Low-Temperature Combustion: An Advanced Technology for Internal Combustion Engines

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Abstract Universal concerns about degradation of ambient environmental conditions, stringent emission legislations, depletion of petroleum reserves, security of fuel supply, and global warming have motivated R&D of engines operating on alternative combustion concepts, which have the capability of using renewable fuels. Low-temperature combustion (LTC) is an advanced combustion concept for internal combustion (IC) engines, which has attracted global attention in recent years. LTC is radically different from conventional spark ignition (SI) combustion and compression ignition (CI) diffusion combustion concepts. LTC technology offers prominent benefits in terms of simultaneous reduction of both oxides of nitrogen (NOx) and particulate matter (PM) in addition to reducing specific fuel consumption. However, controlling ignition timing and heat release rate (HRR) are primary challenges to be tackled before LTC technology can be implemented in automotive engines commercially. This chapter reviews fundamental aspects of development of LTC engines and their evolution, historical background, and origin of LTC concept and its future prospects. Detailed insights into preparation of homogeneous charge by external and internal measures for diesel like fuels are discussed. Combustion characteristics of LTC engines including combustion chemistry, HRR, and knock characteristics are also touched upon in this chapter. Emission characteristics are also reviewed along with insights into PM and NOx emissions from LTC engines.

Keywords Low temperature combustion · Oxides of nitrogen · Particulate matter
Combustion control

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1 Introduction

Transport is an essential component by which people not just connect with each other but also progress. To fulfill increasing demand for safe, reliable, environmental friendly, economical and efficient transport system, development of novel automotive technologies has become crucial. Automotive technology refers to the technologies incorporated in vehicles for their design and prototyping. These technologies are essential for evolution and adaptation in existing vehicles. With rapidly increasing demand as well as expectations of consumers for higher safety standards, low-carbon future is embodied aggressively in evolving fuel economy standards and stringent emissions norms. According to World Energy Outlook (2011) factsheet of International Energy Agency (IEA), global demand for primary energy is expected to increase by one-third between 2010 and 2035 and energy-related CO_2 emissions are expected to increase by 20% (reaching up to 37 $GtCO_2$ by 2035) [1, 2]. Rapidly dwindling petroleum reserves are another major concern for the automotive sector. Therefore, research efforts have focused on exploration of alternative energy resources, including renewable fuels such as biofuels, solar energy, and hydrogen.

Direct injection compression ignition (DICI) and spark ignition (SI) engines are the main technologies, which have reputed and established applications in the automotive sector. Over the past several decades, diesel engines have become more efficient, durable, quieter, and vibration-free. Diesel vehicles have undergone dramatic changes in the last decade with the advent of common rail direct injection (CRDI) technology. CRDI technology offers unprecedented flexibility, which was previously not available for DICI engines, and it delivers 25% higher power output compared to baseline DICI engines. Apart from engine performance, control of harmful pollutants like oxides of nitrogen (NOx), particulate matter (PM)/soot, carbon monoxide (CO), and hydrocarbons (HC) is essential in order to preserve the environment and protect the human health. Diesel engines are one of the major sources of PM, which mainly consist of soot laced with polycyclic aromatic hydrocarbons (PAHs), trace metals, and sulfates. PM is known to have adverse impact on human health and the environment through inhalation pathway, toxic contamination of different environmental media, visibility reduction (due to smoke), and global climate change (due to black carbon emissions) [3].

Different emission reduction techniques are being developed to comply with prevailing emission standards. These techniques can be broadly classified into active and passive emission reduction techniques. In the active emission reduction, polluting species are prevented from formation during combustion. The governing principle to avoid pollutant formation in the combustion chamber is to optimize the combustion. Combustion and pollutant formation in diesel engines are dependent on in-cylinder conditions, which are primarily governed by fuel injection parameters, in-cylinder air temperature, pressure, and charge motion. Numerous techniques such as turbo-charging, exhaust gas recirculation (EGR), high-speed direct injection (HSDI), modifications in engine configuration, and design of flow control valves have been implemented to control the formation of pollutants during combustion. In passive emission reduction, combustion products are neutralized before their exit from the tailpipe into the atmosphere. These methods include exhaust gas after treatment, which have been developed over decades. Three way catalytic convertors (TWC), diesel particulate filters (DPF), diesel oxidation catalysts (DOC), selective catalytic reduction (SCR) technique, and lean NOx traps (LNT) are some of the popular exhaust gas after-treatment techniques. Emission control hardware is located in the exhaust system of vehicles, where they oxidize and reduce pollutants before the exhaust is released into the atmosphere. Current and emerging after-treatment techniques promise significant emission reduction; however, the cost and complexities involved in their implementation threaten their application to the diesel engines.

Additionally, use of alternative fuels and hybrid vehicles can also be considered for emission control. In spite of the fact that fossil fuels are the backbone of the energy supply, depletion in their reserves and stringent emission norms have motivated researchers to develop advanced vehicles such as battery-operated vehicles, fuel-cell vehicles. Another concept for emission reduction is the use of hybrid vehicles, which are powered by electric motors along with IC engines. The electric motors provide the benefit of high power and efficiency but no emissions. According to driving conditions, in hybrid vehicles, power source can be switched between an electric motor and an IC engine, resulting in higher fuel economy and lower emissions. However, hybrid vehicles suffer from the limitation of higher cost, scarcity of raw materials (rare earth metals), large size and weight, which has resulted in very small share of hybrid vehicles among new vehicles sales. New vehicle technologies collectively are expected to account for 6% of new passenger vehicle sales by 2020 and 19% by 2035, bulk of which would be hybrids. Figure 1 shows the relative growth of different automobile technologies among new vehicle sales.

In such a scenario, automotive industry desperately requires technologies, which are cleaner and efficient, improve ambient air quality in an efficient manner, reduce greenhouse gas emissions, and contribute to energy security [5–9]. Considering stringent emission regulations and scarcity of primary energy resources, development of new highly efficient, and environment friendly combustion concepts and systems capable of utilizing alternative fuels in addition to conventional fuels have become increasingly important. Several experimental studies have been carried out

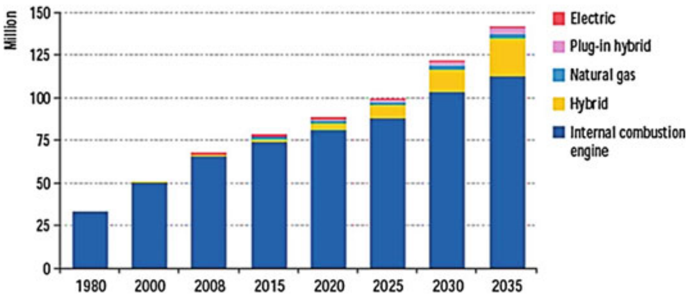


Fig. 1 Present and future status of light-duty vehicle sales [4]

to develop novel combustion concepts such as low-temperature combustion (LTC), which demonstrate the prospects of meeting stringent environmental challenges faced by automotive engines. In recent years, researchers have focused on LTC technology development primarily due to its extremely low NOx and PM emissions and high efficiency potential.

1.1 Advanced Combustion Techniques

LTC engines have great potential to achieve high thermal efficiency and ultra-low emissions of NOx and PM. This has attracted attention of researchers and automotive industry alike. Significant efforts are being made to understand the physical and chemical processes involved in LTC, which affect engine performance and emissions. LTC engines operate on the same fundamental principle as a four-stroke engine and use basic elements of CI and SI engines. The LTC principle is shown in Fig. 2.

In a LTC engine, during the intake stroke, a nearly homogeneous fuel–air mixture is introduced. After intake valve closing (IVC), the piston starts to compress the fuel–air mixture, which increases the in-cylinder temperature and pressure. As the piston approaches TDC, charge attains auto-ignition conditions. Chemical kinetics of the charge can be accelerated by increasing the charge temperature in the beginning of compression stroke by preheating the intake air or by retaining a fraction of hot exhaust gas from the previous engine cycle in the cylinder. In both strategies, chemical reactions occurring in the homogeneous fuel–air mixture accelerate due to relatively higher charge temperature and pressure of residuals [11]. Start of combustion (SoC) in LTC mode can be controlled by a combination of variables such as compression ratio, inlet charge temperature, and pressure. As soon as the auto-ignition temperature is attained during the compression stroke, fuel starts

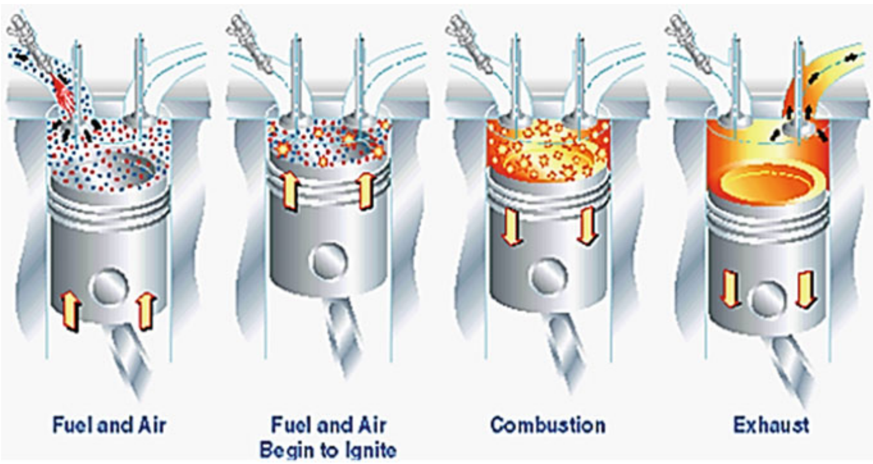


Fig. 2 Homogeneous charge compression ignition combustion principle [10]

oxidizing rapidly and its chemical energy is released instantaneously. Auto-ignition in LTC engine occurs simultaneously at several locations throughout the engine cylinder, and these locations are called hot spots. This quick heat release causes pressure rise in a significantly shorter time span compared to conventional combustion, while the peak cylinder local and global temperature still remains significantly lower. The fuel–air mixture temperature and pressure, therefore, increase further during combustion. During the expansion stroke, work is done by the expanding gases on the piston to produce a net positive torque, which is available at the crankshaft. The cycle is completed after the piston ascends to TDC during the exhaust stroke, forcing products of combustion out of the cylinder. In summary, LTC consists of the following steps:

(a) Preparation of a highly dilute fuel–air mixture using EGR to control combustion and the heat release rate.
(b) At the end of the compression stroke, fuel–air mixture temperature approaches auto-ignition temperature, leading to simultaneous spontaneous ignition of entire charge in the cylinder at several locations.
(c) Precise control of heat release rate (HRR) to achieve trade-off between combustion efficiency and emissions [12].

1.2 Advantages of LTC

This section describes potential advantages and scientific challenges in exploiting full advantage of this novel LTC concept, referred as homogeneous charge compression ignition (HCCI) combustion. LTC offers several advantages over the conventional combustion modes [13, 14]:

- LTC approximates a constant volumetric combustion in a very short combustion duration, and it can be achieved for high compression ratio; therefore, it results in higher thermal efficiency. Relatively lower peak combustion temperature in LTC leads to better energy utilization due to lower radiation losses. Throttling losses are also absent in a LTC engine in comparison to a SI engine.
- LTC has potential of significantly lower emissions compared to DICI and DISI engines with simultaneous reduction in NOx and PM emissions. There is no flame front, i.e., there is complete absence of localized areas of excessively high temperature and rich mixtures due to superior homogeneity of the fuel–air mixture. Therefore, there is no soot production. Further, there are low-temperature conditions and more uniform distribution of bulk gas temperature in the cylinder; therefore, NOx emissions are restricted to ultra-low levels. Hence, LTC is not affected by Soot–NOx trade-off.
- Main advantage of LTC is its fuel flexibility. LTC can be achieved by a wide range of fuels including gasoline, mineral diesel, biodiesel, alcohols, etc. Fuel flexibility of LTC engines enables the use of various alternative fuels that could reduce rapid depletion rate of petroleum reserves [15–17].

- LTC engines are suitable for the replacement of conventional SI and CI engines. These engines can also be coupled with advanced hybrid engines, i.e., to combine the advantages of highly efficient IC engines with electrical series hybrid powertrains.

1.3 Challenges in LTC

The main challenges that hinder the realization of LTC are as follows:

- Difficulties in vaporization of diesel hinder the development of diesel LTC because the fuel injection timings of LTC are significantly advanced compared to direct injection diesel combustion. When diesel is injected, the cylinder pressure and temperatures are close to atmospheric conditions. Viscous diesel fuel does not vaporize under these conditions. Therefore, preheating of intake air is required for vaporization of mineral diesel.
- LTC does not offer precise control over the start of combustion across wide range of engine speeds and loads. This issue becomes more important at the time of transient engine operation. Although several attempts have been made to resolve this issue by EGR control techniques such as variable valve timings; however, there is scope for further improvement in this area.
- LTC regime suffers from load limitations and can be implemented only at low-to-medium loads. For real-world application of LTC, the engine operation modes have to be switched back and forth between LTC mode at lower loads and conventional CI mode at higher loads.
- LTC is characterized by leaner air–fuel ratios. However, rich fuel–air mixtures at higher loads cause deterioration in engine noise, very rapid heat release rates, reduction in engine power output, etc.
- Lower in-cylinder temperature in case of LTC impedes post-oxidation of HCs and conversion of CO to CO_2. Thus, LTC basically suffers from the problem of high HC and CO emissions.

2 Premixed Charge Compression Ignition (PCCI): An Advanced LTC Technique

Different LTC systems can be differentiated by control over combustion phasing. Adaptation of HCCI technique results in reduced NOx and PM in diesel engines; however, HCCI combustion results in overall inferior thermal efficiency, and it also suffers from the lack of control over the combustion phasing. In case of a HCCI engine, combustion phasing is dominated by chemical reaction kinetics and decoupled from injection timing, which further results in lack of control over combustion events. Researchers have observed either too advanced or too retarded combustion phasing in case of HCCI combustion, which results in lower thermal efficiency. Poor combustion phasing results in relatively higher HC and CO emissions due to lower in-cylinder temperatures. These issues motivated researchers to develop a new LTC strategy known as premixed charge compression ignition (PCCI) combustion.

PCCI combustion is an advancement over HCCI combustion in terms of combustion stability. In PCCI combustion, control over combustion events with injection strategy is retained and a greater percentage of the total charge is premixed prior to ignition relative to conventional diesel combustion. In PCCI engine, fuel is injected at an intermediate timing between that of HCCI and conventional CI engine. This results in a partially premixed fuel–air mixture, which auto-ignites similar to HCCI combustion mode. PCCI combustion seems better compared to HCCI combustion due to better control over the combustion events, which leads to relatively superior engine performance. Various injection strategies are available for PCCI combustion, but commonly advanced injection timings are used to increase fuel–air mixing time. Despite the charge not being completely premixed (homogeneous), the same principles are applied to obtain low emissions as with HCCI. The factors used to promote combustion conditions toward the PCCI mode of operation are primarily the injection strategy and EGR rate. PCCI combustion is a single-stage combustion technique in which most fuel is burnt in premixed combustion phase. There is very small or practically no fuel remaining in the combustion chamber for diffusion combustion, which results in a relatively lower bulk temperature inside the combustion chamber. PCCI engines at high loads are facilitated with high boost pressure, which helps in oxidation of fuel resulting in relatively lower CO and HC emissions. Therefore, PCCI engine not only offers benefits of LTC with lower NOx and PM emissions but also results in significantly lower HC and CO emissions.

2.1 Charge Preparation for PCCI Combustion

Charge preparation, i.e., mixing of fuel and air is a very important feature of IC engines. The combustion process and its control are very much dependent on quality of mixtures and the technique employed for charge preparation. One of the major challenges of PCCI combustion is to prepare the premixed charge (highly diluted fuel–air mixture to give reasonable burn rates) before auto-ignition temperature is attained and combustion starts in the combustion chamber. In PCCI combustion engines, effective mixture preparation technique is required for achieving high efficiency, low HC, and PM emissions and preventing lubricating oil dilution. There are several techniques employed for charge preparation in PCCI combustion engines, depending on test fuel properties and control strategies being used.

The PCCI charge preparation techniques can be divided into three main categories, including external charge preparation (port fuel injection), internal charge preparation (in-cylinder direct injection), and concepts using both types of charge preparation techniques (dual-fuel mode). These strategies differ from each other in

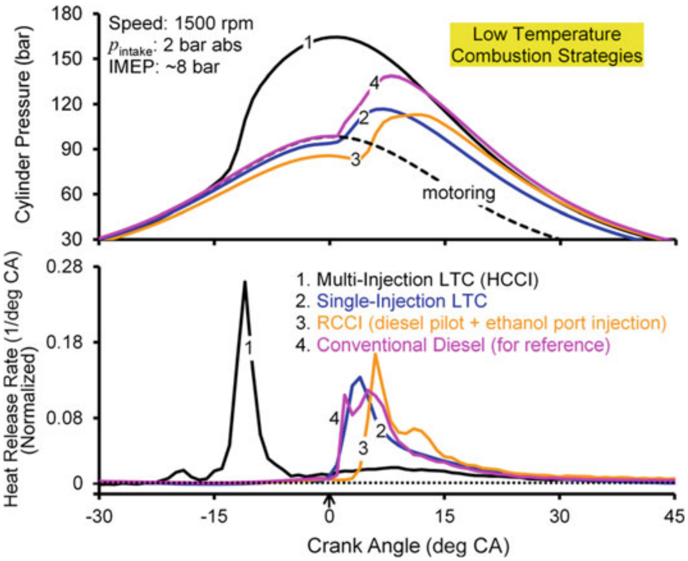


Fig. 3 Common LTC strategies for diesel engines [18]

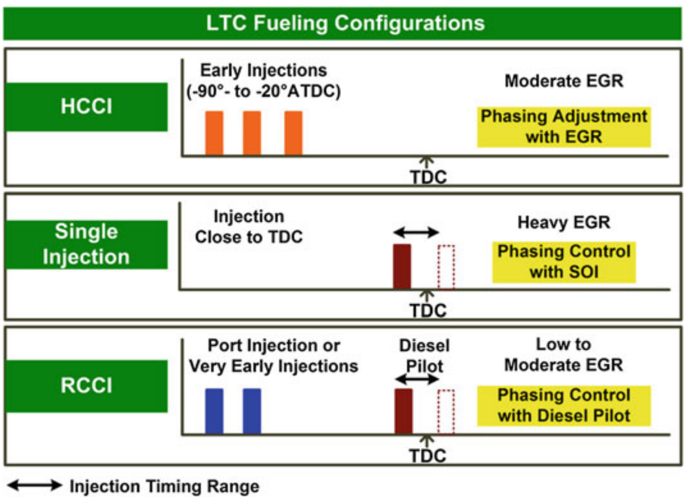


Fig. 4 LTC fueling configurations [18]

terms of time available for mixing and in degree of mixture homogeneity, which is achieved at the time of SoC [18].

Common strategies for achieving LTC include HCCI [19–22], single-injection LTC [23–26] and reactivity controlled compression ignition (RCCI) [27, 28], as shown in Fig. 3. An overview of fueling configurations is shown in Fig. 4. To achieve the diesel-fueled PCCI combustion, a multiple-fuel injection strategy is preferred due to its capability of generating nearly homogeneous fuel/air mixture [18].

2.2 *Fuel–Air Mixture Homogeneity*

Main requirement of LTC is the availability of homogeneous fuel–air mixture before SoC. In an IC engine, fuel–air mixing is governed by many parameters such as fuel properties, fuel injection strategy, in-cylinder conditions, fuel spray characteristics, in-cylinder flow patterns. These parameters are closely related to each other, i.e., in-cylinder conditions can be optimized by controlling fuel injection parameters and in-cylinder flows. Air motion redistributes dense liquid core of fuel throughout the combustion chamber. In-cylinder flows have strong impact on fuel evaporation; hence, they affect both the physical and chemical delay part of the ignition delay. Mainly in-cylinder flows near the intake and exhaust manifolds have been the focus for investigations of fuel–air mixing and its cyclic variations. Most researchers have operated engines in motoring mode. A common observation from these studies has been that there were large-scale dissipation of in-cylinder turbulent flow structures of the intake jet into small eddies with progression of an engine thermodynamic cycle. Among different flow structures that get formed inside the combustion chamber, “swirl,” “tumble,” and “squish” are of particular interest because of their significant impact on fuel–air mixing. Swirl is an organized rotational motion of air around the cylinder axis. Swirl is generated during the intake stroke due to specific intake manifold geometry and during compression stroke because of geometry of the piston and cylinder.

Fuel spray characteristics also significantly affect the fuel–air mixing inside the combustion chamber; therefore, it has been also been studied by many researchers using experiments as well as numerical techniques [29, 30]. They emphasized on the fuel spray atomization, which is required to enhance the in-cylinder fuel–air mixture homogeneity. They suggested that spray breakup processes become more complex due to higher ambient air density, which results in a dominant aerodynamic and viscous effects. Therefore, optimized fuel injection parameters are required to achieve a trade-off between in-cylinder conditions and fuel spray characteristics.

3 Combustion Characteristics of LTC

For any combustion mode, combustion characteristics inside the combustion chamber affect overall performance parameters of the engine such as power output, emissions. Considering the fluid mechanics, PCCI combustion can be divided into three distinct phases, namely pre-combustion, combustion, and post-combustion (Fig. 5).

(a) Pre-combustion: Flow dominates; small change in species.
(b) Combustion: Chemistry dominates; heat release occurs so rapidly and globally that turbulent mixing does not have time to be a significant influence.
(c) Post-combustion: Chemistry and turbulent mixing are likely to have some coupling, but no chemical heat release occurs (Fig. 6).

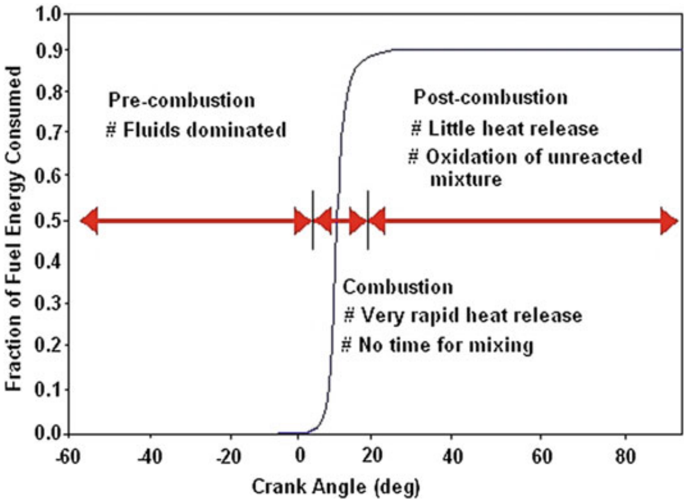
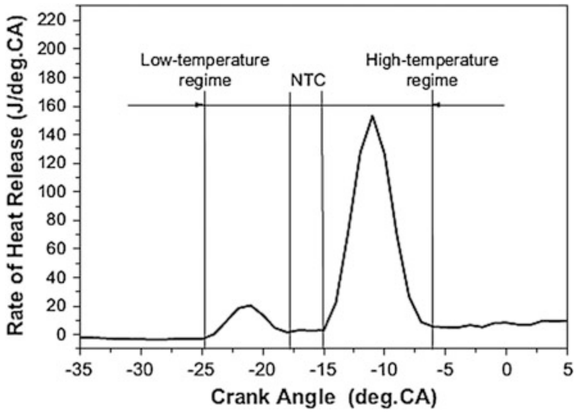


Fig. 5 Phases in LTC [31]

Fig. 6 Typical heat release curve from LTC of *n*-heptane [32, 33]



Due to small heat release, during early compression stroke, in-cylinder pressure, and temperature increases slightly. The low heat release (LHR) is associated with low-temperature chemical kinetics reactions. After LHT, the high heat release (HHR) occurs, which is attributed to negative temperature coefficient (NTC) regime [33]. NTC is the intermediate temperature region between LHR and HHR and is regarded as being the general characteristic in fully or partially premixed charge. Increasing pressure and cool flames result in lower NTC duration because these accelerate the activation of hot flame region [34].

The temperature range of the NTC area is between 700 and 950 K [35, 36]. In the NTC regime, overall reaction rate decreases with increasing in-cylinder temperature, resulting in a lower mixture reactivity. Heat release from low-temperature reactions is mainly related to the fuel and the engine operating conditions. In particular, in case of mineral diesel with a relatively high auto-ignition tendency or CN [37], LHR was observed. In case of gasoline-like fuels with low CN (high octane number), LHR was lower compared to mineral diesel like fuels under the same condition. Consequently, heat release from low-temperature reactions is too little to be observed expectedly in the heat release profile at most conditions for gasoline-like fuels [38]. In case of HCCI-DI, diffusive combustion is also noted due to directly injected mineral diesel [34]. Oxidation of hydrocarbon fuels mainly takes place via two general routes shown in Fig. 7.

Due to auto-ignition of hydrocarbons, low-temperature reactions start in the combustion chamber, which produce intermediate species (CH_2O, HO_2, and O radicals) [39]. After some time, thermal flame reactions start, followed by the main heat release. Domination of high-temperature oxidation (HTO) reactions of hydrocarbon fuel can be clearly seen in HRR of main combustion (Fig. 7). High concentrations of CH, H, and OH radicals are indicative of the dominance of high-temperature chemistry during bulk combustion [40]. These intermediate species are produced by thermal decomposition reactions, including the chain breaking of C–C bonds in the fuel. The other important concern of HCCI combustion is the steep rate of pressure rise produced by auto-ignition of nearly homogeneous fuel–air mixture. The in-cylinder gas temperatures, at which the low and high-temperature oxidation reactions start, are significantly different. The LTO and HTO start at ~790 and ~970 K, respectively, for n-pentane, which is independent

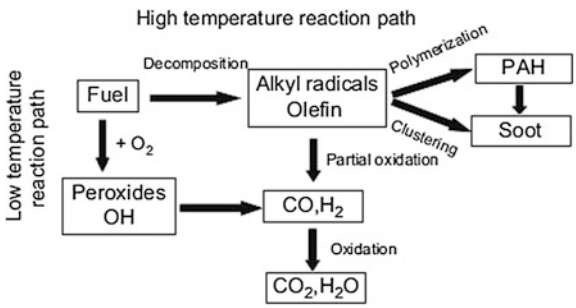


Fig. 7 Reaction pathways of hydrocarbon fuels in low- and high-temperature reactions [38]

of equivalence ratio, EGR rate and intake air temperature (T_i) [41]. Najt and Foster [42] reported that the auto-ignition of homogeneous fuel–air mixture was controlled by low-temperature (<1000 K) chemistry, and the bulk energy release was controlled by the high-temperature (>1000 K) chemistry dominated by CO oxidation.

4 Emission Characteristics of LTC

This section is divided into three subsections, namely regulated emissions, unregulated emissions, and particulate emissions.

4.1 Regulated Emissions from LTC

The basic motivation behind the development of this novel technology is its potential for significant reduction in exhaust emission as compared to conventional CI engines. In a conventional CI engine, there is a trade-off between NOx and PM. Figure 8 shows the advanced technology options, which can be used for simultaneous reduction of NOx and PM. In the CI engine, NOx is formed in the high-temperature zones under close to stoichiometric conditions and soot is formed in the fuel-rich spray core region. When engine runs at lower loads, its peak cylinder temperature is low, which reduces NOx formation but lower oxidation levels enhance soot formation. On the other hand, when engine runs at higher loads, its peak cylinder temperature is higher. This increases the NOx level but reduces the PM level due to improved oxidation at higher in-cylinder temperature. This proves that CI engine must use exhaust gas after treatment for NOx or/and PM. Although the in-cylinder average equivalence ratio is always lean, the combustion process

DEVELOPMENT SCENARIO (Heavy Duty Diesel)

	Euro 3 to Euro 4				Euro 4 to Euro 5				Euro 5 to Euro 6			
	NOx	PM	HC	CO	NOx	PM	HC	CO	NOx	PM	HC	CO
Emission reduction	30%	80%	30%	29%	43%	0	0	0	80%	50%	72%	0
Base Technology	High pressure CRDI, Fuel metering Timing retard, EGR 2017				-- 2019				-- 2021			
Engine-out emission control technology	Improved engine combustion improved engine calibration (PM) TCIC, cooled EGR				Further improved combustion & calibration, Multi-Phased injection, VGT, NOx control – cooled EGR				VGT Advance combustion – PCCI, LTC			
After treatment Technology	NOx control - SCR (open loop) PM control – DPF				NOx control - SCR (closed loop) PM control - DPF				NOx control - SCR (closed loop) PM control - DPF			

Fig. 8 Advanced technology options for emissions control [43]

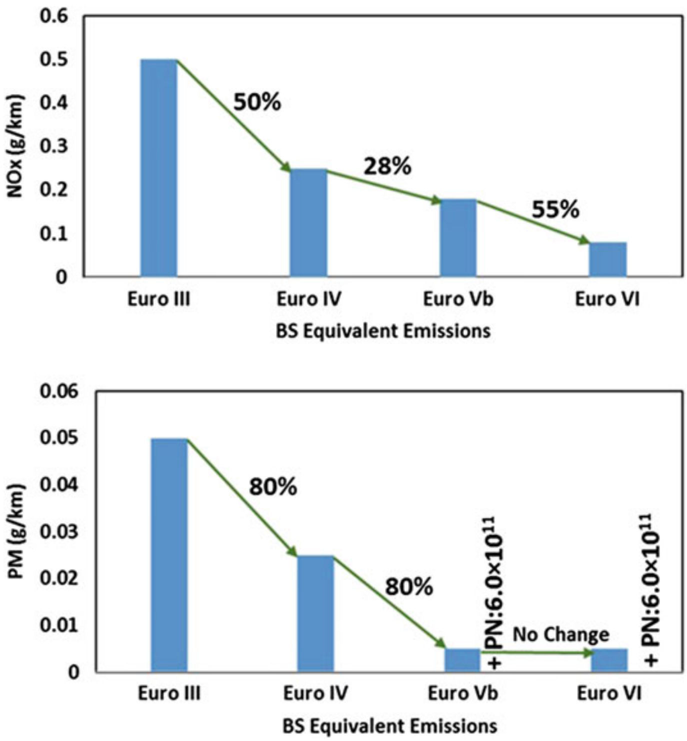


Fig. 9 Emissions from diesel passenger car [43]

does not complete in overall lean conditions. These characteristics show large potential for LTC to reduce NOx and PM levels simultaneously.

At present, a large fraction of NOx and PM concentration are originating from the heavy-duty vehicles, which use CI combustion. Figure 9 shows the emissions from light-duty vehicles and heavy-duty vehicles.

It becomes very challenging to develop a system, which can be used as an alternative to conventional CI engines. LTC technology is a potentially strong alternative to the CI combustion; however, till now, it can be used only at light engine loads.

Control of NOx levels is the most attractive aspect of LTC, and quantitatively, it reduces 90–98% NOx as compared to conventional diesel combustion [44, 45]. The basic reason of NOx formation in a standard CIDI engine is the presence of localized high-temperature regions. When the fuel is sprayed in the combustion chamber, oxygen interacts at the boundary surface between the air and the fuel droplets. This is the boundary where combustion takes place and generates high temperature locally. This provides favorable conditions for NOx formation because of availability of excess oxygen along with high temperatures in the localized regions. The underlying mechanism responsible for low NOx levels in LTC is the absence of high-temperature regions in the combustion chamber. The availability of excess oxygen is also reduced by introduction of EGR, which further reduces the NOx level during LTC. The combustion products such as CO_2 and H_2O present in EGR have a higher specific heat per unit mass compared to the fresh air, which absorbs the thermal energy and results in lower combustion temperatures, which slows down the chemical kinetics of fuel–air mixtures.

Takeda et al. [46] performed experiments in a direct injection four-stroke naturally aspirated single-cylinder engine. Three injectors (one at the center, two on the sides) were used. A dramatic reduction in NOx by early fuel injection timing due to lean fuel/air mixture was reported. Reduction in NOx emissions was accompanied by an increase in THC and CO levels due to incomplete combustion of over-lean fuel/air mixture. Gray et al. [47] reported 90–98% reduction in BSNOx under all operating conditions. Iwabuchi et al. [48] performed their experiments on PCCI combustion and reported ultra-low NOx emissions at a cost of slightly higher specific fuel consumption. Kimura et al. [49] developed a new combustion concept "Modulated Kinetics" (MK) and reported 90% reduction in NOx levels as compared to CIDI engines.

Hydrocarbon emissions from the LTC indicated incomplete combustion. For LTC, the whole cylinder volume was full of homogeneous fuel–air mixture and the combustion temperature was relatively lower, which promoted formation of HC emissions. Increasing EGR resulted in higher HC emissions primarily due to reduction of in-cylinder temperatures. The mixture trapped in crevices will be too cold to ignite during LTC. Fraction of HC emissions originating from crevice volume increases with increasing compression ratio. Due to increasing compression ratio, the amount of charge trapped in crevice volume increases; hence, HC emissions also increase.

It has been found that LTC engines usually have elevated CO emission levels, particularly at low loads. This was due to low in-cylinder temperature of LTC; hence, fuel near the cylinder walls does not burn. In the conventional CI combustion mode, a large fraction of CO is oxidized into CO_2 due to high combustion temperature. Low combustion temperature in case of LTC mode also reduces the oxidation of CO into CO_2.

4.2 Unregulated Emissions from LTC

Major pollutants emitted in HCCI combustion studies for different engine operating conditions and combustion chamber configurations are regulated emissions. The formation mechanism, sources, and harmful effects of unregulated emissions from HCCI combustion have not been fully explored and understood yet. Polycyclic aromatic hydrocarbons (PAHs) are potentially carcinogenic, while oxygenated hydrocarbons (OHC) such as aldehydes or ketones act as ozone precursors.

Many researchers have investigated the health effects and environmental effects of unregulated gaseous emission species (Table 1). Ravindra et al. [51] suggested

Table 1 Health and environmental effects of unregulated emission species [50]

Unregulated emission species	Possible health and environmental effects
Methane (CH_4)	• GHG with greenhouse index 21 times that of CO_2. • Simple asphyxiant, when inhaled • Leads to headache, dizziness, weakness, nausea, vomiting, and loss of consciousness
Normal-butane (n-C_4H_{10})	• Inhalation causes euphoria, drowsiness, narcosis, asphyxia, cardiac arrhythmia, and fluctuations in blood pressure
Isobutane (iso-C_4H_{10})	• Simple asphyxiant, when inhaled • Causes fatigue, dizziness, headache, and nervous system damage
Normal pentane (n-C_5H_{12})	• Affects central nervous system • Causes erythema, hyperemia, swelling, pigmentation, and anoxia • Burning sensation accompanied by itching and blisters
Normal octane (n-C_8H_{18})	• Giddiness, vertigo, skin redness and rashes, brain irritation, or apneic anoxia • Throat and lungs problems and headache
Ethylene (C_2H_4)	• Causes headache, drowsiness, dizziness, nausea, weakness, and unconsciousness • Causes irritation to respiratory system, alters carbohydrate metabolism • Acts as ozone formation agent
Acetylene (C_2H_2)	• Causes suffocation, dizziness, headache, unconsciousness, and nausea • Inhalation results in high blood pressure, fits and abnormal heart rhythm
Benzene (C_6H_6)	• Drowsiness, dizziness, rapid or irregular heartbeats, headache, tremors, confusion, unconsciousness, and carcinogenic • Chromosomal aberrations in human peripheral lymphocytes
Formaldehyde (HCHO)	• Irritation in eyes, nose, and throat, coughing, and skin irritation • Considered as human carcinogen, causes asthma-like respiratory problems • Affects pregnancy and reproductive system
Acetaldehyde (CH_3CHO)	• Irritation of skin, eyes, mucous membrane, throat, respiratory tract, nausea, vomiting and headache • Probable carcinogen
Formic acid (HCOOH)	• Causes teary eyes, running nose, coughing, sore throat, bronchitis, shortness of breath, pulmonary edema, liver and kidney damage • Burns tissues and membrane of the skin, and respiratory tract
Ethanol (C_2H_5OH)	• Causes unconsciousness • Affects formation of antidiuretic hormones, leading to brain disability • Affects nervous system of developing embryo and fetus
Sulfur dioxide (SO_2)	• Higher concentration (>100 ppm) causes danger to life and health • Burning sensation in nose and throat, breathing difficulties, and severe airway obstructions

that there should be appropriate regulations for PAHs. PAHs, carbonyl compounds, benzene, toluene, ethylbenzene and xylene (BTEX) are harmful for human health. These are categorized as “possible carcinogens.”

Merritt et al. [52] carried out experiments in a light-duty high-speed diesel engine using different combustion modes and compared the different regulated and unregulated exhaust species emitted from PCCI and LTC combustion modes. They observed significantly higher carbonyl compounds from all LTC modes and PCCI combustion at lean conditions compared to baseline CI combustion. However, PCCI combustion at rich conditions produced much lower carbonyl emissions than diesel operations. In PCCI combustion, PAHs were found to be substantially higher compared to baseline diesel operation. Total NPAH emissions were much higher at rich and lean LTC operation compared to baseline diesel operation. Sluder et al. [53] reported that different organic species in engine exhaust including formaldehyde, 1,3-cyclo-pentadiene, and benzene increased at different rates, when combustion mode was changed from conventional CI to a PCCI, indicating a change in fundamental combustion process. Natti et al. [54] studied the effect of operating parameters such as swirl ratios, injection pressures, injection timings, and EGR rate on regulated and unregulated emissions and their sources in a high-speed direct injection (HSDI) diesel engine operating in LTC regime using low sulfur diesel. They reported high levels of volatile organic compounds (VOCs) and PAHs together with UHC and CO emissions during the LTC regime. Similar results were also reported by Bohac et al. [55] during their investigations on speciated hydrocarbon emissions from a diesel engine and diesel oxidation catalyst (DOC) using conventional and PCCI combustion.

Ogawa and Li [56] investigated the unregulated harmful emissions from a diesel engine under different operating conditions. They reported the significance of VOCs and aldehyde compounds at low-load or idling conditions compared to total hydrocarbons (THC). Also, there was notable increase in formaldehyde and acetaldehyde emissions with low coolant temperatures at light loads. Further, they observed a drastic increase in VOCs and some low-molecular HCs with intake oxygen content lower than 14% due to EGR. They finally concluded that oxidation catalysts were effective in reducing VOC emissions including aldehydes and some unsaturated HCs. However, at overall rich fuel–air mixture condition, use of catalysts showed no significant reduction in aromatics and methane generation from ultra-high EGR LTC.

4.3 Particulate Emission Characteristics of LTC

PM emissions, especially small-sized particles emitted from engines, have harmful impact on urban air quality and human health. Studies have already shown the correlation between human health and PM emissions; therefore, environmental protection agencies are more concerned about PM emitted from IC engines [57].

Depending on size, particulates are categorized into three distinct types, namely (i) nucleation mode (<50 nm), (ii) accumulation mode (50–1000 nm), and (iii) coarse mode (>1000 nm) [58–60] (Fig. 10). Area corresponding to the curve in any size range showed the concentration of particles in that size range (Fig. 10).

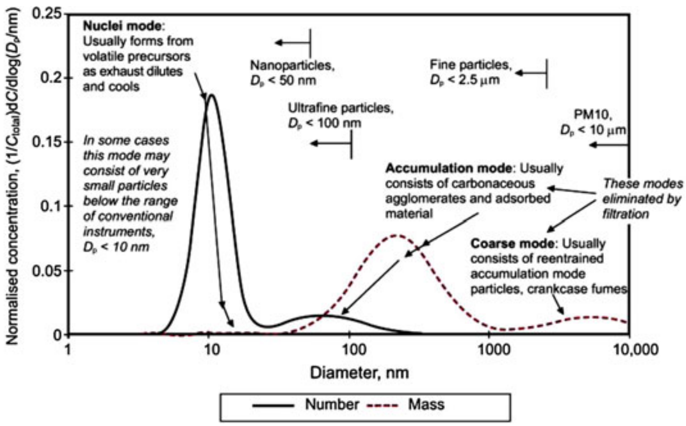


Fig. 10 Typical particle size distribution from IC engines [58]

The environmental impact of particles also depends on particle size since it influences residence time of the particulate in the atmosphere [61], optical properties of the particulate [62], particle surface area available for adsorption [63], its ability to participate in atmospheric chemistry [58], and its health impact [64].

LTC concept is known for its potential for very low NOx and PM emissions, which are usually close to negligible. However, recent investigations have shown that though the total mass of PM emitted from LTC is negligible; however, number concentration of relatively smaller particles (in the size range <100 nm mobility diameter) cannot be neglected [65–68]. This size range of particulate can be measured by modern nanoparticle sizing instruments, which are suitable for studies of LTC particulate. Singh and Agarwal [69] performed LTC experiments using different test fuels (mineral diesel, dieseline, diesohol, and diesosene) to investigate the effect of fuel volatility on particulate emission characteristics. The experiments were carried out at constant EGR and intake charge temperature at different engine loads. They observed that diesel particle number concentration was higher in ultra-fine range; however, it was slightly lower in nanoparticle range. Lower in-cylinder temperature with extremely lean operation prevented full oxidation of the boundary layer and crevice bound hydrocarbons, thereby increasing concentration of HC precursors, which enabled higher nucleation. Presence of large accumulation mode particles for all the test fuels was explained by the existence of at least some degree of diffusion burning.

Misztal et al. [66] carried out LTC experiments to investigate detailed characteristics of particulate emitted from DI-HCCI system using unleaded gasoline and NVO to capture the residuals. The main focus of this work was to explain the consequences of intake air heating on PM emissions in a LTC engine. This study suggested that by preheating the inlet air, PM emissions from LTC engines could be reduced. The effect was mainly due to higher in-cylinder temperature during the compression stroke, leading to improved fuel evaporation. Since evaporation and wall wetting phenomenon are unique to DI fueling strategies, this trend may not be expected as characteristic of all LTC engines. Another investigation by Misztal et al. [67] examined the role of injection timing in PM formation in the same engine.

Franklin [70] reported that HCCI combustion resulted in negligible accumulation mode (soot) particles; however, significant nucleation mode particles were present in the exhaust of a fully premixed HCCI engine. They suggested that volatile species present in the lubricating oil acted as precursors for these nucleation mode particles. Effect of intake air pressure on particle size–number distribution was studied by Desantes et al. [71]. They investigated the effect of engine parameters such as intake air oxygen content, intake air pressure on the engine out emissions. They observed that a slight increase in intake air pressure caused a significant reduction in CO, HC, PM mass and number emissions. Maurya et al. [68] reported the effect of port fuel injection timings on particulate emissions from a methanol-fueled HCCI engine. Effect of SoI timings on particulate emissions at different T_i for constant fuel quantity injected (25 mg/cycle) is shown in Fig. 11. They reported that the peak concentration of particles increased with increasing T_i up to 170 °C and further increase in T_i did not increase the peak concentration of particles.

Maurya et al. [68] also investigated the effect of SoI on particulate as a function of different fueling at constant T_i (Fig. 12).

Above studies suggested that in HCCI engines, significant number of particles remained in the size range <100 nm mobility diameter which cannot be neglected. Various researchers have already shown the health effects of particulate [72]; therefore, further research is needed to characterize PM formation in HCCI engines with different control strategies and new fuels.

Agarwal et al. [73] performed diesel HCCI experiments and investigated particulate emission characteristics at different λ and EGR rates. They observed that most diesel HCCI particles were ultra-fine particles. Increasing EGR rate resulted in higher particle number concentration. They also suggested that increasing EGR rate

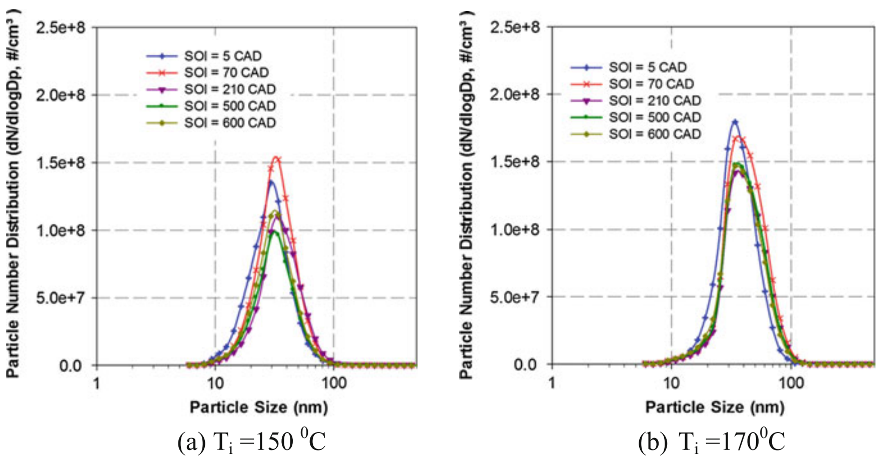


Fig. 11 Particle size–number distribution at 1500 rpm with varying SoI for different inlet air temperatures [68]

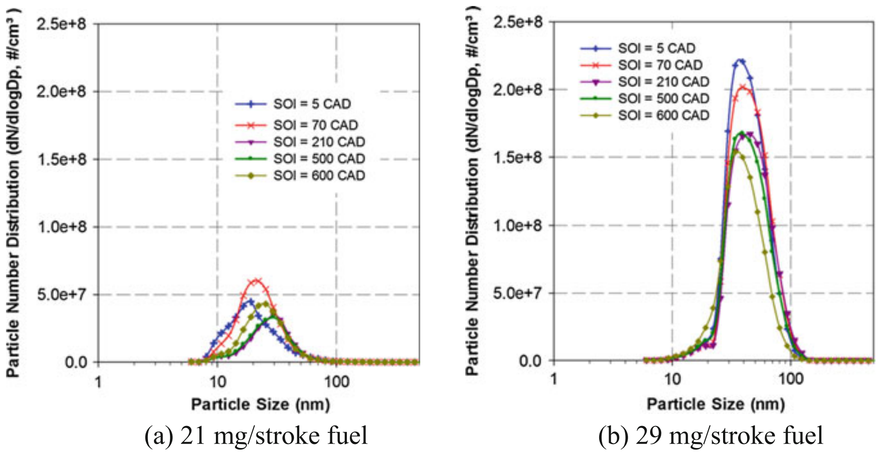


Fig. 12 Particle size–number distribution at 1500 rpm for varying SoI for different fuel injection quantities [68]

and λ resulted in higher number of accumulation mode particles, which was mainly due to higher BSOF of the PM. According to Kittleson [58], approximately 10% (w/w) of PM is inorganic, which primarily includes trace metals and ash. In a study carried out by Agarwal et al. [74], gasoline-fueled HCCI combustion was investigated. They reported that PM emissions from HCCI engine largely depended on EGR rate, λ, and inlet air temperature (T_i). In their experiment, total particle number concentration increased with increasing T_i; however, it reduced for leaner mixtures. Increasing T_i led to lower surface area of the PM, which showed lesser toxic substance carrying capacity of PM and this was further reduced by decreasing λ. Many researchers experimentally investigated the particulate emission characteristics of biodiesel-fueled engines and reported that biodiesel showed sharp reduction in particle mass emissions compared to baseline mineral diesel. Park et al. [75] investigated the nanoparticle size distribution of particulate emitted by diesel engine fueled by 20% biodiesel blend and the application of EGR reduced particle number and mass emissions from both B20 and mineral diesel by $\sim$43%.

Several researchers studied the effect of fuel injection parameters and strategies on particulate number–size distribution using a single-cylinder research engine and reported that particulate number–size distribution reduced with increasing FIP [76, 77]. Total particulate numbers emitted by Karanja biodiesel blends were lower than mineral diesel [78]. Agarwal et al. reported the lowest particulate numbers emitted by 10% Karanja biodiesel blend [78]. Dhar and Agarwal [79] reported that total particulate number concentration of B20 and B50 were lower than baseline mineral diesel. Increasing FIP resulted in relatively lesser particulate number concentration. Fuel injection timing also affected the particulate number–size distribution, and it increased at retarded main injection timings. Di et al. [80] reported that with increasing oxygen content of diglyme (DGM) blended with ULSD, smoke opacity, particulate mass emission, and geometric mean diameter of particles reduced.

Previous studies reported that bioavailable, soluble, and particle-bound trace metals can harm the human health [81, 82]. Fine particle-associated trace metals (such as vanadium and aluminum) can affect iron (Fe) status of alveolar macrophage and alter the pulmonary immune competence of exposed hosts [83]. Nanoparticles (Dp < 50 nm) as carrier of heavy metals (such as cobalt and manganese) enhance the formation of reactive oxygen species (ROS) by a factor of eight compared to pure aqueous solution of the same metals [84]. Certain trace metals in the exhaust are of interest for their relevance to potential health effects, such as lead (Pb), manganese (Mn), nickel (Ni), arsenic (As), cadmium (Cd), and chromium (Cr) and have been classified by USEPA as mobile source air toxics (MSAT). Hu et al. [85] performed particulate bound trace metal analysis from a heavy-duty diesel engine equipped with emission reduction devices. They divided the trace metals into several categories, namely oil additives metals (Ca and Zn), Fe, Cu, platinum group metals (PGE), (V and Ti), MSAT metals (As, Cr, Pb, Mn, and Ni), and other metals. Valavanidis et al. [86] reported that deposition of these trace metals, which are originally from diesel particulate, in the lower airway of the human respiratory system could generate hydrogen radicals and then trigger production of oxygen free radicals, which can potentially cause both acute and chronic lung injuries. Agarwal et al. [73, 74] performed HCCI experiments to investigate particulate bound trace metal analysis from mineral diesel and gasoline-fueled HCCI engines. They reported that the trace metals detected were comparatively lower in PM emitted from diesel-fueled HCCI engine. Trace metal concentration and BSOF increased with increasing EGR rate. They reported that BSOF from gasoline HCCI was negligible; therefore, gasoline could be mixed with mineral diesel to reduce BSOF.

5 LTC Control Strategies

Stable and efficient operation of LTC engines need precisely controlled combustion timings. One of the main challenges in LTC engines is the combustion control since onset of combustion depends on in-cylinder temperature, pressure, and fuel–air mixing inside the combustion chamber, and there is no direct control for initiating the combustion. When combustion control is not fast enough, too advanced or too retarded combustion can take place in the engine. Too advanced combustion can yield unacceptable RoPR or unacceptable peak cylinder pressure, thus causing excessive noise, which may potentially damage the engine. Additionally, NOx emissions from the engine tend to increase with ignition advance [87]. Another driver for gaining an effective closed-loop combustion control is the fact that late combustion timing leads to incomplete combustion and increasing emissions of CO and HC. The worst case of “too late combustion” leads to a complete misfire, which if repeated, can cause the engine to stall.

Several means to actuate combustion phasing for LTC engine control have been suggested by various researchers [90–92] such as dual fuel, variable valve timing

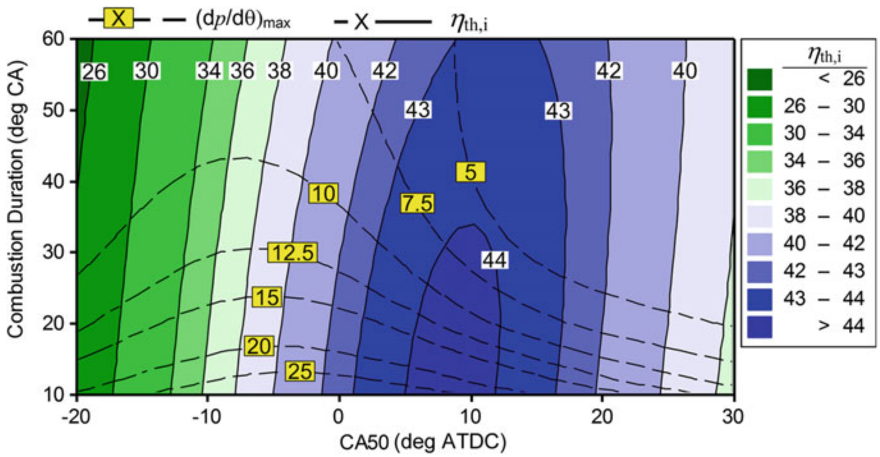


Fig. 13 Thermal efficiency variation with combustion phasing [18]

(VVT), variable compression ratio (VCR), and active thermal management. Riseberg et al. [93] investigated influence of NO on combustion phasing in a single-cylinder LTC engine. Isooctane/*n*-heptane blend (primary reference fuels; PRF), toluene/*n*-heptane mixture (Tertiary reference fuels; TRF), and full boiling range gasoline were tested at two different intake charge temperatures. They reported that NO concentration in the air significantly affected combustion phasing of the LTC engine using different test fuels. They explained this behavior using chemical kinetics theory. Asad et al. [18] showed a relationship between combustion duration, combustion phasing and indicated thermal efficiency (ITE). They stated that combustion phasing for the highest ITE lies in a small crank angle window between 7° and 12° aTDC. Any deviation (advanced or retarded combustion) resulted in a rapid drop in thermal efficiency (Fig. 13).

Following subsections describe different control strategies and their status in LTC engines.

5.1 Dual-Fuel Control Strategy

Dual-fuel combustion is commonly referred to as RCCI combustion and has been demonstrated extensively for mineral diesel–gasoline [27] and mineral diesel–ethanol blends [94]. In dual-fuel-type controls, two fuels with different auto-ignition properties are used. The system would have a main fuel with a high octane number and a secondary fuel with low octane number. Different auto-ignition properties of dual-fuel systems are used to control the combustion phasing in LTC as blending two fuels in different proportions changes their auto-ignition properties. Use of commercial fuels or mixtures of single-component and commercial fuels; PRFs have been investigated in several studies [95–97]. For better understanding of the dual-fuel mode operation of CI engines, Mancaruso and Vaglieco [98] performed PCCI experiments using ethanol and mineral diesel. In these experiments, ethanol was injected in the intake manifold; however, mineral diesel was injected directly into the cylinder. The experiments were performed at different premixed fuel ratios, and it was reported that the LTC governing parameter (OH^- radicals) was significantly controlled by premixed fuel ratio. Ma et al. [97] investigated the effects of different diesel injection strategies on combustion, emissions, and fuel economy of a modified single-cylinder diesel engine fueled by gasoline/mineral diesel dual fuel. This gasoline/diesel dual-fuel combustion mode proposes port fuel injection of gasoline and direct injection of mineral diesel with rapid in-cylinder fuel blending.

5.2 Variable Compression Ratio (VCR) Strategy

VCR can be used to control combustion phasing by increasing the compression ratio and charge temperature after the compression. VCR can be achieved by several different methods. Lack of control over an individual cylinder, which is necessary to obtain good combustion phasing control, is the main drawback of the VCR system. Cost and complexity of VCR systems are other major obstacles for their application in LTC engines. Asad et al. [18] carried out LTC experiments at different CR and reported that a lower CR improves combustion phasing, reduces maximum RoPR and peak cylinder pressure; therefore, LTC operating range can be increased (Fig. 14). A CR of 14–16 with advanced turbo-charging, VVT, and improved cylinder charge cooling may provide a realistic compromise between high efficiency CI combustion and clean diesel LTC.

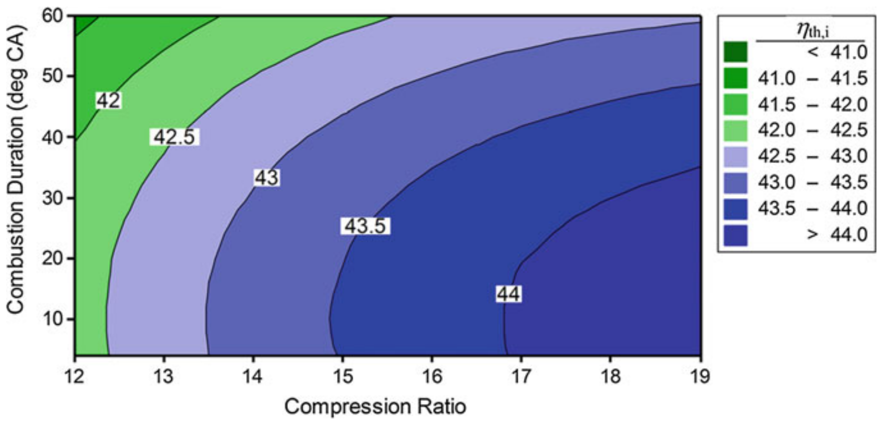


Fig. 14 ITE variations with the compression ratio [18]

5.3 Exhaust Gas Recirculation Strategy

EGR is essential to achieve simultaneous reduction in soot and NOx emissions from LTC without prohibitively high fuel consumption penalties due to poor combustion phasing. Tuning the amount of EGR is the most commonly used technique to adjust the in-cylinder temperature, which controls the SoC. Initially, Thring [99] achieved LTC by varying the inlet air temperature and EGR fraction over a range of equivalence ratios. High heat capacity constituents of EGR are CO_2, H_2O, N_2, O_2, CO, PM, HC, NOx, and other intermediate species of combustion reactions which control the LTC [100–102]. These constituents showed following four effects on the combustion and emissions. First was the preheating effect, in which the inlet charge temperature increased when hot EGR was mixed with the fuel–air mixture. Second was the dilution effect, where by the introduction of EGR led to substantial reduction in oxygen concentration. Third was the heat capacity effect, in which total heat capacity of the mixture of EGR, air, and fuel would be higher owing to higher heat capacity of CO_2 and water vapor. This would lead to a reduction in gas temperature at the end of the compression stroke. Fourth and final was the chemical effect, where unburnt combustion products in the EGR would take part in chemical reactions. HC, CO, CO_2, NO, H_2O, etc., in the EGR take part in chemical reactions and lead to a moderate effect on the reaction rates. Integrating all these effects, SoC during the LTC and combustion duration of overall HCCI-DI combustion can be controlled by regulating the EGR quantity. Therefore, EGR makes it possible to suppress the excessively advanced SoC by low-temperature reactions in the LTC phase. This excessively advanced and rapid combustion causes knocking, which limits the operating range of LTC [103]. EGR can be classified as internal EGR and external EGR. Internal EGR rate can be controlled by changing the valve overlap period and the external EGR rate can be adjusted by the combined effect of the exhaust backpressure and EGR. For high-octane fuels such as gasoline, NVO is recognized as one of the possible implementation strategies for LTC. The effect of inlet air temperature via NVO is insignificant when the engine runs well within the LTC operating range [104]. Cooled external EGR reduces the fuel–air mixture temperature in the compression stroke and hence delays the SoC of high cetane fuels such as biodiesel.

EGR stratification was a novel technique demonstrated by André et al. [105], which could be used for the controlling rapid HRR and combustion noise in the LTC engines thus extending the operating range of PCCI combustion engines. The exhaust gas was inducted into the combustion chamber via a helical port and induction of fresh air was through the tangential port. Thus, a delay in combustion, in the stratified case, was caused by the stratified exhaust gas present close to the TDC. This exhaust gas was present in the fuel-rich zone and caused delay in combustion, hence gaining a superior control over the combustion phasing. Even though this technique offered benefits of combustion control, it still needs to be explored in greater detail before its practical implementation because of its high dependence on various fuel injection parameters. Charge dilution using either EGR or non-reacting species such as CO_2 and N_2 in order to achieve LTC has been extensively analyzed. Kook et al. [106] and Kanda et al. [107] carried out experiments using various dilution rates to attain PCCI combustion. They observed a direct correlation of NOx and soot luminosity with adiabatic flame temperature and reported that adiabatic flame temperature decreased with addition of EGR. The high oxidation rates at higher peak temperatures led to reduction in CO emissions. However, the researchers also pointed out the need to control dilution ratios because maximum fuel conversion efficiency was obtained at moderate charge dilution levels. Over-dilution leads to poor trade-off between work conversion efficiency and combustion efficiency, thus reducing fuel conversion efficiency. Another advantage of charge dilution is increased ignition delay, which improves IMEP and COV. Asad et al. [18] performed LTC experiments using different EGR rates to postpone SoC by increasing the ignition delay and to reduce the severity of high RoPR. They stated that EGR was effective in delaying combustion phasing toward higher thermal efficiency window by withholding the cylinder charge from early ignition. Figure 15 shows that increasing EGR rate results in stable combustion. It was concluded that combustion efficiency reduced with increasing EGR, which was

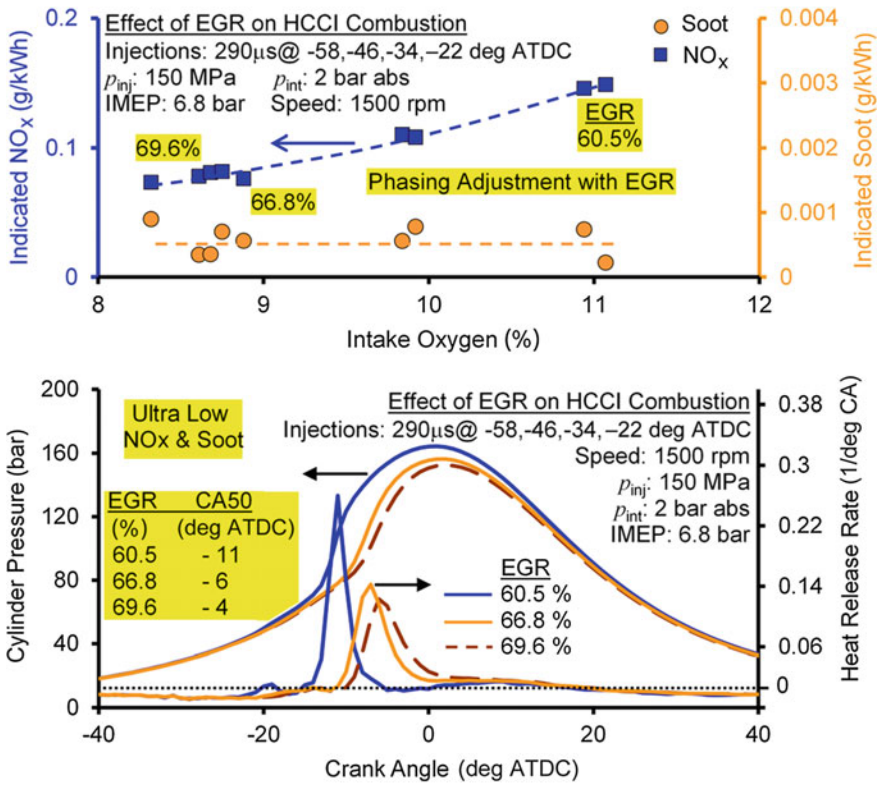


Fig. 15 Effect of EGR on HCCI combustion and emissions [18]

compensated by improvement in combustion phasing. This trade-off between combustion efficiency and emissions showed the importance of EGR in LTC engines.

5.4 Combustion Control by Fuel Additives

Fuel composition has little influence on reaction rate and reaction duration once reactions have been initiated; however, it defines the auto-ignition temperature, and hence can control SoC of LTC engines. Fuel composition mainly affects LTR, which, in turn, affects the start of main reactions. Main fuel parameters influencing the physical delay part of the ignition delay (ID) are density, heating value, and latent heat of vaporization. The chemical delay part of ID is influenced by auto-ignition and distillation properties of the fuel. An increase of fuel density, volatilization difficulties, and higher latent heat of vaporization (due to decreasing fuel–air mixture temperature), all result in delayed combustion start/ignition. Common ways to classify fuels are according to the ease of auto-ignition, which is defined as CN and resistance to auto-ignition, which is defined by ON. A high CN represents less resistance to auto-ignition, which includes straight chain paraffin (iso-cetane defines CN = 100). A high octane number represents the resistance against auto-ignition, which includes branched chain paraffins (isooctane defines ON = 100). Gasoline has a high octane number and therefore has little or no low-temperature reactions; and the combustion initiation takes place at around 950 K. Diesel-like fuels show significant low-temperature reactions and have initiation temperatures in the range of 750 K [108].

Starck et al. [109] carried out experiments in quest of impact of fuel properties on LTC and found lower CN fuels to be superior LTC fuels. They reported that a lower CN fuel and an optimum combustion speed could improve the LTC operation range because lower combustion speed results in more time for homogenization, resulting in superior LTC. Tanaka et al. [110] used a Rapid Compression Machine (RCM) to study the effects of fuel structure and additives on homogeneous charge compression ignition (HCCI) of pure hydrocarbon fuels and mixtures. They investigated the effect of fuel additives on LTC performance and found that fuels with saturated compounds lead to two-stage combustion and those with unsaturated compounds led to single-stage combustion. Higher octane number results in higher ignition delay and a lower burn rate.

5.5 LTC Control by Fuel Injection Strategy

Early injection led to impingement of mineral diesel on the cylinder walls, particularly at high BMEPs [111–113]. Single-injection LTC is applicable to limiting conditions, where tighter controls on operating conditions are required compared to conventional CI combustion. Issues of LTC such as high HRR and uncontrolled combustion can be resolved by using split fuel injection strategy. Kook and Bae [114] used split injection in order to promote low-temperature ignition and to gain better combustion control. Major quantity of fuel was injected early in the compression stroke (100° bTDC) to prepare premixed charge, and a pilot quantity was injected near TDC to control SoC. This resulted in better combustion characteristics, precise control of SoC, and higher BMEP. Results clearly showed that NOx emissions from PCCI combustion were much lower compared to CI combustion and advanced pilot injection (from 100° BTDC to 150° BTDC) showed further reduction in NOx.

The effect of split injection strategy on emission formation in a PCCI diesel engine was investigated by Horibe et al. [115] and Torregrosa et al. [116]. The researchers realized that higher thermal efficiency and lower NOx emissions at moderate loads could be achieved by single-injection strategy; however, they experienced problem of very high RoPR. In case of split injection strategy, a small quantity of pilot injection helped in suppressing higher RoPR. The application of early pilot injection resulted in a significant improvement in thermal efficiency and reduction in engine noise and emissions by optimizing SoI timings and EGR rate. They later dealt mainly with effect of pilot injection on engine noise and performance. Engine noise remained one of the major factors governing combustion and performance characteristics. They reported a reduction in BMEP with an increase in pilot quantity above 40%. Further, relatively higher engine noise was observed for almost all early single-injection timings, mainly due to very high RoPR. The inclusion of pilot injection proved to be very effective in reducing noise, but it also led to reduction in BMEP. Neely et al. [117] investigated the effect of number of pilot injections (up to 3) to achieve PCCI combustion in order to reduce NOx in light-duty and heavy-duty vehicles. They stated that an early single pilot injection was effective for ~14% NOx reduction, but it was at the expense of higher CO and BSFC. However, CO and BSFC penalty significantly reduced along with NOx by employing multiple pilot injections at lower loads. This was mainly due to superior fuel–air mixing. For heavy-duty vehicles, multiple pilot injections proved to be ineffective in reducing NOx compared to single pilot injection. In addition, multiple pilot injections also led to higher HC and CO emissions. Asad et al. [18] performed HCCI experiments and suggested that optimized SoI of the multiple injections could assist in preparation of a near-homogeneous charge that resulted in near-zero soot emissions. Yehliu [118] observed slightly higher NOx emissions from B100 compared to mineral diesel in single-injection mode. Split injection reduced NOx emissions from both fuels, but higher reduction was observed in case of B100 fueled engine, which showed 18% lower NOx emission compared to mineral diesel.

6 Path Forward for LTC

Recent research activities related to LTC have significantly influenced the global perspective about it because of development of different control mechanisms and new strategies. Hence, prior to commercial production of LTC engines for heavy-duty and light-duty applications, tremendous R&D effort is required. Some of the possible areas for future research for improving this LTC concept are as follows:

(i) Development of control methods for maintaining ignition timing at different engine loads and speeds is the first challenge, which needs to be resolved. Optimization of ignition timing is quite important for LTC engines compared to conventional engines because LTC engines have no direct control over ignition timing such as by using spark or fuel injection.
(ii) Methodology development to slowdown the rate of combustion in LTC engines at high engine loads is the next challenge, which needs to be resolved to prevent excessive noise and engine damage.
(iii) LTC engines emit very low NOx at low-to-medium engine loads; therefore, no emission control is required; however, at higher engine loads, NOx emission become too high, which required emission control equipment. Therefore, low-cost emission control equipment needs to be developed to control NOx emissions at higher engine loads.
(iv) For the development of production grade LTC engines, closed-loop control of different operating parameters needs to developed. Control mechanisms, sensors, and appropriate control algorithms are key enabling technologies for practical LTC engines.
(v) In conventional SI or CI engines, small differences in intake and exhaust flow between cylinders do not affect engine combustion and performance characteristics significantly. However, LTC engines are very sensitive to small changes in compressed-charge temperature, which leads to significant cylinder-to-cylinder variations in combustion timings. Therefore, research is required for development of intake and exhaust manifold designs for multi-cylinder engines so that difference in the inlet and exhaust flows between different cylinders can be minimized.

7 Conclusions

LTC is a combustion concept, which has evolved over decades in response to the need for improved thermal efficiency of gasoline-fueled engines and ultra-low NOx and soot emissions of diesel-fueled engines. Although remarkable progress has been made in LTC technology, large-scale production of LTC engines for commercial applications has encountered several challenges. Limited operating range, lack of direct control on SoC, homogeneous fuel–air mixture preparation and higher HC and CO emissions are the main obstacles faced by LTC technology's adaptation commercially. Several techniques have been developed for low-load application of LTC technology in heavy-duty engines; however, full load application even in light-duty engines has not been demonstrated till now. To control the SoC, some advanced concepts such as spark assisted LTC and laser assisted LTC have also been investigated, in which combustion events were precisely controlled using a spark plug or a laser. Different derivatives of LTC such as PCCI, HCCI were thoroughly investigated, and suitability of each derivative has been defined for a particular operating range. These derivatives of LTC can be achieved by varying engine operating and control parameters. Fuel flexibility is the other important feature of LTC. Fuel properties significantly affect chemical kinetics, which has a dominating role in LTC. In LTC, auto-ignition was controlled by modifications of the fuel properties in order to make it more chemically reactive by adding an ignition promoter or inhibitor. In all derivatives of LTC, control is the most critical issue, which was resolved using various techniques such as dual-fuel injection, VCR, VVT, EGR. However, these techniques have their own merits and challenges. Based on these research directions, several researchers proposed use of dual combustion system, which seems to be an effective solution for commercializing LTC technology.

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