low-emission technologies for aviation. In this aspect, RCCI significantly contributes to the large reduction of NO_x and PM [65]. Zou et al. [66] investigated the EGR, which is required for controlling the phases of combustion, and the combustion characteristics of RCCI engines are reviewed [67].

In the Methanol RCCI mode, when diesel is injected with twin pulses, the thermal efficiency is greater than in the traditional dual-fuel mode, the NO emissions are significantly lower, the soot, UHC, and CO emissions are comparable, and the methanol share is increased [68]. The addition of nano cerium oxide and methyl tert-butyl either with gasoline or with diesel further reduces the emissions and also improves the performance of the engine [69].

5. Conclusion

As a result, a thorough investigation has been conducted into advancements in Internal Combustion (IC) engines for future automotive sector solutions. This review discusses as many current research areas as possible. Various forms of Low Temperature Combustion (LTC), like Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity Controlled Compression Ignition (RCCI), have been discussed in detail. In the end, the advantages of LTC have been presented with a comparison of conventional techniques.

- More harmful items from engines, like Oxides of Nitrogen (NO_x) and Particulate Matter (PM) reduction ideas, were discussed. Emission characteristics were discussed in detail, and it was found that RCCI has a significant impact on reducing NO_x and PM compared to PCCI and CI. Though LTC reduces NO_x emissions considerably, it has various challenges that need to be addressed;
- Furthermore, for small loads, LTC performs well, and for larger load variations, the performance of LTC is minimal;
- Overall, the research suggests that the LTC has the potential for efficiency improvements over conventional engines. Thus, this study showed that all LTC techniques may be utilised to eliminate PM and NO_x, but the RCCI combustion approach was more effective at doing so while also having a great potential to employ alternative fuel in the development of sustainable transportation options;
- The analysis of various LTC strategies demonstrates that a low amount of NO_x emissions would arise if the temperature of the combustion could be adjusted in any manner. Controlling the combustion is the main problem with the LTC. Other issues with LTC technology include its constrained working range and greater UHC and Carbon monoxide (CO) emissions.

Nomenclature

BTE	Brake Thermal Efficiency
CD	Combustion Duration
CDC	Conventional Diesel Combustion
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CSBD	Cotton Seed Biodiesel
DME	Di-Methyl Ether
EGR	Exhaust Gas Recirculation
FIP	Fuel Injection Pressure
g/kW h	Gram/kiloWatt-hour
H_2	Hydrogen
HCCI	Homogeneous Charge Compression Ignition
IC	Internal Combustion
ID	Ignition Delay
IMEP	Indicated Mean Effective Pressure
LPDDI	Low Pressure Dual-fuel Direct Injection
LTC	Low Temperature Combustion
LTO	Low Temperature Oxidation
MWCNT	Multi-Walled Carbon Nano Tube
NO_x	Oxides of nitrogen
PCCI	Premixed Charge Compression Ignition
PHCCI	Partial Homogeneous Charge Compression Ignition
PM	Particulate Matter
PPLCCI	Partially Premixed Lean Charge Compression Ignition
ppm	Parts Per Million
RCCI	Reactivity Controlled Compression Ignition
RSM	Response Surface Methodology
SFC	Specific Fuel Consumption
SI	Spark Ignition
SOC	Start of Combustion
UHC	Unburned Hydro-Carbon

Competing Interests

The authors declare no competing financial interest.

Funding

The authors acknowledge that there are no external funding/grants received for this research work.

Authors contribution statement

First author: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing – original draft;

Second author: Conceptualization; Methodology; Project administration; Resources; Supervision; Validation; Writing – review and editing;

Third author: Data curation; Investigation; Software; Validation; Visualization;

Fourth author: Formal analysis; Resources; Software; Writing – review and editing;

Fifth author: Investigation; Methodology; Validation; Writing – review and editing.

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