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A REVIEW ON REACTIVITY-CONTROLLED COMPRESSION IGNITION (RCCI) ENGINE

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ABSTRACT

An internal combustion engine is the prime source of transportation throughout the world like trucks, buses, passenger cars, three-wheeler and two-wheelers. Due to the use of hydrocarbon fuels these IC engines produce lot of engine emission which ultimately create problems to the humans, living organisms and to the environment. The low temperature combustion strategyis likely to help in overcoming this problem and this can be achieved majorly through homogenously charged compression ignition, premixed charged compression ignition and reactivity-controlled compression ignition.The low temperature combustion engine is very effective and has special ability that can be used in place of conventionalinternal combustion engine. The low temperature combustion engine has more than 50% thermal efficiency,reduce fuel consumption and reduce engine emissions level below EROU VI.However, low temperature combustion engines are suffered from some disadvantages such as low control over combustion, low load capacity, cycle-to-cycle variation in combustion, etc. Among all variants of low temperature combustion engine, reactivity-controlled compression ignition has an upper hand due to its number of advantages over others. The reactivity-controlled compression ignition can operate at different loads, use alternate fuels effectively, produce lower emissions, have lower cycle to cycle variations etc. However more research is required to make them commercially viable.

Keywords:Low temperature combustion engine, premixed charged compression ignition, homogeneous charge compression ignition, reactivity-controlled compression ignition, internal combustion engine, pollution, emissions.

1. INTRODUCTION

The world has more than 4.8 billion vehicles including passenger cars, commercial vehicles, transport vehicles, railways and marine ships in the world which are uninterruptedly increasing. More than 99.9% of these are powered via internal combustion engines (ICE) and they use liquid hydrocarbon (HC) fuel for their power production. Due to the new findings and retrieval rates, global crude oil supply size has been growing quicker and it is projected that demand of oil will continue to increase and demand will be at peak by about 2040. So, the ICEs and HC fuel will continue to be the leading/first choice for years to come but the major problems related with ICEs are harmful exhaust emissionsthat they produce [1, 2].To deal with this, presently, there are only limited alternatives to petroleum-based fuels viz., biofuels, natural gas (NG), dimethyl ether (DME), compressed natural gas (CNG) and liquified petroleum gas (LPG), which collectively contribute only about 5% of the total requirement and are likely to go upto 10% share of the entire global transport energy. The share of electricity is insignificant and that of hydrogen or synthetic fuelsis negligible. To overcome numerous problems related with ICEs various governments showed sufficient interest in electric vehicles (EVs) and declared banning of vehicles powered by ICEs but didnot evidently mention about their strategies.Electric vehicles possibly will not be effective everywhere like commercial transport, sea transport and air transport. If by 2040 all the light duty vehicles (LDVs) in the world are converted to be fully electric, as aspired, even then it would cater to less than half of the transport energy demand.Subsequently, commercial transport cannot realistically be operated on electricity alone.Also, some serious challenges related with electricity are lack of electric energy generation, less charging stations, low battery size, problem of battery disposal etc. Another alternative to the ICE is the fuel cell vehicle driven by hydrogen which needs an incredible global infrastructure to be built for hydrogen production [1, 3].

Therefore, even by year 2040 about 90% of the transportation energy will come from petroleum-based combustion powered engines i.e., internal combustion engines (ICEs). It would be very difficult to remove ICEs and banning the production of ICEs, would have dangerous economic, social, environmental and political impact. It may be said that the two basic types of ICEs are still the best possible transport and power option,and will remain to operate for many years to come until unless a successful, efficient and convenient option is developed. Out of compression ignition (CI) and spark ignition (SI) engines used in transportation, CI engine is superior as it hascharacteristics such as high combustion efficiency, ability to use high compression ratios without knocking, lack of throttling losses,favourable gas properties for work extraction owing to lean operation etc. Due to the heterogeneous combustion process in diesel engine, the combustion tends to form emissions of oxides of nitrogen (NOx) and soot (major fraction of particulate matter (PM)). This is due to the sudden rise in cylinder pressure and temperature which promotes the formation of NOx emissions. These NOx and PM emissions cause adverse effects on human and environment like cardiovascular diseases, acid rain, photochemical smog, greenhouse effect, etc. [4].

Nevertheless, several techniques viz. exhaust gas recirculation (EGR), retarding/advancing the fuel injection timing, modified fuel injection systems and employing exhaust gas after-treatment system are used but simultaneous control of these two exhaust emissions is not so easy because of the nature of diesel combustion. Though, in order to encounter the tightened emission regulations that are imposed from time to time, it has become necessary to further explore alternate strategies in order to lessen NOx and soot emissions simultaneously. During past few years, various alternate fuels have been proposed; amongst them biodiesel attracted several researchers because of its renewable nature and being CO_2 neutral. Though, it has beenfound that use of biodiesel fuel increase NOx emissions in conventional diesel engines [5].

1.1 MAJOR ENGINE EMISSIONS PRODUCED BY DIESEL ENGINE AND THEIR ADVERSE EFFECTS

The chemical reaction in ideal combustion situation when complete combustion with oxygen takes place inside the engine cylinder is shown in the following equation (1) [6]:

$$C_nH_{2n+2} + \frac{3n+1}{2} \cdot O_2 \rightarrow (n+1)H_2O + nCO_2 + heat \qquad (1)$$

But due to various operating parameters and conditions, complete combustion of fuel does not take place resulting in production of various kinds of emissions as shown in equation (2):

$$Fuel + Air\ (incomplete\ combustion) \rightarrow Unburned\ HC + NOx + CO_2 + CO + H_2O \quad (2)$$

Burning of diesel fuel in a diesel engine typically produces approximately 67% N_2, 12% CO_2, 11% H_2O, 9% O_2 and 1% other pollutant emissions containing CO, HC, SO_2, NOx and PM. Also, if 1 kg of diesel fuel is burnt, it would produce around 3.1 kg of CO_2 and 1.3 kg of H_2O [7, 8].These emissions adversely affect both human and environment.

(i) Nitrogen oxides (NOx): **-** NOx emission contains NO which is a non-coloured gas without smell, whereas NO_2 is a reddish-brown penetrating odour gas in colour.Diesel engine produces more than 50% of nitrogen oxides of total emissions produced. These are responsible for many environmental problems such as smog formation, acid rain, acidification of water bodies, nutrient enrichment, formation of ozone and health related problems like human lung disease, respiratory infection, pollutant haze, which impairs visibility [9].

(ii) Particulate matter (PM): **-** PM emissions emitted by diesel engine are the second largest emission content of total exhaust emissions. The impacts of PM on environment are air and water pollution; soiling on structures and monuments; low agriculture productivity; visibility loss or impairment; change in global environmental conditions etc., effect on human health are asthma, dyspnoea, suffocation, lung cancer, premature death etc., the further leads to other types of cardiovascular diseases [10, 11].

(iii) Carbon monoxide (CO): **-** CO is a colourless, odourless gas and has several adverse effects on human health. When CO is inhaled with air, it combines with haemoglobin and reduces oxygen transfer capacity. Also, it leads to asphyxiation, affects functioning of various human organs, culminates in slow reflexes, causes concentration, bewilderment and confusion [11].

(iv) Hydrocarbons (HC): - HC have several hazardous effects on environment, climate conditions, living organisms and human health. They form ground-level ozone, toxic, cause cancer and respiratory tract irritation [9, 12].

Table 1. Heavy-duty vehicles engine European Union emission norms[13].

Euro norms	**HC (mg/kWh)**	**CO (mg/kWh)**	**PM (mg/kWh)**	**NOx (mg/kWh)**
EU-1	1100	4500	610	8000
EU-2	1100	4000	150	7000
EU-3	660	2100	130	5000
EU-4	460	1500	20	3500
EU-5	460	1500	20	2000
EU-6	130	1500	10	400

Due tothese effects of emissions on environment and human life, various regulations havebeen imposed by different governments and organisations on the automobile sectors. For example, Environmental protection agency (USA), Energy policy of China, Canadian Environmental protection act, Bharat stage emission standards (India) and Euro norms (European Union) have their own emission norms. The Euro emission norms are listed in table 1, showingthe limiting value of the four major defined pollutants emitted by IC engines i.e., CO, HC, PM and NOx emission.

1.2 METHODS OF CONTROLLING ENGINE EMISSIONS

It is clear from the table 1, that strict emission regulationshave been imposed on transportation sector from time to time. These regulations are majorly focused on PM and NOx reduction. Different types of emission controlling systems are used on engines. Exhaust gas recirculation (EGR), Lean NOx trap (LNT), selective catalytic reduction (SCR) etc. are used for NOx emission reduction. The NOx emissions are produced due to the high temperature inside the combustion chamber. These systems are used to trap the exhaust gases and with the help of a catalyst material complete the chemical rection in order to reduce NOx emissions [9, 14, 15]. Diesel particulate filter (DPF) is used for PM reduction. PM emissions are produced incomplete combustion of fuel caused due to less time and less oxygen available. The DPF traps and collects PM in a honeycomb like structure. But if the quantity of PM is too much, it starts building up back pressure, which affects the engine performance [15-17]. Diesel oxidation catalyst (DOC) is are used for HC and CO emissions reduction. This system traps the HC and CO emissions in a honeycomb structure which contains some catalyst material like rhodium, palladium, platinum etc. These catalyst materials by oxidising themself form H_2O and CO_2[14, 15, 18].The efficiency and performance of these systems are affected by high temperature and the maximum efficiency of these systems lies between 40-90%.

1.3 NOx AND SOOT TRADE OFF

Due to the heterogeneous nature of combustion in diesel engine high NOx and soot emissions are observed. However various methods are used to control both as discussed in the previous section but simultaneous control of these two emissions is very difficult. It has been observed experimentally that if NOx emission is controlled, PM emissions wouldincrease, as can be seenin case of EGR and retarded fuel injection. On the other hand, if the injection timing is advanced,PM emissions would reduce but it would result in increase of NOx emissions. Optimum conditions are to be used to minimize both NOx and PM in the allowable range.Different methods and techniques have been explored to find the solution of NOx-PM trade off likefine-tuning fuel injection timing, higher injection pressure, turbocharging,different levels of EGR, combustion chamber design, improved fuel injection system, alternate fuels etc., [19-21]. But as the emission regulation are tightened more and more, it is becoming difficult to further minimize both simultaneously. The effect of this condition is that, some of the automobile companies have announce that they are going to stop production of diesel cars. NOx and PM emission can be reduced when a condition of fuel-rich regions and high temperature i.e., more than 2000 K isconcurrently avoided.Low temperature combustion engines (LTCE) are among the best effective approach that could be used for reducing both NOx and PM emissions together.However, LTCE would increase the CO and HC emissions but these emissions can be reduced by using oxygenated fuels and catalytic converters [22-24].

2. LOW TEMPERATURE COMBUSTION ENGINE

Low Temperature Combustion Engine (LTCE) is an emerging Internal combustion engine technology that offers an attractive alternative to replace both spark ignition and compression ignition engines.Some advantages of LTCE are reduced emissions, low fuel consumption, use of wide variety of alternate fuels, high efficiency, fast combustion, controlled combustion etc. These are mainly divided into three types viz. premixed charged compression ignition (PCCI) engine, homogeneously charged compression ignition (HCCI) engine and reactivity-controlled compression ignition (RCCI) engine [25, 26].

2.1. HOMOGENEOUSLY CHARGE COMPRESSION IGNITION ENGINE

An HCCI engine is a combination of both conventional Spark-Ignition engine and Compression Ignition engine. The blending of these two engine designs offers diesel-like high efficiency without any difficulty and is inexpensive to deal with NOx and particulate matter emissions. The result is the best of both engines i.e., low fuel usage and low emissions [26].Hasan et al. [27]studied HCCI combustion at CR 11, speed 1500-2500 rpm with direct injection gasoline at a injection pressure of 200-225 bar.The results show reduction in NOx and HC emissions while CO emissions are increased. The fuel consumption is also decreased by 14%. Kim and Lee et al. [28]investigated HCCI combustion on a four stroke, single cylinder engine with gasoline, diesel and n-haptane as fuels. The engine was operated at CR 13, speed 1200 rpm and 40% EGR with premixed fuel condition. The results showedrise in cylinder pressure, heat release rate, HC emission and specific fuel consumption with increasing premixed ratio.It was also obsearved that the NOx and soot emissions are reducedwith gasoline fuel.Ahmet uyumaz et al. [29]performed expermental study on a single cylinder, four stroke HCCI combustion with CR 13, speed 1200 rpm. The fuel used was n-haptane.In this, isopropanol/n-haptane and n-butanol/n-haptanemixture is port injected at 200-225 bar injection pressure. The results showedincrease in IMEP by 25.71% whilereduction in combustion duration, heat release rate and cylinder pressure for the blend were observed.Reduction in IMEP were obsearved for higher inlet air temperature.The results also showedreduction in NOx emission while increase in CO and HC emissions was there.Kozarac et al. [30]studied the effect of biogas and n-haptane mixture on a multi cylinder, four stroke HCCI combustion engine with CR 17, speed 1800 rpm. The results showedreduction in IMEP for 20% n-haptane and increase in BTE for 18% n-haptane. It was also obsearved that combustion efficiency, cylinder temperature and peak heat release ratewere decreased. The NOx emissions werereduced while CO and HC emissions were increased.Jimenez-Espadafor et al. [31]investigated a single cylinder, four stroke with CR 18.4, speed 2100 rpm, operated withcolza biodiesel blendsas fuel with injection pressure of 300 bar. The results showedreduction in cylinder pressure and heat release rate, with increased EGR rate. The results also showed that the NOx emissions were decreased while CO, HC and smoke emissions were increased with increasing EGR rate.

The advantages of this engine are increased fuel efficiency, higher thermal efficiency, lower radiation loss, low soot and NOx emissions, use of variety of fuels, clean & fast combustion, and less frictional pumping loss.While the main challenges of HCCI combustion are difficulty in combustion phasing control, high levels of unburnt hydrocarbon (UHC) and carbon monoxide (CO) emissions, limited range of operation, cold start capacity, difficult homogeneous mixture preparation for poor volatile fuels, abnormal pressure rise with noise, it is necessary to study cycle to cycle variations, next generation engine control strategies and systems, cylinder to cylinder variation, etc., precise combustion model is needed to be developed with accurate chemical mechanism[25, 32].

2.2. PREMIXED CHARGED COMPRESSION IGNITION ENGINE

Premixed Charged Compression Ignition (PCCI) is a modern combustion process which is intended to be used in internal combustion engines and other types of motorized vehicles in future. A PCCI engine injects fuel and premixes the inlet charge during compression stroke. Thus, premixed charge is too lean to ignite during the compression stroke; the charge will ignite only after the last fuel injection that ends near the top dead centre (TDC). The fuel efficiency and working principle of a PCCI engine resembles with that of diesel engine, but a PCCI engine can run with variety of fuels and also, the partially premixed charge burns clean. Due to the advantages like higher specific power output, higher fuel efficiency and low engine exhaust, it is a promising future engine technology.Kiplimo et al. [33]studied PCCI combustion in a single cylinder, four stroke engine with CR 17.5, speed 1000 rpm. The fuel used was diesel using common rail system with injection pressure of 80 and 120 MPa. The results showed increase in IMEP and ITE of 48.7%, while peak cylinder pressure and heat release rate was decreased while using EGR. The results also showed reduction in NOx and smoke emissions, while CO and HC emissions were increased. Parks et al. [34]investigated PCCI combustion in a four cylinder engine using diesel fuel. The results showed reduction in NOx emissions which were <5g/bhp-hr and PM emissions where 0.35g/kg of fuel, while increase in CO emissions from 11.12 to 27.08g/bhp-hr and HC emissions from 1.59 to 8.13g/bhp-hr were obsearved. Liu et al. [35]performed an experimental study on a PCCI combustion in a single cylinder, four stroke engine with CR 16.5, speed1600 rpm. The fuel used was a blend of gasoline and diesel using common rail system with injection pressure of 80 bar. The results showed decrease in ITE, NOx, HC and soot emissions while increase in CO emissions at higher loads. Srihari et al. [36]studied PCCI combustion in a single cylinder, four stroke engine with CR 18, speed 2000 rpm. The fuel used was a blend of diethyle ether-biodiesel-diesel with two injections using common rail system; pilot injection given at 3.5 bar and main injection at 180 bar. The results showedreduction in BSFC of 0.2593 kg/kWh and increase in BTE 6.5% at higher loads. The peak cylinder pressure of 64.19 bar was obtained with the addition of diethyle ether. The results showed reduction in NOx, HC and smoke emissions, while CO emissions were increased.Lee et al. [37]investigated PCCI combustion in a single cylinder, four stroke engine with CR 15, speed 1500 rpm. The fuels used were propane and diesel in duel fuel mode using common rail system withan injection pressure of 75 Mpa. The results showed reduction in heat release rateand combustion duration upto 4.97 deg for dual mode. The results also showed reduction in NOx and PM emissions, while CO and HC emissions were increased.

2.3. REACTIVITY CONTROLLED COMPRESSION IGNITION ENGINE

Reactivity controlled compression ignition (RCCI) engine is a combination of HCCI engine and PCCI engine. Reactivity controlled compression ignition engine is a form of low temperature combustion engine in which a low-reactivity fuel and air are well-mixed and compressed but the auto-ignition temperature of inlet fuel is not reached. During compression stroke a high-reactivity fuel is injected into the cylinder to form a localized mixture of low-reactive and high-reactive fuel. After injection, the whole fuel charge is ignited at top dead centre (TDC) by injection of a high-reactivity fuel. The RCCI combustion processes require two different fuels for its working. Low-reactivity fuel gets injected to the intake ports with a low pressure during the intake stroke. A High-reactivity fuel gets injected to the cylinder with high pressure during and after compression stroke as in conventional CI engine. Because of the compression ignition and lack of throttle control, RCCI resembles much with diesel engine process [21, 25, 38].

Benajes et al. [39]used diesel in RCCI combustion as high reactivity fuel and gasoline as low reactivity fuel with up to 45% EGR. Results showed decrease in heat release rate and flame temperature. The results also showed reduction in NOx and soot emissions, while CO and HC emissions were increased.Li et al. [40]performed a numerical investigation of RCCI engine using palm oil methyl ester as high reactivity fuel and gasoline as low reactivity fuel. The result showed increase in heat release rate and cylinder pressure, while reduction in NOx and soot emission with increasing gasoline ratio.Benajes et al. [41]used biodiesel (7%)-diesel blend as high reactivity fuel and ethanol as low reactivity fuel with up to 45% EGR. The results showed decrease in IMEP, HRR and increased combustion duration with increasing premixed ratio. Also, decrease in NOx emissions of<1.5g/kwh, smoke emission of<0.01g/kwh up to medium loads,and increase in CO & HC emission of <4 g/kwh athigher loads were observed.Qian et al. [42]in RCCI engine used diesel as high reactivity fuel and gasoline & ethanol as low reactivity fuels. The results showed increase in indicated thermal efficiency for gasoline injection, increase in peak heat release rate and lower cylinder pressure for ethanol and increase in cylinder pressure & temperature with increasing premixed ratio for gasoline. The results also showed reduction in NOx emission of <20ppm at 0.8 PR and smoke emission of < 0.1m-1 at 0.8 PRfor ethanol, while increase in CO emission up to 0.5% and HC emission up to 1541 ppm at higher premixed ratios were observed. Qian et al. [43]performed a study on a RCCI combustion used n-heptane as high reactivity fuel and ethanol, n-butanol and n-amyl alcohol as low reactivity fuel. The results showed decrease in peak cylinder pressure up to 56.42 bar and heat release rate 31.9 degree/CA for higher premixed ratios. Also, the results showed reduction in NOx emission up to 89.5% and soot emission of 0.06m-1, while increase in CO emission up to 0.51% for ethanol and HC emission up to 1651ppm were observed.

Zhu et al. [44] analysed RCCI combustion using*n*-heptane as high reactivity fuel and gasoline, ethanol and *n*-butanol low reactivity fuel. The results showed increase in indicated thermal efficiency with advancing injection timing and increase in cylinder pressure and heat release rate for *n*-butanol fuel,longer ignition delay and cylinder pressure with advancing SOI. The results also showed reduction in NOx emission with increasing premixed ratio, reduction in CO, HC and smoke emission with advancing injection timing.Benajes et al. [41]performed experiments on a low load RCCI combustion engine by using B7 diesel as high reactivity fuel and E10-95, E10-98, E20-95 and E85 as low reactivity fuel. The results showed increase in indicated efficiency,and decrease in heat release rate. Also, reduction in NOx and smoke emissionswere observed, while increase in CO and UHC emissions observed were greater than EURO VI norms.Benajes et al. [45]investigated RCCI combustion using diesel as high reactivity fuel and gasoline as low reactivity fuel with up to 45% EGR. Results showed no change in heat release rate and flame temperature. The results also showed reduction in NOx emission by <0.4g/kWh, reduction in HC emission up to 45% EGR, reduction in soot and CO emissions up to 76% EGR.Benajes et al. [41]studied RCCI/CDC combustion mode using biodiesel (7%)-diesel blend as high reactivity fuel and 20% ethanol with 80% gasoline. The results found increase in maximum pressure. Reduction in NOx emissions below EURO VI norms and reduction in soot emission by 58%, while increase in CO emission by 37g/kWh and increase in HC emission by 23 g/kWh were observed.

Tong et al. [46]investigated RCCI combustion using diesel and polyoxymethylene dimethyl ethers (PODE) as high reactivity fuel and gasoline as low reactivity fuel. The results showed increase in indicated thermal efficiency at low load and increased cylinder pressure. Increase in NOx emission of 0.429g/kWh at full load and increase in CO emission of 16.87g/kWh were observed, while there was reduction in HC and Soot emissions.Nazemi and shahbakhti [47]did modelling analysis of RCCI engine using diesel as high reactivity fuel and gasoline as low reactivity fuel with up to 52% EGR. The results showed increase in peak cylinder pressure and temperature. Increase in NOx emission, while decrease in CO, HC and soot emission with advancing start of injection (SOI) of -63 aTDC were observed. Wang et al. [48]performed experiments on RCCI combustion using diesel as high reactivity fuel and gasoline as low reactivity fuel. The results showed decrease in fuel combustion with increasing gasoline fraction. Increase in MPRR and in-cylinder temperature were observed. Reduction in NOx emission of <2.5g/kwh, reduction in soot emission of <1mg/kwh, reduction in CO and HC emissions with optimizing operating conditions were also observed.Park et al. [49] investigated a dual fuel RCCI combustion using dimethyl ether (DME) as high reactivity fuel and ethanol as low reactivity fuel. The results showed reduction in indicated mean effective pressure up to 2.7 bar with advancing injection timing. An increase in ignition delay, combustion duration with retarded combustion phasing with increasing gasoline fraction were observed. Also, the results showed reduction in NOx emission of <0.4g/kWh and reduction in soot emission of < 1mg/kWh, while increase in CO emission up to 16g/kWh and increase in HC emission up to 1.46g/kWh were observed.

Isik and aydin [50]applied RCCI combustion in a diesel generator using safflower biodiesel-diesel blends as high reactivity fuel and ethanol as low reactivity fuel. The results showed increase in fuel combustion of about 360g/kwh, increase in BTE with addition of biodiesel fuel, increase in peak cylinder pressure and peak heat release rate for biodiesel addition. The resultsalso showed decrease in smoke and NOx by <490 ppm, while increase in CO emission up to 0.069% and HC emission of 730.54ppm.Benajes et al. [51]performed RCCI combustion mode using diesel as high reactivity fuel and gasoline as low reactivity fuel along with up to 60% EGR. The results showed decrease in ISFC with increasing gasoline fraction; and decrease in cylinder pressure and decrease in heat release rate. Also, results showed decrease in NOx and soot emissions below EURO VI while increase in CO and HC emissions.Zhang et al. [52]used n-heptane as high reactivity fuel and n-butanol as low reactivity fuel in a RCCI engine. The results showed increase in indicated thermal efficiency, cylinder pressure and heat release rate. Increase in CO and HC emissions, while reduction in NOx emission were observed.In RCCI combustionBenajes et al. [53] used diesel as high reactivity fuel and gasoline as low reactivity fuel. The results showed higher maximum gas temperature and decrease in NOx emission below EURO VI up to 75% load.Decrease in soot emission was observed, while CO and HC emission were increased with increasing engine speed and load.Benajes et al. [54]used diesel as high reactivity fuel and gasoline as low reactivity fuel. The results showed increase in heat release rate and cylinder pressure with increasing engine load. Decrease in HC and PM emission with increasing engine speed and load were observed.

Table 2. summary of performance, combustion and emission characteristics of RCCI engines.

Investigators	Fuel HRF/LRF	EGR (%)	Emission			
			NOx	CO	HC	PM/ Soot
Fang et al. [55]	Diesel/Gasoline	0–29%	Low	Low	High	Low
Benajes et al. [56]	Diesel/Gasoline	45%	Low	High	High	Low
Wang et al. [48]	Diesel/Gasoline	Up to 70%	Low	Low	Low	Low
Nazemi and Shahbakhti[47]	Diesel/Gasoline	Up to 52%	High	Low	Low	Low
Garcia et al. [57]	Diesel/Gasoline		Low	High	High	same
Poorghasemi et al. [58]	Diesel/NG	-	Low	High	High	-
Paykani et al. [59]	Diesel/NG	-	Low	High	High	Low
Kalsi and Subramanian [60]	Diesel/CNG	Up to 30%	Low	High	High	Low
Kalsi and Subramanian [61]	Pongamia pinnata biodiesel/ Hydrogen blendedwith CNG (HCNG)	-	Low	High	High	Low
Gharehghani et al. [62]	Waste fish oil biodiesel/ NG	-	Low	High	High	-
Park and Yoon [49]	Diesel/Biogas	-	Low	High	High	Low
Qian et al. [63]	Diesel/Biogas	-	-	-	-	Low
Krishnan et al. [64]	Diesel/Propane gas	-	Low	High	High	Low
Pedrozo et al. [65]	Diesel/Ethanol	-	Low	Low	Low	Low
Benajes et al. [41]	Biodiesel (7%)- Diesel blends/Ethanol	Up to 45%	Low	High	High	Low
Li et al. [66]	Diesel/Gasoline,Methanol	-	Low	High	High	-

3. CHALLENGES OF LTCE/RCCI

As discussed in the previous sections, all the variants of low temperature combustion engines are facing many challenges such as difficulty to operate in full load range, knocking phenomenon occurred at higher loads, higher HC and CO emissions, cycle-to-cycle variations etc. Some of the major drawbacks and their remedies are summarized below [21].

(i). Higher HC and CO emissions: The low temperature can be achieved by EGR and fuel reactivity. Due to the low temperature available for combustion in LTCE, complete combustion of fuel does not occur hence produces higher HC and CO emissions. These emissions can be effectively treated by some after-treatment device. But the efficiency and effectiveness of the after-treatment devices are also much dependent on temperature of exhaust gases. So, some more research is required to increase the effectiveness of after-treatment devices.

(ii). Higher load working: The LTCE at higher loads, produces more NOx, higher PRR and noise. This problem can be solved by using compound injection strategies and boosting device. Some renewable fuels such as biodiesel and ethanol can be used with diesel in blend form to extend the load range.

(iii). Ignition timing and combustion control: The combustion phenomenon in LTCE is administered by chemical kinetics of the fuel and is very difficult to control. The solution to this problem can be achieved by managing the fuel properties and air-fuel mixture time-temperature history. This can be done by changing intake air temperature, EGR, compression ratio, etc.

(iv). Combustion noise and stability: The un-stability of LTCE occurs due to misfiring and torque oscillations. These are difficult to control and this poses challenge in implementation in practical applications. There are number of factors such as ignition delay, ignition timing, combustion phasing, and peak pressure which are needed to be controlled. This can be done by using a close-loop control system with the help of different signals obtained from the cylinder.

(v). Cold start: The fuel properties, fuel injection strategy, engine design, operating parameters could significantly affect the combustion. So, the optimization of these parameters is very important. One of the possible solutions to this problem wouldbe to use some fuel additive or fuel vaporizer (for biodiesel) and providing glow plugs.

4. COMPARISON BETWEEN THE VARIANTS OF LTCE

RCCI is a dual fuel engine combustion technology and is a variant of homogeneous charge compression ignition (HCCI) that provides more control over the combustion process and has the potential to dramatically lower fuel consumption and emissions. The advantages of this engine are low NOx and PM emissions, low heat transfer losses, high fuel efficiency, increases thermal efficiency, use of alternative fuels and no after-treatment system requirement[67].The various disadvantages associated with RCCI engine are increased HC and CO emissions in comparison to conventional diesel combustion, implementation challenges andcontrol challenges. It needs a separate port fuel injector, a reservoir, fuel filter, fuel meter, electrically driven pump and heat exchanger [5]**.**By comparing of different low temperature combustion strategies, it is evident that amongst them RCCI engine proves to be the superior. Few points that summarise the superiority of RCCI engine on HCCI and PCCI are as follows:

(i) A RCCI engine can operate at loads ranging from low to high.

(ii) RCCI can use any type of fuel for its working.

(iii) RCCI produces thermal efficiency more than 50%.

(iv) No need of exhaust gas after-treatment device for NOx & PM emissions.

(v) Very low/negligible amount of NOx and soot emissions are produced.

(vi) CO and HC emissions produced are on a little higher side, that can be controlled by catalytic converter.

(vii) The exhaust emissions produced are below EURO VI level.

5. COMPARISON BETWEEN LTCE AND CDC

The figure 1 shows relation between cylinder temperature and equivalence ratio. It can be seen clearly that NOx emissions are increasing with increasing temperature, while soot emissions are increasing with increasingequivalence ratio. This is commonly known as NOx-soot trade off i.e., if temperature is increased NOx emissions are increased but soot emissions are reduced or vice-versa. It can be seen that CDC is emitting more emissions that LTCE, because of higher equivalence ratio and higher operating temperature. On the other hand,LTCE operating temperature is much lower i.e., below 2000 K and equivalence ratio up to 4.5.In LTCE, NOx versus (CO+UHC) trade-off has been observedwhile in CDC engine, NOx versus PM trade-off relationship has been observed [68]**.**

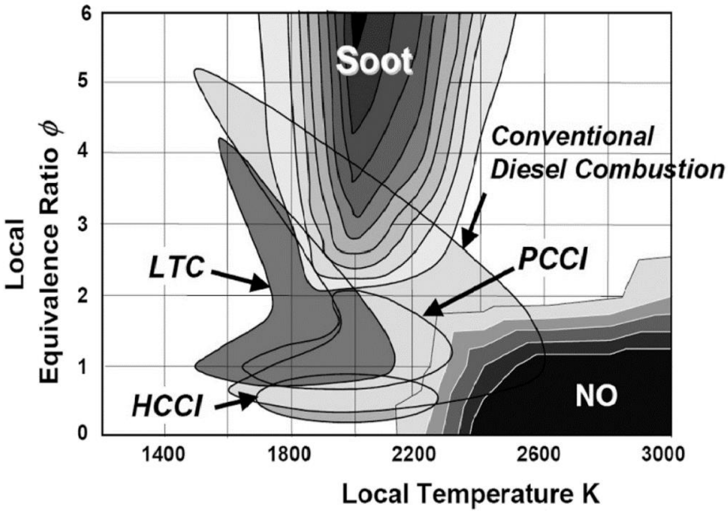

Figure 1. HCCI, PCCI, LTC and CDC operating T-Φ range [69].

Since invention, LTCE has shown great potential and abilityto produce high thermal efficiency, lower heat transfer losses, but at the same time it has also shown reduction in emissions specially NOx, PM and CO_2[70]. A comparison between CDC and LTC engine is shown in table 3.

Table 3. Comparison between LTCE and CDC engine [69, 71].

Factors	LTC Engine	CI Engine
Major Emissions	CO, HC	Low (CO & HC), High (PM & NOx)
Exhaust gas treatment	Required for CO and HC	Required
Temperature	Low (below 2100 K)	High (2700 K)
Heat transfer losses	12-14%	16%
Thermal efficiency	50%	30-35%
Net work output	45-53%	44%
Fuel air ratio (Φ)	Lean (fuel rich regions are absent)	Rich (fuel rich regions present)

6. CONCLUSION

Today more than 90% of transportation sector depends on IC engines which are responsible for 60-70% local pollution. The emissions produced by diesel engines are creating harmful effects on both human and environment. Various tools, techniques and devices are being used to control these emissions but all of them are seem to be insufficient. One effective method is to use LTCE that can not only increase the efficiency of engine but also reduces emissions. However, LTCE has some disadvantages such as low control over combustion,low load capacity, cycle-to-cycle variation in combustion, etc. Even though, this review article concludes that the LTCE exhibits promising future engine technology that can be used for transportation and power sector.

RCCI engine is able to reduce NOx and PM/soot emissions a level below EURO VI norms, but at the same time CO and HC emissions areincreased. The CO and HC emissions can be controlled by using catalytic converter as after-treatment of exhaust gases and brought down emissions below emission norms. It is also observed that low temperature combustion engine is very effective and has special ability that can be used in place of convention ICEs.LTCE on one hand increases efficiency, reduces fuel consumption and on the other hand reduces engine emissions to a great extent. It is also observed that low temperature combustion engine has thermal efficiency of more than 50%. Among all variants of LTCE, RCCI has an upper hand due to its number of advantages over others. The RCCI can operate at different loads, can use alternate fuels effectively, has lower emissions, lower cycle to cycle variations etc. However, more research is required to make them commercially viable.

REFERENCE

[1]. Kalghatgi G (2018) Is it really the end of internal combustion engines and petroleum in transport? Appl Energy 225:965–974. https://doi.org/10.1016/j.apenergy.2018.05.076.

[2]. Sioshansi F, Webb J (2019) Transitioning from conventional to electric vehicles: The effect of cost and environmental drivers on peak oil demand. Econ Anal Policy 61:7–15. https://doi.org/10.1016/j.eap.2018.12.005.

[3]. Askun T, Norsuzila Ya'acob1, Mardina Abdullah1, 2 and Mahamod Ismail1 2, Medina M, et al (2018) We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. Intech 32:137–144.

[4]. Kakaee AH, Rahnama P, Paykani A (2015) CFD Study of Reactivity Controlled Compression Ignition (RCCI) combustion in a heavy-duty diesel engine. Period Polytech Transp Eng 43:177–183. https://doi.org/10.3311/PPtr.7756.

[5]. Waritu J, Molvi I (2018) Review on Combustion and Performance Analysis of Reactivity Controlled Compression Ignition (Rcci) Engine. Int J Adv Eng Res Dev 5:556–564.

[6]. Mollenhauer K, Tschoeke H (2011) Handbook of diesel engines.

[7]. Kozina A, Radica G, Nižetić S (2020) Analysis of methods towards reduction of harmful pollutants from diesel engines. J Clean Prod 262:. https://doi.org/10.1016/j.jclepro.2020.121105.

[8]. Reşitoılu IA, Altinişik K, Keskin A (2015) The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technol Environ Policy 17:15–27. https://doi.org/10.1007/s10098-014-0793-9.

[9]. Olabi AG, Maizak D, Wilberforce T (2020) Review of the regulations and techniques to eliminate toxic emissions from diesel engine cars. Sci Total Environ 748:141249. https://doi.org/10.1016/j.scitotenv.2020.141249.

[10]. Englert N (2004) Fine particles and human health - A review of epidemiological studies. Toxicol Lett 149:235–242. https://doi.org/10.1016/j.toxlet.2003.12.035.

[11]. Baig K S, M Y (2017) Coal Fired Power Plants: Emission Problems and Controlling Techniques. J Earth Sci Clim Change 08: https://doi.org/10.4172/2157-7617.1000404.

[12]. Vehicle_emissions_control @ en.wikipedia.org.

[13]. Hoekman SK, Robbins C (2012) Review of the effects of biodiesel on NOx emissions. Fuel Process Technol 96:237–249. https://doi.org/10.1016/j.fuproc.2011.12.036.

[14]. Hamada H, Haneda M (2012) A review of selective catalytic reduction of nitrogen oxides with hydrogen and carbon monoxide. Appl Catal A Gen 421–422:1–13. https://doi.org/10.1016/j.apcata.2012.02.005.

[15]. Lao CT, Akroyd J, Eaves N, et al (2020) Investigation of the impact of the configuration of exhaust after-treatment system for diesel engines. Appl Energy 267:114844. https://doi.org/10.1016/j.apenergy.2020.114844.

[16]. Tsuneyoshi K, Yamamoto K (2012) A study on the cell structure and the performances of wall-flow diesel particulate filter. Energy 48:492–499. https://doi.org/10.1016/j.energy.2012.10.007.

[17]. Apicella B, Mancaruso E, Russo C, et al (2020) Effect of after-treatment systems on particulate matter emissions in diesel engine exhaust. Exp Therm Fluid Sci 116:110107. https://doi.org/10.1016/j.expthermflusci.2020.110107.

[18]. Zheng M, Banerjee S (2009) Diesel oxidation catalyst and particulate filter modeling in active - Flow configurations. Appl Therm Eng 29:3021–3035. https://doi.org/10.1016/j.applthermaleng.2009.04.017.

[19]. Kato T, Tsujimura K, Shintani M, et al (1989) Spray characteristics and combustion improvement of D.I. diesel engine with high pressure fuel injection. SAE Tech Pap. https://doi.org/10.4271/890265.

[20]. Arikado H (2002) NII-Electronic Library Service. Chem Pharm Bull 2091.
[21]. Pachiannan T, Zhong W, Rajkumar S, et al (2019) A literature review of fuel effects on performance and emission characteristics of low-temperature combustion strategies. Appl Energy 251:. https://doi.org/10.1016/j.apenergy.2019.113380.
[22]. Gupta SK, Anand K (2019) Experimental investigations to reduce unburned emissions in reactivity controlled compression ignition through fuel modifications. Appl Therm Eng 146:622–634. https://doi.org/10.1016/j.applthermaleng.2018.10.036.
[23]. Lilik GK, Boehman AL (2011) Advanced diesel combustion of a high cetane number fuel with low hydrocarbon and carbon monoxide emissions. Energy and Fuels 25:1444–1456. https://doi.org/10.1021/ef101653h.
[24]. Hodges KA, Aniello A, Krishnan SR, Srinivasan KK (2017) Impact of propane energy fraction on diesel-ignited propane dual fuel low temperature combustion. Fuel 209:769–775. https://doi.org/10.1016/j.fuel.2017.07.096.
[25]. Maurya RK (2017) Characteristics and Control of Low Temperature Combustion Engines.
[26]. Canyon Hydro, Summary E, Of F, et al (2013) We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. Intech 32:137–144.
[27]. Hasan AO, Abu-Jrai A, Al-Muhtaseb AH, et al (2016) HC, CO and NOx emissions reduction efficiency of a prototype catalyst in gasoline bi-mode SI/HCCI engine. J Environ Chem Eng 4:2410–2416. https://doi.org/10.1016/j.jece.2016.04.015.
[28]. Kim DS, Lee CS (2006) Improved emission characteristics of HCCI engine by various premixed fuels and cooled EGR. Fuel 85:695–704. https://doi.org/10.1016/j.fuel.2005.08.041.
[29]. Uyumaz A (2015) An experimental investigation into combustion and performance characteristics of an HCCI gasoline engine fueled with n-heptane, isopropanol and n-butanol fuel blends at different inlet air temperatures. Energy Convers Manag 98:199–207. https://doi.org/10.1016/j.enconman.2015.03.043.
[30]. Kozarac D, Taritas I, Vuilleumier D, et al (2016) Experimental and numerical analysis of the performance and exhaust gas emissions of a biogas/n-heptane fueled HCCI engine. Energy 115:180–193. https://doi.org/10.1016/j.energy.2016.08.055.
[31]. Jiménez-Espadafor FJ, Torres M, Velez JA, et al (2012) Experimental analysis of low temperature combustion mode with diesel and biodiesel fuels: A method for reducing NOx and soot emissions. Fuel Process Technol 103:57–63. https://doi.org/10.1016/j.fuproc.2011.11.014.
[32]. Sharma TK, Rao GAP, Murthy KM (2016) Homogeneous charge compression ignition (HCCI) engines: A review. Arch Comput Methods Eng 23:623–657. https://doi.org/10.1007/s11831-015-9153-0.
[33]. Kiplimo R, Tomita E, Kawahara N, Yokobe S (2012) Effects of spray impingement, injection parameters, and EGR on the combustion and emission characteristics of a PCCI diesel engine. Appl Therm Eng 37:165–175. https://doi.org/10.1016/j.applthermaleng.2011.11.011.
[34]. Parks JE, Prikhodko V, Storey JME, et al (2010) Emissions from premixed charge compression ignition (PCCI) combustion and affect on emission control devices. Catal Today 151:278–284. https://doi.org/10.1016/j.cattod.2010.02.053.
[35]. Liu H, Wang Z, Wang J, He X (2014) Effects of gasoline research octane number on premixed low-temperature combustion of wide distillation fuel by gasoline/diesel blend. Fuel 134:381–388. https://doi.org/10.1016/j.fuel.2014.06.019.
[36]. Srihari S, Thirumalini S, Prashanth K (2017) An experimental study on the performance and emission characteristics of PCCI-DI engine fuelled with diethyl ether-biodiesel-diesel blends. Renew Energy 107:440–447. https://doi.org/10.1016/j.renene.2017.01.015.
[37]. Lee J, Chu S, Cha J, et al (2015) Effect of the diesel injection strategy on the combustion and emissions of propane/diesel dual fuel premixed charge compression ignition engines. Energy 93:1041–1052. https://doi.org/10.1016/j.energy.2015.09.032.
[38]. Hassan BAR, Yusoff ZBM, Othman MAH, et al (2012) We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. Intech 32:13.
[39]. Benajes J, Molina S, García A, et al (2014) An investigation on RCCI combustion in a heavy duty diesel engine using in-cylinder blending of diesel and gasoline fuels. Appl Therm Eng 63:66–76. https://doi.org/10.1016/j.applthermaleng.2013.10.052
[40]. Li J, Yang WM, An H, Zhao D (2015) Effects of fuel ratio and injection timing on gasoline/biodiesel fueled RCCI engine: A modeling study. Appl Energy 155:59–67.

https://doi.org/10.1016/j.apenergy.2015.05.114.
[41]. Benajes J, Molina S, García A, Monsalve-Serrano J (2015) Effects of direct injection timing and blending ratio on RCCI combustion with different low reactivity fuels. Energy Convers Manag 99:193–209. https://doi.org/10.1016/j.enconman.2015.04.046.
[42]. Qian Y, Wang X, Zhu L, Lu X (2015) Experimental studies on combustion and emissions of RCCI (reactivity controlled compression ignition) with gasoline/n-heptane and ethanol/n-heptane as fuels. Energy 88:584–594. https://doi.org/10.1016/j.energy.2015.05.083.
[43]. Qian Y, Ouyang L, Wang X, et al (2015) Experimental studies on combustion and emissions of RCCI fueled with n-heptane/alcohols fuels. Fuel 162:239–250. https://doi.org/10.1016/j.fuel.2015.09.022.
[44]. Zhu L, Qian Y, Wang X, Lu X (2015) Effects of direct injection timing and premixed ratio on combustion and emissions characteristics of RCCI (Reactivity Controlled Compression Ignition) with N-heptane/gasoline-like fuels. Energy 93:383–392. https://doi.org/10.1016/j.energy.2015.09.069.
[45]. Benajes J, Pastor J V., García A, Monsalve-Serrano J (2015) The potential of RCCI concept to meet EURO VI NOx limitation and ultra-low soot emissions in a heavy-duty engine over the whole engine map. Fuel 159:952–961. https://doi.org/10.1016/j.fuel.2015.07.064.
[46]. Tong L, Wang H, Zheng Z, et al (2016) Experimental study of RCCI combustion and load extension in a compression ignition engine fueled with gasoline and PODE. Fuel 181:878–886. https://doi.org/10.1016/j.fuel.2016.05.037.
[47]. Nazemi M, Shahbakhti M (2016) Modeling and analysis of fuel injection parameters for combustion and performance of an RCCI engine. Appl Energy 165:135–150. https://doi.org/10.1016/j.apenergy.2015.11.093.
[48]. Wang Y, Yao M, Li T, et al (2016) A parametric study for enabling reactivity controlled compression ignition (RCCI) operation in diesel engines at various engine loads. Appl Energy 175:389–402. https://doi.org/10.1016/j.apenergy.2016.04.095.
[49]. Park SH, Yoon SH (2016) Effect of dual-fuel combustion strategies on combustion and emission characteristics in reactivity controlled compression ignition (RCCI) engine. Fuel 181:310–318. https://doi.org/10.1016/j.fuel.2016.04.118.
[50]. Işık MZ, Aydın H (2016) Analysis of ethanol RCCI application with safflower biodiesel blends in a high load diesel power generator. Fuel 184:248–260. https://doi.org/10.1016/j.fuel.2016.07.017.
[51]. Benajes J, Pastor J V., García A, Boronat V (2016) A RCCI operational limits assessment in a medium duty compression ignition engine using an adapted compression ratio. Energy Convers Manag 126:497–508. https://doi.org/10.1016/j.enconman.2016.08.023.
[52]. Zhang C, Zhang C, Xue L, Li Y (2017) Combustion characteristics and operation range of a RCCI combustion engine fueled with direct injection n-heptane and pipe injection n-butanol. Energy 125:439–448. https://doi.org/10.1016/j.energy.2017.02.148.
[53]. Benajes J, García A, Monsalve-Serrano J, Boronat V (2017) Achieving clean and efficient engine operation up to full load by combining optimized RCCI and dual-fuel diesel-gasoline combustion strategies. Energy Convers Manag 136:142–151. https://doi.org/10.1016/j.enconman.2017.01.010.
[54]. Benajes J, García A, Monsalve-Serrano J, Boronat V (2017) An investigation on the particulate number and size distributions over the whole engine map from an optimized combustion strategy combining RCCI and dual-fuel diesel-gasoline. Energy Convers Manag 140:98–108. https://doi.org/10.1016/j.enconman.2017.02.073.
[55]. Fang W, Kittelson DB, Northrop WF (2015) Optimization of reactivity-controlled compression ignition combustion fueled with diesel and hydrous ethanol using response surface methodology. Fuel 160:446–457. https://doi.org/10.1016/j.fuel.2015.07.055.
[56]. Benajes J, García A, Monsalve-Serrano J, Boronat V (2017) Gaseous emissions and particle size distribution of dual-mode dual-fuel diesel-gasoline concept from low to full load. Appl Therm Eng 120:138–149. https://doi.org/10.1016/j.applthermaleng.2017.04.005.
[57]. García A, Monsalve-Serrano J, Rückert Roso V, Santos Martins ME (2017) Evaluating the emissions and performance of two dual-mode RCCI combustion strategies under the World Harmonized Vehicle Cycle (WHVC). Energy Convers Manag 149:263–274. https://doi.org/10.1016/j.enconman.2017.07.034.
[58]. Poorghasemi K, Saray RK, Ansari E, et al (2017) Effect of diesel injection strategies on natural gas/diesel RCCI combustion characteristics in a light duty diesel engine. Appl Energy 199:430–446. https://doi.org/10.1016/j.apenergy.2017.05.011.

[59]. Paykani A, Kakaee AH, Rahnama P, Reitz RD (2015) Effects of diesel injection strategy on natural gas/diesel reactivity controlled compression ignition combustion. Energy 90:814–826. https://doi.org/10.1016/j.energy.2015.07.112.

[60]. Singh Kalsi S, Subramanian KA (2016) Experimental investigations of effects of EGR on performance and emissions characteristics of CNG fueled reactivity controlled compression ignition (RCCI) engine. Energy Convers Manag 130:91–105. https://doi.org/10.1016/j.enconman.2016.10.044.

[61]. Kalsi SS, Subramanian KA (2017) Experimental investigations of effects of hydrogen blended CNG on performance, combustion and emissions characteristics of a biodiesel fueled reactivity controlled compression ignition engine (RCCI). Int J Hydrogen Energy 42:4548–4560. https://doi.org/10.1016/j.ijhydene.2016.12.147.

[62]. Gharehghani A, Hosseini R, Mirsalim M, et al (2015) An experimental study on reactivity controlled compression ignition engine fueled with biodiesel/natural gas. Energy 89:558–567. https://doi.org/10.1016/j.energy.2015.06.014.

[63]. Qian Y, Zhang Y, Wang X, Lu X (2017) Particulate matter emission characteristics of a reactivity controlled compression ignition engine fueled with biogas/diesel dual fuel. J Aerosol Sci 113:166–177. https://doi.org/10.1016/j.jaerosci.2017.08.003.

[64]. Krishnan SR, Srinivasan KK, Raihan MS (2016) The effect of injection parameters and boost pressure on diesel-propane dual fuel low temperature combustion in a single-cylinder research engine. Fuel 184:490–502. https://doi.org/10.1016/j.fuel.2016.07.042.

[65]. Pedrozo VB, May I, Lanzanova TDM, Zhao H (2016) Potential of internal EGR and throttled operation for low load extension of ethanol-diesel dual-fuel reactivity controlled compression ignition combustion on a heavy-duty engine. Fuel 179:391–405. https://doi.org/10.1016/j.fuel.2016.03.090.

[66]. Li Y, Jia M, Chang Y, et al (2016) Towards a comprehensive understanding of the influence of fuel properties on the combustion characteristics of a RCCI (reactivity controlled compression ignition) engine. Energy 99:69–82. https://doi.org/10.1016/j.energy.2016.01.056.

[67]. Abdul Siddique Sk and Nataraj TSC (2016) Effect of modified design on engine fuel efficiency. Int. Journal of Engineering Research and Applicatio ISSN : 2248-9622, Vol. 6, Issue 9, (Part -2) September 2016, pp.19-27.

[68]. Kreicbergs J, Grislis A, Zalcmanis G, Rudzitis J (2014) Effect of modified diesel fuel on engine fuel efficiency. Eng Rural Dev 13:283–287.

[69]. Simescu S, Fiveland SB, Dodge LG (2003) An experimental investigation of PCCI-DI combustion and emissions in a heavy-duty diesel engine. SAE Tech Pap 2003:. https://doi.org/10.4271/2003-01-0345.

[70]. Neely GD, Sasaki S, Huang Y, et al (2005) New diesel emission control strategy to meet US tier 2 emissions regulations. SAE Tech Pap 2005:. https://doi.org/10.4271/2005-01-1091.

[71]. Shim E, Park H, Bae C (2020) Comparisons of advanced combustion technologies (HCCI, PCCI, and dual-fuel PCCI) on engine performance and emission characteristics in a heavy-duty diesel engine. Fuel 262:116436. https://doi.org/10.1016/j.fuel.2019.116436.

[72]. Foster DE (2012) Topic Paper # 6 Low Temperature Combustion.