Chapter 10
Closure

Abstract Research towards the development of internal combustion engine having high fuel conversion efficiency and ultralow emissions is driven by stringent emission legislations, degradation of ambient environmental conditions, depletion of fossil resources, energy security and global warming. The low temperature combustion (LTC) engines are one of the potential options to fulfil the objective of high fuel conversion efficiency along with ultralow emissions of NOx and particulate matter. The LTC engines are radically different from conventional spark ignition and compression ignition engines. Research has been conducted on various LTC concepts using conventional and alternative fuels on both light-duty (LD) and heavy-duty (HD) engines. Performance, combustion and emissions characteristics along with different control strategies of LTC engines are discussed in previous chapters of the present book. Summary of main findings regarding performance, combustion and emissions characteristics of various LTC strategies is presented in this chapter, and recommendations for further work are also outlined.

Keywords LTC • HCCI • PPC • RCCI • Dual fuel • Combustion control • Engine • Gasoline • Diesel • Stratification • Emissions • IMEP • Ignition • SI • CI

10.1 Summary

The internal combustion engines, fuelled mostly by petroleum-derived liquid fuels, have been the main source of transport power over the past century and are likely to remain so in the foreseeable future, though alternatives such as electrification of transport play a role. However, combustion engines are continuously changing, primarily driven by the need to be more efficient and meet the stringent emission legislations along with satisfying the customer demands such as driveability at an affordable cost. These requirements stimulate new developments in both conventional and alternative engines as well as fuels. To address the challenges in fuels and combustion engines, there are four possible approaches, i.e. (1) improvement of conventional engines, (2) improvement of conventional fuels, (3) development of alternative engine and (4) utilization of alternative fuels, and their combinations. Conventional and alternative fuels are continuously evolving to minimize the local

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and global environmental impact in their manufacturing process and in their use in combustion engines. Premixed LTC is an alternative combustion concept for reciprocating internal combustion engines, which offers prominent benefits in terms of simultaneous reduction of both NO_x and particulate emissions to ultralow levels along with reduction in fuel consumption.

Among the LTC strategies, homogeneous charge compression ignition (HCCI) concept is evolved as third major engine combustion modes in addition to the conventional spark ignition (SI) and compression ignition (CI) modes of engine combustion. The HCCI combustion mode used well-mixed fuel–air mixture, and hence, simultaneous autoignition of entire mixture in the cylinder leads to very high-pressure rise rate and combustion noise. To control the combustion rate, HCCI engines are operated on diluted lean fuel–air mixture, which results into lower engine operating range. Fuel and thermal stratification in the combustion chamber is found beneficial in reduction of heat release rate by sequential autoignition starting from most favourable conditions (locally richer mixture/hotter region). Fuel stratification in the cylinder can be easily controlled by direct fuel injection system. Therefore, different levels of fuel stratification are used to increase the load range of HCCI combustion while keeping its benefit of ultralow NO_x and soot emissions. All the LTC strategies using gasoline direct injection are grouped in the three main categories based on stratification of charge: (1) partial fuel stratification (PFS), (2) moderate fuel stratification (MFS) and (3) heavy fuel stratification (HFS). Partially premixed combustion (PPC) in HFS regime is able to achieve the engine load similar to CI engines using gasoline-like fuels. To control the high combustion rate, a very high amount (~50% or more) of exhaust gas reticulation (EGR) is used. To reduce the requirement of EGR in PPC strategy, dual fuel reactivity controlled compression ignition (RCCI) strategy is developed, where fuel stratification as well as reactivity stratification is used to control the combustion rate. Presently, PPC and RCCI are the most widely investigated LTC strategies for automotive engine application. To further improve the RCCI engine efficiency and combustion control, direct injection dual fuel stratification (DDFS) strategy is demonstrated, where both low and high reactivity fuels are directly injected into the engine cylinder.

Fuel properties and composition play an important role in all the physical and chemical processes involved in LTC process. Autoignition chemistry depends on the fuel composition and mixture quality (equivalence ratio and homogeneity). Creation of premixed charge in the combustion chamber is the key feature of LTC engines. Quality of fuel–air mixture governs the combustion process and its rate. Formation of premixed charge is required prior to the start of combustion in LTC engine. Depending on LTC strategy, different qualities of premixed charge (degree of homogeneity) are required for higher thermal efficiency and to control the combustion rate. The premixed charge can be created by injecting fuel, outside the engine cylinder (external charge preparation) or inside the cylinder (internal charge preparation), depending on fuel properties and combustion strategy. Typically, in well-mixed HCCI combustion, external charge preparation is used, and in other LTC strategies, internal charge preparation is also used. To enable and control the LTC engines, two main approaches are used: (1) altering pressure–temperature history of the charge in the cylinder and (2) altering fuel reactivity of charge. Temperature history of the charge in the cylinder can be altered by several parameters such as intake conditions (temperature and pressure), EGR, variable valve timings (VVT), variable compression ratio (VCR), water injection, supercharging and fuel injection strategies. Fuel reactivity of charge in the cylinder can be altered by various parameters such as equivalence ratio (Φ), fuel stratification, fuel additives, ozone additions and dual fuel.

The LTC operating range is typically constrained by several limiting factors such as combustion noise, combustion instability, maximum cylinder pressure, oxygen availability, excessive reactivity and emission limits. Typically, ringing intensity (RI) is used to define the high load limit. Acceptable RI value mostly used is below 5 $\mathrm{MW/m^2}$ in LTC engines. The coefficient of variation in indicated mean effective pressure (IMEP) is typically used to define the lower engine operating range with limiting value of 3.5%. Using these operating limits, maximum IMEP achieved is typically around 5 bar in naturally aspirated HCCI engine using well-mixed fuel–air mixture. In HCCI operating range, the IMEP mainly depends on the amount of energy input in the cylinder or maximum equivalence ratio of engine operation. It is demonstrated that high octane fuels (gasoline-like fuels) can be best utilized in compression ignition engines. The maximum engine load up to 20 bar IMEP in well-mixed HCCI combustion and 25 bar IMEP with PPC combustion is achieved while maintaining the emission level of NOx and soot below EURO VI limits. This engine loads achieved in HCCI and PPC engines are comparable to the conventional diesel engines. However, higher boost pressure up to 3.6 bar is used to achieve this engine load, and this level of boost requirement cannot be achieved by present turbocharger used in vehicles. It is demonstrated that partial fuel stratification can reduce the requirement of boost pressure for the same maximum engine load operation in well-mixed HCCI combustion.

The HCCI engine has higher thermodynamic efficiency in comparison to the conventional SI engine. Higher thermal efficiency is one of the main benefits of LTC combustion engines. Gross indicated thermal efficiency up to 57% in PPC mode using gasoline-like fuels and up to 58% in dual fuel RCCI engine is demonstrated (Chap. 7). Higher thermal efficiency leads to reduction in specific fuel consumption of the engine and saves the fuel. Thus, fuel economy of vehicles with LTC engine powertrain is better than conventional engines.

Depending on the fuel used in LTC engines, single-stage and two-stage heat release characteristics are observed during combustion. In single-stage heat release fuel, only high temperature heat release (HTHR) is observed, while in two-stage heat release fuels, low temperature heat release (LTHR) is also observed along with HTHR. Fuels exhibiting LTHR typically require less intake temperature for enabling the autoignition in the cylinder. However, LTHR is affected by intake pressure and temperature, EGR, and engine speed in addition to fuel type. Some fuels like gasoline exhibit LTHR or intermediate temperature heat release (ITHR) at higher intake (boost) pressure, while in naturally aspirated conditions, only single-stage HTHR is observed. Typically, LTC engine has very high heat release rate (HRR) due to premixed combustion, and it can be controlled by using high amount of EGR, dilution and stratification. Typically, EGR has higher specific heat that lowers the combustion temperature. Lower combustion temperature due to EGR retards the combustion phasing which lowers the peak heat release rate. However, trace species present in EGR such as NO can also advance the start of combustion due to participation of trace species of EGR in autoignition reactions. In LTC engines, combustion instability (cycle-to-cycle variations) can be very high in some of the operating conditions particularly at retarded combustion phasing and leaner mixture operation at lower engine loads. Cyclic variations in LTC combustion can be random normal variations as well as deterministic or periodic patterns.

Due to its nature, premixed LTC strategy has the potential to generate very low levels of NO_x and soot emissions. Typically, all the LTC strategies are able to achieve NO_x and PM emissions below EURO VI norms in LTC operating range without any exhaust after-treatment system. The ultralow NO_x and PM emissions are the most beneficial part in LTC engines. However, LTC engines generally have very high amount of unburned hydrocarbon (HC) and carbon mono-oxide (CO) emissions, which can be easily handled by oxidation catalyst. For effective conversion efficiency, oxidation catalyst requires higher operating temperature than its light-off temperature. However, LTC engines have very low exhaust gas temperatures particularly at lower engine loads, where HC and CO emissions are also higher. This is one of the challenges to be tackled in LTC engines. Particulate matter emitted from LTC engines is generally lower on mass basis; however particle number emissions are significantly emitted. Most of the particles emitted from the LTC engines are of volatile nature depending upon the LTC strategy and fuel used.

The LTC engines, particularly HCCI combustion, need closed-loop combustion control, and map-based engine operation is not possible as some of the engine operating conditions are unstable (Chap. 9). Typically, cylinder pressure sensor and ion current sensors are used for sensing of combustion phasing of LTC engine for closed-loop control. The HCCI combustion control variables are divided into four major groups, namely, (1) control of combustion phasing, (2) control of engine load, (3) control of exhaust treatment efficiency (exhaust gas temperature) and (4) control of HCCI dynamics for combustion mode switching between HCCI and conventional SI or CI modes. Closed-loop control of combustion phasing and engine load is demonstrated using manually tuned controller and several model-based controllers in HCCI, PPC and RCCI engines. Advanced controllers such as adaptive controller and model-based predictive controller are more effective in controlling combustion phasing in a wide range of operating conditions of LTC engines.

10.2 Future Directions

Research activities from the last few decades lead to the development of different LTC strategies such as HCCI, PPC and RCCI combustion modes that demonstrated higher fuel conversion efficiency as well as very low NOx and PM emissions. Several technical challenges are still to be resolved before mass commercialization of high-efficiency, emissions-compliant LTC engine-based powertrains in heavy- and light-duty vehicles. Research and development effort is required in the following direction for improving the present LTC mode engines.

1. *Load range extension*: Engine operating range of LTC combustion strategies is typically lower than conventional engines. However, PPC combustion has demonstrated IMEP up to 25 bar at fixed engine speed with a very high boost pressure (~3.6 bar). This engine load is similar to the engine load possibly achieved by CI engines; however required boost pressure level is very high and it cannot be achieved by turbocharger used in present CI engines. Research is required to reduce the boost to engine load ratio in LTC engines by optimizing fuel injection strategies, engine operating conditions (EGR, intake temperature, compression ratio) and fuel. Several renewable fuels are being developed that have potential for load range extension of LTC engines in combination with optimized engine operating strategies. Fundamental combustion studies (modelling and optical engine experiments) need to be conducted for different LTC strategies (RCCI, DDFS, PPC) with alternative and conventional fuels to better understand the combustion process, which helps in operating range extension. Comprehensive study of combustion noise level and ringing is also required, which limits the load range of LTC engines.
2. *Optimization of air handling system*: The LTC strategies such as HCCI and RCCI are highly sensitive to initial intake conditions, which are strongly affected by the gas exchange process. Air handling systems including EGR, turbocharger/supercharger performance and valve timing affect the gas exchange process of engine. Therefore, optimization of air handling system is required for different LTC strategies, especially determination of system parameters and air handling configurations for high engine load operations. Redesign of manifold and variable valve actuation (VVA) strategies can be investigated for reducing pumping and friction work during engine operation. To improve the turbocharger efficiency, a newly proposed strategy called active control turbocharging [1] could be explored for LTC engine applications. Utilization of mixed flow turbine is another strategy to maximize the work extraction and increase the turbocharger efficiency [2], and it may be used for LTC engine turbocharging. Optimization and closed-loop control of fuel and air handling system can lead to optimal combustion characteristics of LTC engines.
3. *Premixed charge optimization*: Premixed charge preparation plays an important role in LTC strategies. Fuel and reactivity distribution in the cylinder determines the combustion characteristics. The optimization of injection strategies (number of injection, fuel injection timings, fuel injection pressure, injector cone angle

and nozzle geometry), swirl and combustion chamber geometry is required for desired combustion characteristics. In more complex strategies like DDFS, optimization of the injection strategy of both high and low reactivity fuels along with other parameters involved in charge preparation could lead to improved engine efficiency and reduced emissions. Flow characteristics such as swirl affect the mixing process of air and fuel. Therefore, manifold design and manifold wave dynamics can also affect the charge preparation, and hence, it needs to be optimally designed for particular LTC strategy.

4. *Cold start and transient operation control*: The LTC engines, particularly HCCI combustion, are very sensitive to initial charge conditions, and minor variations can significantly affect the combustion phasing. Additionally, intake temperature required for autoignition varies with engine operating conditions and fuel properties. Under cold start conditions, it is difficult to autoignite the charge due to lower compressed gas temperature achieved in the engine cylinder during cold start condition. One possible suggestion to address the cold start issue is to start the engine in conventional mode and then shift to LTC mode. In this case, combustion mode transition needs to be controlled efficiently. Most of the LTC studies are conducted on steady-state operation. Automotive engine needs to operate on frequent transition in a driving cycle. Therefore, transient characteristics need to be investigated, and the required control strategies for transient engine operation needs to be developed for LTC engines.
5. *Particle emission characterization*: Although LTC engines have very low particulate matter on mass basis, the particle number emissions are significant. Particle number distribution in various LTC strategies including HCCI, PPC and RCCI combustion is investigated with certain range of operating conditions. Particles emitted from LTC modes have large fraction of volatile particles. Volatile and non-volatile particle characterization from different LTC strategies with different fuels over a wide range of engine operating conditions needs to be conducted. Fuel composition and physical properties have great impact on particulate formation, and hence, investigation is required for particulate emission with oxygenated fuels and fuels with short carbon chains (low C/H ratio), which are potential candidate for low particulate emissions. Air–fuel mixing affects the soot formation, and hence, soot reduction can be improved further by enhancing the fuel-wall interactions in the cylinder. To find a good combination of turbulence and injection process (for a specific fuel) for particle emission in LTC engine, several parameters such as swirl ratio, injection spray angle, piston geometry and injector parameters should be investigated. Particles emission from LTC engines needs further investigation including particle chemical composition, optical properties and micro- and nanostructure using different fuels. Study of other unregulated species (such as PAH, carbonyl compounds, etc.) and their toxicity can also be investigated on LTC engines using conventional and alternative fuels.
6. *Exhaust after-treatment development*: In LTC engines, NO_x and soot emissions are controlled in cylinder, and no exhaust after-treatment system is required to meet the emission legislation for NO_x and PM. However, HC and CO emissions

are very high in LTC engines. To maintain acceptable level of emissions, development of suitable exhaust after-treatment along with appropriate control strategy is required. To mitigate the HC and CO emissions, typically oxidation catalyst is used, which works efficiently above its light-off temperature. Exhaust gas temperature in LTC engines is very low at some of the operating conditions. This makes the emission control problem further difficult. Two possible approaches can be used to handle this issue. First, exhaust gas temperature control system can be developed to maintain the required exhaust gas temperature in the exhaust line. Second option is to develop the catalyst that can work efficiently at lower exhaust temperatures achieved in LTC engines.

7. *Closed-loop control development*: Closed-loop control is required in HCCI engines particularly at high engine load operation. Closed-loop control of combustion phasing and engine load is demonstrated in HCCI, PPC and RCCI combustion strategies using different actuators (Chap. 9). Different aspects of control structure needs to be thoroughly addressed, and precisely validated with experimental data to achieve the benefits of HCCI combustion with all its advantages. In current scenario, exhaust gas temperature is also a control variable along with combustion phasing and engine load in HCCI engines. Model-based predictive control (MPC) is found to be a better option for closed-loop control of LTC engines. To effectively utilize and implement, accurate predictive model of LTC engine is required including all the parameters over a wide range of engine operating conditions. For closed-loop control, sensing of combustion phasing is typically based on cylinder pressure measurement. Low-cost cylinder pressure sensor development is required to use it on production engine. Different control structure issues need to be further explored so that a final viable control structure can be developed and implemented in LTC engines.
8. *Mode switching and integration of LTC engines with other powertrains*: Dual-mode engine operation (SI-HCCI or CI-HCCI) seems to be a potential solution for full load operation in production engines by adapting HCCI mode. Research and development efforts are required for development of mode transition control and robust operation of LTC mode. In dual-mode engine operation, exhaust after-treatment for NO_x and PM needs to be installed in exhaust line. During conventional mode engine operation, to mitigate NO_x and PM emission, after-treatment system is required. Integration of HCCI engine into hybrid electric vehicles (HEVs) may become a viable solution to address some of the HCCI engine control challenges. Depending on the HEV architecture, most of the vehicle transient operations can be handled by the electric motor, which facilitates the steady-state operation of HCCI engine at fixed load. HCCI engine operation can be better controlled during steady-state conditions. In HEV application, option of supercharger instead of turbocharger can also be explored to increase the engine load range of HCCI engine.

Review papers in reference [3–10] may be helpful for additional details about the present developments of LTC engines and future directions for path to be followed for further improvement in current LTC strategies.

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