International Journal of Future Generation Communication and Networking
Vol. 13, No. 3s, (2020), pp. 1155–1161

Recent Trends and Technologies in Diesel Engine Combustion: A Review

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Abstract

Combustion is utilized for many different applications viz. to drive Internal Combustion Engines, to cook foods, to heat space, to convert water into steam to run steam turbines etc. Hence it is very important to understand the combustion phenomenon and ways to improve combustion characteristics. There are many parameters which affect the diesel engine combustion characteristics, but few important parameters are viz. combustor geometry (to improve the mixture preparation characteristics), type of fuel (to generate required power and improve fuel economy), control of the spray of the diesel in the combustor for proper mixture preparation and maintaining its required concentration (because for diesel engines mixture is heterogeneous), pressure and temperature during combustion, emissions from the combustion process (because emissions norms have become very stringent nowadays), combustor material etc. Present paper's main aim is to discuss the importance and degree of success achieved by the implementation of specific technology in diesel engine combustion characteristics. Different successful technologies implemented to improve diesel engine characteristics are viz. coating to combustion chambers to reduce emissions, use of homogeneous charge combustion ignition (HCCI) to prepare mixture properly, reactivity controlled compression ignition, low temperature combustion to reduce the NOx emissions, development of the fuel jet spray in the combustor, modification in the combustor geometry, use of transient low pressure wall-impinging gas jet for proper mixture formation etc. This paper discusses the recent trends and technologies with their advantages and disadvantages over normal diesel engine combustion characteristics.

***Keywords** - combustion, diesel engines, recent technologies, review*

INTRODUCTION

Recent advances in the technologies calls for precise development of diesel engines. Diesel engines are used in variety of applications. Ships, automobile, ground fitted units to produce power (diesel generators), trucks and buses, trains, mining and farm vehicles and large-scale portable power generators etc. are the main applications where diesel engines are used. In diesel engines temperature and pressure is raised to start the combustion of mixture of diesel and oxidizer. Preparation of homogeneous mixture of fuel and oxidizer is not achieved (i.e. different locations in the combustion chamber has different A/F ratios) in case of diesel engines. The main problem associated with the diesel engines is the heat wastage in different following ways; in the coolant, in the exhaust, to the different parts which are in contact with the heat produced in the combustion chamber. Heat wastage reduces the engine efficiency. Recently attempts have been made to coat the parts of the combustion chamber to reduce the heat wastage [1], [2]. Recently because of limited availability of fuel resources, techniques used to save the fuel will be searched. Homogeneous charge compression ignition (HCCI) and reactivity controlled compression ignition (RCCI) can be used to improve fuel efficiency and reduce emissions. Review on the HCCI was conducted by Mohammad Izadi Najafabadi and Nuraini Abdul Aziz [3]. Experimental and numerical results obtained by using RCCI technique in engines was studied by Rolf D. Reitz and Ganesh Duraisamy [4]. Proper fuel burning in the combustion chamber reduces emissions. As combustion temperatures are higher in diesel engines NOx production in the emissions of the diesel engines is unavoidable. The way to reduce the NOx production is to reduce the combustion temperature. Low temperature combustion technologies implementation to internal combustion engine was discussed by Akhilendra Pratap Singh and Avinash Kumar Agarwal [5]. The importance of the fuel jet sprays in the combustion is discussed in [6-7]. The proper mixture formation techniques in the diesel engines help to improve efficiency of the engines.. The present papers main aim is to summarize advantages and disadvantages of the recent trends and technologies over conventional diesel engines available in the market.

ISSN: 2233-7857 IJFGCN

I. TECHNOLOGIES DISCUSSION AND FINDINGS

The recent advancements in the diesel engines are discussed briefly in the following sections.

A. Thermal Barrier Coating of Different Metals to Avoid Heat Wastage

Coating of different materials can be provided on the different parts of engines and these are viz. cylinder, piston crown, cylinder head, and valves. Different properties coating materials must have are viz. 1. Should possess high melting point, 2. Should not undergo any phase change between room and operation temperature, 3.Should have low chemical activity and thermal conductivity, 4.Highly adhesive, 5. Higher thermal durability. Thermal Barrier Coatings consists of four layers and these are mainly base layer, bonding layer, thermally grown oxides layer and then upper coating layer. The upper layer and the bonding material layers are ceramic and metallic coat to provide insulation and adhesion respectively. Thickness of layer of the coating will be decided based on type of application for which it is used in the engine. Coating to Piston and cylinder of the Internal Combustion engine provides around 3% rise in the thermal efficiency of the engine [2]. Coating of engine parts not only protects the engine but also acts like an anti-oxidative layer. Coating provided in the diesel engine benefits in the following way,

1. Minimizes heat losses from inside of cylinder to the devices used for cooling,
2. Engine power enhancement (faster conversion of fuel into energy into mechanical energy),
3. Reduces mass of fuel,
4. Cost effective,
5. Reduced emissions,
6. Dependency on the cooling system will be reduced [1],
7. Increase in fatigue life span [2],
8. Low heat rejection from the chamber leads to reduction in ignition delay,
9. Engine can be operated at minimized combustion ratios,
10. Reduction in emissions (particulate matter, NOx etc.)

Different materials used for the coating of the different parts of the engine are mentioned in the table 1.

TABLE I
MATERIALS USED FOR COATING IN THE DIESEL ENGINE

Sr. No.	Materials used for coating	Main benefit
1	Mullite (3Al2O3.2SiO2)	To increase the brake power and reduce brake specific fuel consumption
2	Nickel-chromium alloy (NiCrAlY)	To prevent oxidation and to act as a binding substrate
3	partially stabilized zirconia (PSZ)	To prevent heat loss through piston crown [8]
4	Yttria-stabilized zirconia (YSZ)	Lower thermal expansion coefficient and higher thermal conductivity
5	Alumina with yttriastabilized zirconia	To enhance oxidation resistance, hardness and bonding
6	Cerium dioxide with yttria-stabilized zirconia	To improve the thermal cycling span and shock tolerability
7	Lanthanum zirconate	Lower thermal conductivity and sintering capability [9-11]

B. Homogeneous Charge Compression Ignition

Homogeneous charge compression ignition engines are suggested as an option over the conventional diesel engines because of its cleaner and most efficient operation. Significantly efforts are put by different scientists to understand the physical and chemical processes involved in Low temperature

ISSN: 2233-7857 IJFGCN

combustion (LTC). LTC engine uses same fundamental principles of four-stroke engine and uses basic elements of SI and CI engines. The LTC principle is shown in Fig.1. 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 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 [21].

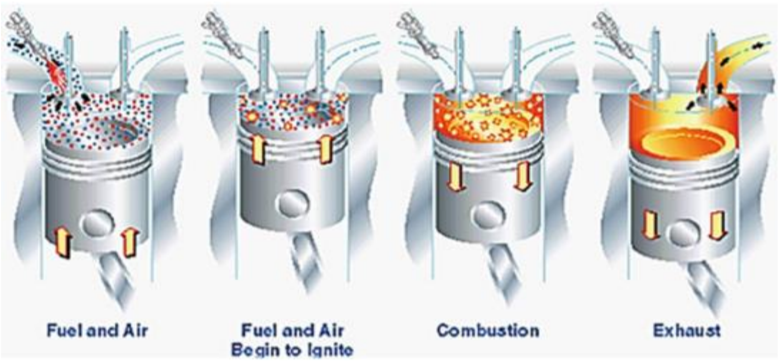

Fig. 1 operating principle of the Homogeneous charge compression ignition [20]

HCCI combustion technology benefits us in the following ways [3]:

1. Cleaner
2. Most efficient in the operation
3. Can be used to any scale/size of the engine

Following are the Disadvantages of using HCCI combustion technology [3]:

1. Controlling of ignition timing,
2. Limited power output, and
3. Weak cold-start capability
4. Greater NOx emissions
5. High CO and unburned HC emissions [12]
6. Homogenous mixture preparation
7. Too advanced or too retarded combustion phasing in case of HCCI combustion, which decreases thermal efficiency of the engine [5].

The possible ways to overcome the difficulties in the HCCI are mentioned in the table 2 [3].

ISSN: 2233-7857 IJFGCN

TABLE III
MATERIALS USED FOR COATING IN THE DIESEL ENGINE

Sr. No.	Difficulty	Solution / way to overcome the difficulty
1	Combustion timing Control	1. Changing temperature history of mixture a. VVT and residual / exhaust gas trapping i. gas trapping in exhaust ii. Modulation of intake and exhaust flows b. Variable compression ratio (VCR) c. Variable exhaust gas recirculation (EGR) d. In-cylinder injection timing e. Modulation of intake temperature f. Water injection 2. Changing mixture reactivity a. modulating two or more fuels b. fuel stratification c. fuel additives and reforming d. variable EGR
2	Limitation on power output	1. Boosting air intake quantity can be performed by supercharging and turbo charging techniques 2. Duel mode engines are a. SI-HCCI b. Diesel-HCCI
3	Homogeneous mixture preparation	1. Fuel injection in a highly turbulent port flow for gaseous and highly volatile fuels. 2. Early in-cylinder injection with sophisticated fuel injectors for diesel fuels

C. Reactivity Controlled Compression Ignition

US national Science foundation (NSF) and the department of Energy (DOE) are targeting to achieve 25 – 40% rise in the fuel economy in the light duty vehicles and 55% improvement in the thermal efficiency [4], [13]. Efforts will be made in all the ways to improve the efficiency and reduce fuel consumption. Running engine on the duel fuel cycle (also called as reactivity controlled combustion) is one of the options available because of its following advantages.

1. Option for an after-treatment plant
2. High thermal efficiency over wide engine loads
3. Three times less production of NOx and six times less production of Soot [4]
4. 16.4 % higher gross indicated efficiency [4]
5. Running engine on higher compression ratio upto 18.7 is possible
6. Clean and quite combustion

Drawbacks of the RCCI

1. Production of CO and HC in the emissions is increased sometimes
2. Fully duel fuel cycle is not possible
3. Scope to reduce the exhaust temperatures
4. Needs after treatment plants
5. Fuel injection modification strategy will be required
6. The data for the higher speed and loads is to be collected yet.

D. Low Temperature Combustion

Depletion of fuel reserves calls for search of the renewable energy sources. Low temperature combustion is preferred because of its tendency to reduce emissions of NOx and particulate matter. As per the guidelines of World Energy Outlook (2011) factsheet of International Energy Agency (IEA),

ISSN: 2233-7857 IJFGCN

demand of primary energy will be increased by one-third between 2010 and 2035 and energy-related CO_2 emissions are expected to increase by 20% [14-15]. The focus is shifted on renewable sources eg. Biofuels, solar energy, and hydrogen. 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 [16].

Following are the advantages of the low temperature combustion technology

1. Constant volume combustion achieved in short time results into increase in compression ratios
2. Effective utilization of the energy produced because of reduced radiation losses
3. Throttling losses are absent
4. Significantly lower emissions compared to Direct injection compression ignition (DICI) and Direct injection spark ignition (DISI)
5. No localized excessive temperatures
6. Fuel flexibility (gasoline, mineral diesel, biodiesel, alcohols can also be used) [17-19]
7. Soot and NOx emission very less
8. Leaner air–fuel ratios can be used
9. Lower in-cylinder temperature in case of LTC impedes post-oxidation of HCs and conversion of CO to CO_2

Disadvantages of the low temperature combustion technology

1. preheating of the intake air is required to get complete vaporization of the mineral diesel
2. precise control on the start of combustion for wide range of engine speeds and loads is difficult to achieve (critical for transient operation of the engine)
3. can be implemented for low to medium loads (low temperature combustion for low loads and conventional combustion for heavy loads)
4. technology is good for the leaner fuel–air mixtures but for rich fuel–air mixtures at higher loads cause deterioration in engine noise, very rapid heat release rates, reduction in engine power output, etc.
5. Problem of CO and HC emissions

E. Development of Fuel Jet Spray

Developments in the diesel engines have reduced the sizes of the diesel engines because of which spray height and spray angles are changed. The changes made in the spray dimensions have changed the performance of the engine in terms of efficiency and emissions. The study of the spray impingement is of great importance in order to improve performance of the engine [22-24]. Environmental density, angle of collision and oil injection pressure are important spray characteristics [6]. Environmental density can be defined as quality of unit volume air for certain temperature and pressure under analysis. Increasing environmental density decreases spray radius and increases spray height [25-26]. Diesel spray characteristics varying with fuel injection pressure was studied by Wang et al. [27] and found out that little effect on the volume of diesel spray and entrainment air quality but great effect on crushing rate by the injection pressure at low back pressure. Effect of injection pressure is minimum on liquid phase spray cone angle but higher injection pressure resulted into the higher vapour phase spray penetration rate [28]. Lower inlet hole angle was favourable for jet penetration at fast rate.

II. CONCLUSION

The present paper is mainly focused on different recent technologies which have great impact on the performance of the diesel engines. The main focus of all the research paper is on the increasing the thermal efficiency of the diesel engines and reducing the exhaust emissions. The advantages and disadvantages of the advanced technologies in diesel combustion over the conventional diesel combustion engines are described. Various advanced technologies mentioned are viz. thermal barrier coatings for the avoiding the heat wastage from the engine and hence to improve the engine efficiency (different coating materials used are also mentioned), homogeneous charge compression ignition (HCCI), Reactivity controlled combustion (RCCI), Low temperature combustion (LTC), technology

ISSN: 2233-7857 IJFGCN

used to control spray characteristics. The target of all the advanced combustion technologies is to save the fuel and improve the thermal efficiency and reduce NOx and HC emissions.

ACKNOWLEDGMENT

Authors wish to mention a sincere thanks to management of TOLANI MARITIME INSTITUTE, INDURI for allowing to conduct research in the institute.

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