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

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***Abstract*—** *The goal with a low temperature combustion (LTC) engine is to achieve high levels of fuel efficiency without producing harmful emissions. Oxides of nitrogen (NOx) and particulate matter (PM, also known as soot) are the two main regulated pollutants in diesel combustion. NOx formation decreases as flame temperature decreases, and PM is minimized with lean combustion. LTC engines burn cool enough and lean enough (low equivalence ratio) to stay out of the high soot and NOx formation zones, yet they are still able to take advantage of the high thermal efficiency of typical compression ignition engines: they have high compression ratios and ideally operate without a throttle.*

Keywords*— *Oxides of Nitrogen, soot, lean mixture, PM

I. 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 CO2 emissions are expected to increase by 20% (reaching up to 37 GtCO2 by 2035) . 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).

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 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.

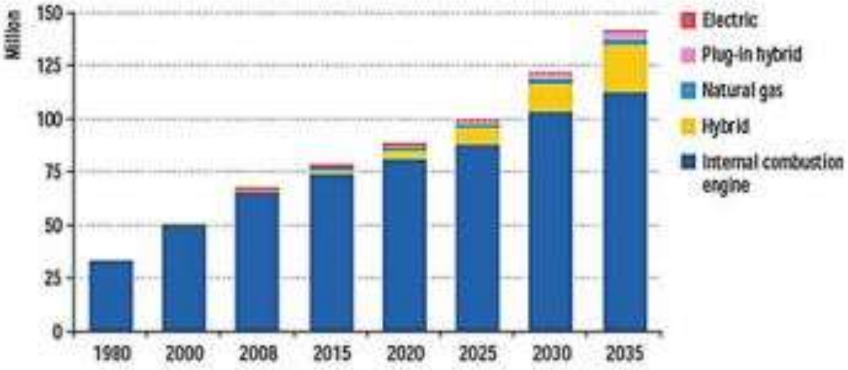

Fig 1: Present And Future Status Of Light-Duty Vehicle Sales

II. 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. 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.

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.

Fig. 2 Homogeneous charge compression ignition combustion principle

2.1 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

- 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.

- 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.

2.2 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 CO2. Thus, LTC basically suffers from the problem of high HC and CO emissions.

III. CONCLUSION

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.

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