Review on Reactivity Controlled Compression Ignition Engines: an Approach for BSVI emission Norms

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Abstract. In BSVI diesel engines, the limits of the NOx (oxides of nitrogen) and PM (particulate matter) reduced by 68% and 82% as compared to BSIV engines for the category of the vehicle having gross weight less than 3500kg. It is subjected to implement a complex and costly emission reduction system which reduces fuel economy. Reactivity controlled compression ignition (RCCI) is a duel fuel combustion strategy which has great potential to reduce NOx and PM and the need for an advanced after treatment system with enhanced thermal efficiency. The paper reviews potential of the RCCI strategy, to achieve the emission standards of BSVI norms, which reflects the need for cost assessment of existing engines equipped with advanced after treatment technologies.

1. Introduction

Stricter emission norms and increasing fuel prices promote the demand of cleaner and efficient combustion. As a part of these, current engine research focused on the new modes of combustion, alternative fuels, and blending and composition, new strategies of fuel supply system, and optimization of the current technology for the enhancement of fuel economy and reduction in exhaust emission.[5, 8,11,28,32,43,44,48,56] Diesel engines have wider applications in the field of transportation as well as the energy because of nearly zero throttled charging, almost fuel-lean combustion, and utilization of higher compression ratio, high power density, etc.[2,8,45] Generally, in modern CI engines the diesel is injected just before the TDC during a compression stroke.[11,28] The diesel fuel having a moderate cetane number as well as it is high viscous and low volatility, it is difficult to get higher degree of hominization of air-fuel mixtures before the combustion initialization. The combustion of diesel engines is consists of pre-mixed and mixing regulated combustion phases.[19,53]At the initial stage, when the mixture prepared during the ignition delay, there is a higher HRR (heat release rate) which nearly burns at chemically correct conditions. Result of this there is a sudden increase in both the pressure as well as temperature inside the cylinder enhances NOx emissions. In case of mixing controlled combustion process, the burning rate of the fuel is managed by the air-fuel mixing rate.[15,41] Due to the injection delay and the various
properties of the diesel fuel, there is generation of the heterogeneous mixture which leads to forming fuel rich zones, responsible for the PM formation.[28,52] There are various adverse effects of the PM and NOx emissions as human health and the environment are concerned, like cardio diseases, acid rain, smog, greenhouse gas effect etc.[14,47] As a trade-off relation between the NOx-PM, in the case of conventional diesel engine, it is very difficult to achieve such a low emission levels.[19,21,51,57,64] There are various methodologies adopted to achieving the targeted limits as per the various regulations such as fuel modifications, use of alternative fuels, engine level changes and the exhaust after-treatment level changes. [17,43,60] As system integration and complexities in operations like reductant storage, passive regeneration, required near about 10% of fuel cost develops the burden on the engine manufacturer as well as the owner of the vehicle.[58] The RCCI technology reduces the need of complex and costly after-treatment system utilized for the reduction of the NOx and PM.[35]

1.1. Objectives

The objectives of this paper are as follows

1.1.1 Investigation of limitations of the conventional diesel engines as emissions is concerned and historical aspects of RCCI.

1.1.2 Study of the chronological development of RCCI engine.

1.1.3 Persual of advanced emission reduction systems and their critical aspects.

1.1.4 Detailed review of critical parameters associated with the implementation of RCCI as an advanced clean and efficient combustion strategy.

1.1.5 Potential of RCCI strategy to achieve targets of BSVI emission norms, their limitations, and possible solutions

2. Historical Review of RCCI

As an effect of simultaneous reductions in the NOx as well as PM emission of the diesel engine without affecting the engine efficiency and the original performance, various low temperature combustion (LTC) strategies have been developed. Amongst various low-temperature combustion strategies, HCCI (homogeneous charge compression ignition), PCCI (premixed charge compression ignition), RCCI are important low-temperature combustion strategies.[9,10,18,37,45,46] The common features of all the LTC strategy are higher degree of charge homonization and overall leaner operation.[1,14] Before RCCI, worldwide researchers have been studied HCCI and PCCI for decades.[32,55] In the case of HCCI combustion control can be carried out by managing the charge condition at the closing of the inlet valve. This was highly dependent on the operating conditions; this was not useful for the full load conditions of the engine.[1,45] Since HCCI gives higher thermal efficiency and reduction in emissions, it has certain issues like shorter combustion duration which is responsible for the high peak pressure rise and develops the problem of noise, vibration and harshness especially due to higher peaks of the pressure rise rates as an effect of advanced injection effects.[45,55] To overcome this issue, Toyota et al proposed premised diesel combustion mode (diesel PCCI). Higher rate of EGR utilized in this strategy to prolong the ignition delay to enhance the mixture homonization.[28] Higher degree of homonization and overall leaner effect reduces the PM and NOx simultaneously.[32] But the combustion stability affected at higher load as an effect of a higherrate of EGR. For limited load capacity, the early injection strategy
improves the combustion stability but this will affect the thermal efficiency.[45] In the case of the PCCI, due to stratification of the charge in the combustion chamber and staged combustion with reduced pressure rise rate, it gives wider range than HCCI but the issue was controlling the combustion and mechanical stresses as an effect of the auto ignition qualities of the diesel fuel. To overcome these problems; kalghatgi et al [28] introduced the methodology of gasoline PPC (partial premixed charge compression ignition) in 2006. Use of fuel with auto ignition temperature higher than diesel allows a large ignition delay period and there is no need for too much EGR fractions, too early injection before TDC, too low CR (compression ratio), or dedicated hardware. As an effect of availability of larger mixing time it leads to lower NOx and PM as in comparison with the conventional diesel combustion process. For lower load operation, gasoline with octane number greater than 90, there were some difficulties, these difficulties tried to overcome by double injection and spark assistance but it leads to a large amount of NOx and PM generation.[41] So the experimentations carried out by the Bessonette et al.[6] concluded that the fuel characteristics can be varied according to the load conditions of the engine for low load operations diesel like fuels can be used while for high load operations gasoline like fuels can be used.

After that Inagaki et al.[27] introduced the concept of the dual fuel combustion, in which there is a port fuel injection of the is octane while the direct injection of the diesel fuel. They reported that there is better control over the combustion process with very low NOx and PM emission. Later on, bessonette et al[6] found that the proper fuel for the HCCI operation having reactivity lies in between the diesel and gasoline. Based on these research and findings, kokjohn et al [47] had conducted various experiments for the duel fuel PCCI and HCCI by varying the reactivity, with a combination of the EGR for the control of combustion with maximum efficiency. They reported that an adjustment in the reactivity of the fuel leads to optimum efficiency in certain operating conditions. In these experimentations there were port injection of the gasoline as a low reactivity fuel (LRF) and direct injection of diesel as a high reactivity fuel (HRF) in the combustion chamber. This phenomenon is called as reactivity controlled compression ignition.[18,45,47,52,12]

3. Fundamentals of RCCI Strategy

The control of fuel reactivity inside the combustion chamber is an important feature of the RCCI.[18, 45, 52,61] By its design, RCCI is a combustion strategy that uses two fuels having different reactivity utilized for fuel mixing in the cylinder. The principle of RCCI operation is as shown in figure 1.[47]
Figure 1 Fundamentals of RCCI operation

Low reactivity fuel is of gasoline category (i.e. low cetane number) is injected too early by port fuel injection (PFI) and high reactivity fuel in the category of diesel fuel (i.e. high cetane number) is directly injected single or multiple times during the combustion cycle.[30] Subsequently, the reactivity stratification is established. The fig. 1 shows the working principle of the RCCI engines.

3.1. RCCI Chemistry

In RCCI combustion strategy 80 to 90 % of low reactivity fuel like gasoline can be transferred through the port while the direct injection of the remaining amount of the high reactivity of the fuel like diesel in the combustion chamber. As an effect of the reactivity gradient it has the potential to reduce the NOx as well as PM even without too much necessity of the EGR (Exhaust gas recirculation) at higher load operations.[45] The combustion process in the RCCI engines mainly depends on the mixture quality of the charge. The combustion process in the RCCI engine is a staged combustion process which extends premixed combustion duration, resulted in higher thermal efficiency with lower emissions as well as, low rate of pressure rise at higher load operation of the engine.[39]

There are three phases of the combustion in RCCI engines are i) Low temperature combustion flame i.e. ignition of the low reactivity regions ii) ignition of low reactivity zones lead to a higher heat release rate as an effect of high mass of premixed charge due to multiple site combustion iii) Generation of the multiple flames due to multiple stage combustion.[4] In rcci, the combustion process initiates from the 10 to 20% of the HRF supplied by the single or double injections and HRR can be controlled by the spray formation process.[52]

3.2. Heat release rate

RCCI consists two stage heat release process. The first stage is known as LTHR (low-temperature heat release) while second is HTHR (high-temperature heat release).

Figure 2 shows the rate of heat release of the RCCI operation in terms of start of high temperature oxidation (HTO) and low temperature oxidation (LTO).[33] The maximum rise of LTHR is mainly controlled by the high reactivity fuel with NTC (negative temperature coefficient). The HTHR is mainly dependent on the quantity of the premixed charge, i.e., LRF (low reactivity fuel) in RCCI combustion.[33]

4. BSVI Emission Regulations
To get rid from consequence of these exhaust emissions, various emission regulations were implemented throughout the world. India have their emission regulations known as Bharat stage emission standards, likewise euro norms for European countries, Canadian Environmental protection act for Canada, Environmental protection agency, United States of America, China Energy policy of China, China has their emission norms.[45,54] Emission regulation or the legislation had set the limits of the exhaust constituents. Table 1 shows the Bharat Stage VI (BSVI) emission norms for the passenger as well as heavy commercial vehicles.

In India, from April 1, 2020, implementation of the Bharat stage 6 (BSVI) norms throughout the country.[23] The target of emission norms BS- VI is to maintain the PM at 0.01 g/kWh and NOx at 0.4 g/kWh levels. India already skipped the Bharat Stage emission norms (BSV) norms, so there is a drastic change in the limit of the exhaust constituents from BSIV to BSVI. For BS-VI, it is proposed to reduce NOx by 89% and PM by more than 50% about the BS-IV limits in case of heavy commercial vehicles.

| Pollutant Types (In g/Km) | Emission standards for passenger vehicles-Diesel |
|--------------------------|-------------------------------------------------|
| Stage | CO | HC | HC+NOx | NOx | PM | PN**x |
| BS-IV | 0.5 | 0 | 0.30 | 0.25 | 0.0250 | - |
| BS-VI | 0.5 | 0 | 0.17 | 0.08 | 0.0045 | 6.0x10^1 |

| Pollutant Types (In g/Km) | Emission standards for heavy commercial vehicles (GVW>3.5T) |
|--------------------------|-------------------------------------------------|
| Stage | CO | HC | HC+NOx | NOx | PM | PN**x |
| BSIV(ESC) | 1.5 | 0.46 | - | 3.50 | 0.02 | - |
| BSIV(ETC) | 4.0 | 0.55 | - | 3.50 | 0.03 | - |
| BSVI(WHSC) | 1.5 | 0.13 | - | 0.40 | 0.01 | 8.0x10^11 |
| BSVI(WTSC) | 4.0 | 0.16 | - | 0.46 | 0.01 | 6.0x10^11 |

ESC- European Steady Cycle; ETC – European Transient cycle
WHSC- World Harmonised Stationery Cycle; WSTC- World Harmonised
Transient CyclePN count for WTSC will be applicable from April 2025.

4.1 Technological transformation review for BSVI and its economical impacts

Emissions regulations in the Bharat Stage VI (BS-VI) pointed out for an after-treatment exhaust system (EATS) with very high PM & NOx mitigation capabilities and the mitigation in PN. All the technologies are associated with the in cylinder technologies and after treatment systems.[45]
Changes in Engine technology BSIV to BSVI

Fuel modification, engine design modifications, exhaust after-treatment, optimization of the existing systems are the various ways to regulate the emission from the engine. As the economics of the transformational changes in the BSIV to BS-VI is a concern, there are an increase in the price from 10 to 15% of the existing cost of the diesel operated vehicle as per the SIAM (Society of Indian automotive manufacturers) reports [24,22]. Table 2 shows segment-wise cost implications of the BSVI technology [25].

To shift the existing engine technology from BSIV to BSVI it is essential to change the existing technologies of engine level as well as exhaust level as shown in figure 3. As well as table 3 technological as well as fuel level changes required for BSVI Transformation.

Table 2 Cost Implications of BSVI Technologies [25]

| Segment                                | Technology required to meet BS-VI Norms | Increase in cost                      |
|----------------------------------------|----------------------------------------|---------------------------------------|
| Diesel operated passenger vehicle      | Main changes in fuel injection system LNT DPF | Vehicle cost may increase by 10 to 12% |
| Light & Medium CVs                     | High Pressure Direct InjectionDOC,EGR + SCR DPF | Increase in engine cost ~50% from a base level of BSIV category of same capacity |
| Heavy CVs                              | High Pressure Direct InjectionDOC,EGR + SCR DPF | Increase in engine cost ~50% from a base level of BSIV category of same capacity |

Table 3 Technology up gradation BSIV to BSVI [55]

| Technologies | From BS IV to BSVI transformation |
|--------------|-----------------------------------|
| Fuel utilized| BS IV fuels BS VI fuels           |
Advancements in combustion and calibration of the engine
- advancements in fuel injection systems
- advanced VGT
Advanced NOx controlled and Electronics
Precise control on EGR rate.

| On-board diagnostics | Advancements in combustion and calibration of the engine |
|----------------------|--------------------------------------------------------|
| OBD Stage I           | - advancements in fuel injection systems |
|                      | - advanced VGT                                      |
|                      | Advanced NOx controlled and Electronics               |
|                      | Precise control on EGR rate.                         |

| After-treatment system | Advancements in combustion and calibration of the engine |
|------------------------|--------------------------------------------------------|
| Open loop SCR for NOx reduction - PM control (for EGR pathway only) | - advancements in fuel injection systems |
|                        | - advanced VGT                                      |
|                        | Advanced NOx controlled and Electronics               |
|                        | Precise control on EGR rate.                         |

5. Implementation of RCCI Combustion

5.1. Fuel Management of RCCI engine

Fuel stratification plays a key role in the case of RCCI combustion characteristics and overall performance of the engine.

5.1.1 Single Fuel Strategy with additives

In a single fuel RCCI strategy only LRF will be used, cetane improver additives are used to develop the reactivity gradient in the combustion chamber and LRF directly injected in the combustion chamber. [52] In this strategy a single fuel tank is sufficient for the operation. In this single fuel strategy, Gasoline, ethanol, methanol, iso-butanol can be used as an LRF for the RCCI combustion. [52] The fuel with cetane improver additives works as an HRF. 2-EHN (Ethylhexyl nitrate) and DTBP (Di tertiary butyl peroxide) have been used for the RCCI combustion.[33,59]

5.1.2 Double Fuel Strategy

Initially, various studies were conducted by using gasoline as HRF and Diesel as LRF. With these conventional fuels different types of renewable fuels like biodiesel, alcohol, natural gas, etc were used for the RCCI combustion. Alcohols and NG creates larger reactivity gradient as compared to gasoline and they can extend the operating loads also. Alcoholic fuels reduce the NOx formation because of its oxygen enrichments.

5.2 Engine Management of RCCI Engines

While adopting the RCCI combustion technology various parameters need to be optimized like injection strategy, SOI (Start of injection) timing, injection duration, spray angle, fuel injection pressure and fuel ratio, piston bowl geometry, etc. These parameters directly affect the combustion characteristics and overall performance of the engine.

5.2.1 Fuel Ratio

Fuel ratio can be defined as the ratio of LRF to HRF in mass, energy or volume, etc. In
cylinder, reactivity can be controlled with the help of fuel ratio. Hanson et al.[20] conducted experimentation on a heavy-duty single-cylinder engine to study the effect of varying the fuel ratio of gasoline percentage of 82, 86, 89% at constant IVC timing 143° ATDC on performance and emission characteristics. They reported that a higher percentage of gasoline retards the combustion phasing as an effect of global fuel reactivity.

![Graph showing the effect of gasoline percentage on emission characteristics](image)

**Figure 4** Effect of gasoline percentage on emission characteristics

This retarded combustion phasing leads to lower heat transfer as well as drops the combustion chamber temperature and allowed for the lowest fuel consumption as well as enhances the indicated thermal efficiency. It also reduces NOx and PM emissions. Figure 4 shows the effect of gasoline percentage on the emission characteristics of the engine.[20]

5.2.2 Effect of first and second injection timings
Figure 5 Effect of SOI1 timing on performance and emission characteristics

Figure 6 Effect of SOI2 timing on emission characteristics
There are various controllable parameters in the RCCI combustion process, the start of combustion is one of them because it is closely associated with the mixing process and combustion kinematics. Both the early, middle, and late injection timing effects on combustion characteristics and reflects in the HRR and the thermal efficiency of the engine. Hanson et al.[20] tested heavy-duty engine for 9 bar net imep and 1300 rpm for the injection timing. The fuel supplied through the port fuel injection systems 73% while 27% diesel through the direct injection system about this 62% quantity of the diesel in the first injection while remaining 28% fuel in the second injection. Figure 5 shows that as advancement in the engine timing (SOI1) retards combustion phasing resulted in peak pressure rise. [20] The NOx reduced and but CO increased and not too much change was observed in the HC emission. Figure 6 shows experimental and simulated results of and rate of heat pressure inside the cylinder and heat releaserate over a SOI2 timing. [20] Retardation of second injection leads provides very less time for the preparation of the charge, this improper mixing generates the local cylinder temperature, increases the NOx and PM. There was no effect on the fuel consumption as well as CO. Advanced SOI2 decreases the pressure rate as a result of homogeneous mixture and delayed combustion.

5.2.3 Mass fraction in the first and second injection

The mass fraction of the split injection depends on the SOI timing of each injection pulse. Hanson et al.[20] conducted an experiments to investigate the influence of mass fraction in the first and second injections of HRF.

![Figure 7 effect of mass fraction on emission characteristics](image)
The mass fraction variation of the diesel fuel injected in SOI1 was from 36% to 62% of the total diesel fuel injected and it was 27% of the total fuel supplied to the combustion chamber in each stroke. For the addition of second injection fuel, NOx and PM have major rises. In the case of later injection of the diesel fuel in the process, results in more stratification of the charge, and increases the reactivity of the charge in the cylinder. These rich and high reactive zones are starting to ignite higher cylinder temperatures earlier, causing a rise in NOx and PM. Figure 7 shows effect of the fraction of diesel in each pulse on performance and emission characteristics of the engine.[20]

5.2.4 Spray Angle

Spray angle performs a key role in the overall combustion process of the RCCI engine. Proper spray angle effects on the distribution of the fuel particles in the combustion chamber and this distribution directly effect on the combustion, performance and emission characteristics of the engine. Spray angle can be defined as the angle between the cone axis of the diesel fuel spray and the axis perpendicular to the piston crown. The spray angle is associated with how much fuel is reaches the location of the squish region of the combustion chamber. Nazemi et al. [42] investigated the effect of various injection parameters on the emission, combustion and performance characteristics of the RCCI engines, they selected. They concluded that spray angle is the important parameters of the injection design which affects on the combustion phasing and also in the heat release rate.

5.2.5 Injection pressure

Homogenization, vaporization and dispersion of diesel fuel are the important sub processes of the cylinder mixing process and that can be affected by the injection pressure.

There are two aspects of the injection pressure one is, if the injection pressure is high,
as a result of a higher rate of vaporization the mixture becomes homogenous and another hand if the particle size reduces the inertia of the particles reduces and reduces the penetration lengthwise. For the same amount of the injected fuel, as the injection pressure increases there is a reduction of injection duration. Higher injection pressure responsible for rapid combustion rates, which resulted in the higher in cylinder temperature. The reduction of the torque as well as power is due to the inefficient transfer of the heat into useful work. The fundamental reason is that the combustion starts in a very small area where the fuel is injected and the dispersion of the flames around the cylinder. During this travel there was not proper utilization of the air.

Nazemi et al [42] have conducted experiments to explore the results of varying injection pressures from 380 bar to 580 bar in the 20 bar range for the 4-cylinder diesel engine. Increased injection pressure from 380 bar to 580 bar was reported to cause a decrease in peak pressure by approximately 10 bar. Figure 9 shows effects of injection pressure on emissions including HC, CO, NOx and soot [42].

The basic cause of this, either raising the injection pressure or reducing the duration of the injection, the fuel parcel diameter decreases and these parcels of smaller diameter unable to distribute as per requirements and deposited together in the high-temperature piston bowl area ineffective self-ignition would also occur, which cannot spread through the entire combustion chamber and which will provide sufficient energy rapid burning of the fuel. The peak HRR decreases by increasing the injection pressure and combustion is progressively delayed. An increase in injection pressure reduces the rate of auto ignition process near the tank of the piston, as less gasoline fuel burns compared to low injection pressure and thus decrease in the peak of the HRR. As a result of higher injection pressure and lower in cylinder gas temperature there were a reduction in the NOx and quite higher values of HC, CO, and soot had reported.

![Figure 9 Effects of injection pressure on emissions including HC, CO, NOx and soot](image_url)

5.2.6 EGR Rate

Exhaust gas recirculation is one that contributes to the reduction of NOx emission and PRR. Durasami et al [16] conducted experimentation to explore the effect of the EGR on
combustion, performance as well as emission characteristics of the methanol/diesel and methanol/PODE RCCI Combustion process for the automotive engine.

They reported that use EGR resulted in a reduction of the peak in-cylinder pressure as well as HRR for both Methanol/Diesel and Methanol/PODE RCCI combustion due to the effect of charge dilution and heat capacity of the EGR. EGR delayed the start of combustion as well as suppressed the cylinder pressure up a certain limit, if the limit exceeds the engine may lead to misfiring.

Ultimately they reported that the combustion phasing and extension of the load range associated with the amount of EGR. As emission is concerned, reduction in the oxygen concentration as an effect of the EGR leads to an increase in the soot, BSHC, and BSCO emissions but the notable reduction in NOx for RCCI combustion with EGR in comparison with without EGR models shown in figure 10. [16] Rate of pressure rise reduced in both cases for EGR in comparison with without EGR which is helpful to enhance the operating range.

![Figure 10](image-url) Effect of EGR on performance on emission characteristics of the engine

### Table 4 Summary of Various Important Parameters of RCCI Emission Characteristics

| Sr.No. | Parameter          | Overall conclusion                                                                 | References                                      |
|--------|--------------------|------------------------------------------------------------------------------------|------------------------------------------------|
| 1      | Pre mixed ratio    | As the gasoline fuel percentage increases there were increases in HC, CO, soot, and reduction NOx. This is because of the reduction in the incylinder gas temperature with increasing gasoline fraction. | Hanson et al. [20] Kokjohn et al. [31] Ma et al. [40] Benajes et al. [4] Dempsey et al. [10] Cha et al. [7] Li et al. [38] Li et al. [34] |
The heat release is a single-stage process for the early start of injection and a two-stage heat release process for late start of injection, increase in pressure rise rate has been observed increases in temperature of the cylinder which increases the NOx but reduces the HC and CO emission.

Ma et al. [40] Benajes et al.[4] Desantes et al. [13] Li et al. [38]

Effect of split injection mass fraction fundamentally depends a lot on the SOI timing of each injection pulse. Split injection fractions may affect the location where the fuel has injected either bowl or squish of the combustion process in the cylinder, and therefore there is an increase in PPRR and ringing intensity. But there was no noticeable impact on the performance and emission characteristics of the engine.

Ma et al. [40] Paykani et al[48] Nieman et al[43]

Spray angle In case of a broader spray angle, fuel burning happens in the area of centreline and squish respectively, and in case of narrower spray angles, it allows the charge to burn close to the cylinder bulk, which produces higher levels of HC and CO emissions near the area of cylinder wall as well as crevice volumes. Also, the emission of NOx is higher with a lower spray angle as a result of higher temperatures and rich and locally high reactive zones.

Amani et al [3], Poorghasemi et al [49] Khatamnejad et al[29]

Injection Pressure For the same amount of the fuel, if injection pressure is higher than the duration of injection reduces. Up to a certain limit of injection pressure provides better atomization results in reduction HC and CO emission

Ramasankaran et al[50] Duraisamy et al[18]

EGR Rate An effect of dilution of the charge and thermodynamic effects of EGR reduces the temperature of the combustion chamber. There is a reduction in the NOx formation. In some cases, increase in CO and HC was observed as an effect of reduction in oxygen availability in the combustion chamber.

Jing Li et al (36) Ma et al[40] Wu et al[62]

6. Applications of RCCI to Meet BSVI Emission Norms

Combustion optimization of the diesel engine is essential for regulating the emission constituents from the exhaust gases, since the RCCI combustion having good control over the combustion event which leads to the drastic reduction in the NOx and PM. Various factors directly affect the NOx formation process, which includes type of fuel used, fuel injection pressure, injection timing, pulses of injection, amount of fuel injected in each pulse, premixed fuel ratio, piston bowl geometry, etc.[1]
Benajes et al [3] experimentally investigated the capability of the RCCI engine to meet the EURO VI emission norm. They tested single cylinder medium duty engine developed for the urban freight transportation. The engine was modified as per the requirement of the RCCI operation. They used three combustion strategies based on the loading condition. Upto 40% there was fully premixed strategy, for 40 to 75% highly premixed, and for 75 to full loading condition the strategy was diffusive. To achieve the EURO VI they followed three steps stable engine operation, the optimistic performance of the engine for NOx parameters, and third for optimization for the HC and CO emission. As NOx emission is concerned it was observed that the shape of the NOx emission map is closely associated with the gasoline mass fraction and the rate of EGR. As the fraction of the diesel fuel increases the locally rich mixture zones and higher temperature which leads to the generate more NOx. As a final result was concerned there is reduction of NOx ranging from 0.6 and 0.8g/kWh and the some peaks of the about the 1.2 to 1.4g/kWh which is typically less than the current diesel engines which operates in full load conditions with SCR. The overall reduction in the NOx varies in the range of 75 to 98% in comparison with CDC operation. So there was no need to use the reductant like urea in SCR to achieve the targets set by the BSVI emission norms, because the engine operation shows the maximum rise of the NOx reduction in the region of low speed, as shown in figure 11.[3]

**Figure 11** NOx and smoke emissions reduction with the dual-fuel strategy versus CDC

For the HC and CO emissions are concerned as load and speed of the engine increases both the unburned hydrocarbon HC and CO increases. For idle and low speed engine operation i.e for the speed range 950-1500 rpm the maximum rise for both the HC and CO pollutants was reported. The combustion strategy was followed in such a way that the temperature of the gas ranges from 1500-1700K, where complete oxidation of the CO lower limit and there were formation of the minimum amount of the NOx. For above 10 bar IMEP, a very small amount of HC emissions were observed, a for the mixture strength is concerned equivalence ratio ranges from 0.7 and 0.8 and gas temperatures about 1700 K without maximum fuel consumption, the CO and HC emission is less with
NOx and ultra-low PM contents, pressure and temperature zones as a source of ignition. It can be concluded that both the CO and HC emissions are the functions of both equivalence ratio as well as gas temperature. There was very little time available for the mixing process and maybe the chance of the soot formation but the injection quantity of the diesel fuel, the exhaust emissions meet the targets of Euro VI/BSVI norms for all speed and 75% load range. Similarly Xu et al [63] investigated the use of variable valve timing (VVT) in RCCI combustion for combustion, performance, and emission characteristics of the heavy-duty engine for wide range of the load. They optimized various parameters like premixed ratio, intake valve closing (IVC) timing, injection timing, and quantity of EGR, intake air pressure, and temperature. The investigations aimed to meet the Euro 6 emission regulation without using exhaust after treatment systems without affecting the thermal efficiency of the engine. They concluded that by optimization of RCCI combustion with the help of VVT strategy, the Euro6/BS6 NOx targets were achieved with ultra-low soot emissions at low medium load range, but for the higher load operation requirement of at least one after treatment device for further elimination of the NOx or soot emissions.

Similarly Xu et al [63] investigated the use of variable valve timing (VVT) in RCCI combustion for combustion, performance, and emission characteristics of the heavy-duty engine for wide range of the load. They optimized various parameters like premixed ratio, intake valve closing (IVC) timing, injection timing, and quantity of EGR, intake air pressure, and temperature. The investigations aimed to meet the Euro 6 emission regulation without using exhaust after treatment systems without affecting the thermal efficiency of the engine. They concluded that by optimization of RCCI combustion with the help of VVT strategy, the Euro6/BS6 NOx targets were achieved with ultra-low soot emissions at low medium load range, but for the higher load operation requirement of at least one after treatment device for further elimination of the NOx or soot emissions.

7. Research directions and future scope

- The key challenge of the RCCI combustion is to control the timing and magnitude of HRR for higher loading. Further studies are required to explore the various options like DDFS and MPCI, multiple pulses, etc.
- In the case of RCCI combustion, normally too early injection is used to develop required reactivity stratification. But early injection of the fuel may lead to fuel droplets adherence on the cylinder wall or called as fuel impingement. This results in incomplete combustion of the charge. To mitigate this, more studies are required to minimize the effects of fuel deposition in the crevice areas with the help of blends of oxygenated fuels, spray angle, spray patterns, nozzle holes, injection pressure, and their cumulative effects on the combustion, performance, and emission characteristics of the engine.
- It is essential to minimize the effects of the HC and CO through a specially designed after-treatment system with low temperature catalyst or there should be provision to increase temperature to perform required catalytic reactions or there may need for fuel-born catalyst.
- There is need to develop effective control models on RCCI combustion as far as commercial use of these strategies is concerned since the vehicular traction requirements continuously changes. As compared to the CDC, RCCI engine is limited by both at high and low operating range. At the high loads, there is an issue of high levels of PPRR and combustion noise. At lowload CDC gives similar efficiencies and
NOx emission with lower UHC and CO emissions in comparison with RCCI engines. Mode switching as per the required load will be the solution for this and efforts are required in this direction.

8. Conclusions:
To achieve the emission regulations prescribed in the BSVI norms both the engine and exhaust level changes are carried out by the various engine manufacturers. Advanced engine combustion process RCCI has a great potential to get higher thermal efficiency as well as reduce the NOx and PM emissions as prescribed limits of the BSVI emission norms as an effect of the higher degree of homonization and effective control through the reactivity stratifications. RCCI will provide the cost-effective solution for emission reduction which reduces the economic burden on the engine manufacturer as well as the owner.

- Advancements in the diesel injection timing, there was better stratification of the mixture and there are few areas of lower local reactivity across the cylinder. That means reducing the first peak of HT HR and raising the second peak.
- RCCI combustion has the potential to reduce the soot and NOx, in comparison with CDC which operates on neat diesel, which shows the ability to achieve the targets, set by the BSVI emission norms. On the downside, higher level CO and unburned HC were assessed, the main reason behind this is fuel deposited in the crevice areas, and where the burning of the fuel is quite difficult.
- Optimized engine and fuel management system of the RCCI engine strategy can be used to achieve wider load range of the operation with higher thermal efficiency and avoids costly after treatment system or there will be minimum requirements of the exhaust after treatment. This will directly reduce the initial as well as the running cost of the vehicle.
- The research reveals that current research is limited with the hybrids vehicles and is in the very initial stage, further modifications like advancement in the engine control as well as engine management systems; changes required to fulfill the traction requirements of the vehicle in various operating conditions like mode swing technologies to provide the required mixture requirements.

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