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REVIEW ARTICLE

A Comprehensive Review on Low-Temperature Combustion Technologies for Emission Reduction in Diesel Engines

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ABSTRACT – Diesel engines are lean burn engines; hence CO and HC emissions in the exhaust are less likely to occur in substantial amounts. The emissions of serious concern in compression ignition engines are particulate matter and nitrogen oxides because of elevated temperature conditions of combustion. Hence the researchers have strived continuously to lower down the temperature of combustion in order to bring down the emissions from CI engines. This has been tried through premixed charge compression ignition, homogeneous charge compression ignition (HCCI), gasoline compression ignition and reactivity controlled compression ignition (RCCI). In this study, an attempt has been made to critically review the literature on low-temperature combustion conditions using various conventional and alternative fuels. The problems and challenges augmented with the strategies have also been described. Water-in-diesel emulsion technology has been discussed in detail. Most of the authors agree over the positive outcomes of water-diesel emulsion for both performance and emissions simultaneously.

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NOMENCLATURE

BS	bharat stage	HC	hydro-carbons
SI	spark ignition	PM	particulate matter
CI	compression ignition	IC	internal combustion
HCCI	homogenous charged compression ignition	LTC	low temperature combustion
RCCI	reactive controlled compression ignition	AQI	air quality index
PPCI	partially premixed compression ignition	DPF	diesel particulate filter
CO	carbon mono-oxide	DOC	diesel oxidation catalysts
NO_x	nitrogen oxides	EGR	exhaust gas recirculation
BTE	brake thermal efficiency	LTR	low temperature range
CN	Cetane number	CR	compression ratio
DBTP	di-tertiary butyl peroxide	CA	crank angle
RCM	rapid combustion machine	WED	water emulsified diesel emulsion

INTRODUCTION

Most of the research associated with the automotive industry is mainly focused on two aspects i.e. first, to provide fuel-efficient technology and second, to reduce exhaust emissions. In automotive applications, CI engines are more common because of their better thermal efficiency and heavy-duty viability. But the high exhaust emissions out of diesel engines limits its use which is a matter of great concern [1]. Authorities are continuously making the emission standards more stringent to control greenhouse emissions (Figure 1). In India, BS-VI is going to be implemented by the year 2020, surpassing BS-V to address the alarming pollution stage. It would be pretty challenging for the automotive industry [2]. These stringent emission regulations and continuous depletion of fossil fuel reserves have enforced the researchers to develop new, efficient, eco-friendly combustion technologies and arrangements which could operate on alternative fuels also. Since compression ignition engines require high-pressure conditions (high compression ratio) and hence it develops a high temperature zone inside the cylinder. These high temperature conditions are responsible for NO, soot, smoke and particulate matter emissions [3]. In various studies by researchers across the globe, it has been tried to lower down this combustion temperature to achieve lower emission goals. These technologies to reduce the combustion zone temperature are specifically called low-temperature combustion (LTC) technologies like premixed charge compression ignition, homogeneous charge compression ignition (HCCI), gasoline compression ignition and reactivity controlled compression

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ignition (RCCI). In this study, an attempt has been made to critically review and present an overview from the fundamentals to the recent advancements on such technologies. Water-in-diesel emulsion (WiDE) technology has also been found as a fuel-efficient and low-emission technology without requiring any modifications in the existing conventional engines. It has been discussed in detail. The problems and challenges augmented with the strategies have also been described.

Global Scenario of Energy and Emissions

The current era of energy crisis, environmental imbalance and stringent emission standards stress for improvement in energy efficiency along with the reduction in harmful emissions. The high rate of increase in population, urbanisation, globalisation and motorisation in the developing world contribute to this imbalance created by the developed world. UN is predicting the world's population to increase by 2 billion further to reach the mark of 9.7 billion in the upcoming 30 years by 2050 [4]. Moreover, the level of comfort and facilities which are being planned for the generations ahead will enhance the energy demand at an even higher rate, as shown in Figure 2. All countries are striving hard to make themselves energy sustainable as energy is the basic entity for humans to survive. Researchers over the globe are attempting to develop smart and efficient technologies for sustainable use of the available resources [5].

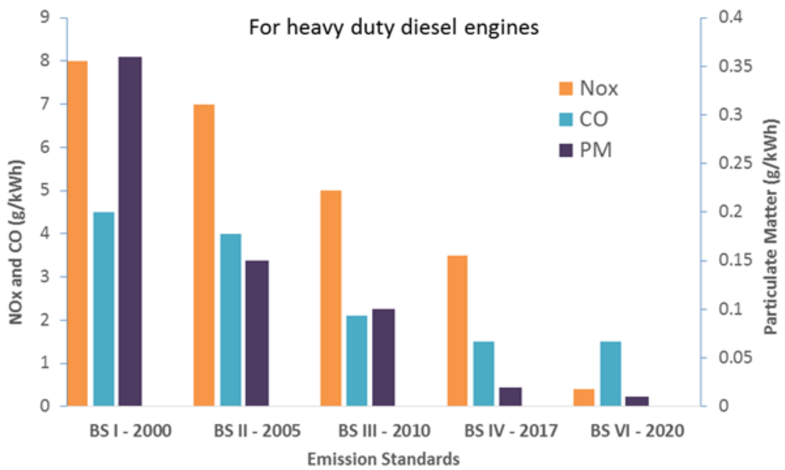

Figure 1. Emission standards getting stringent year by year [6].

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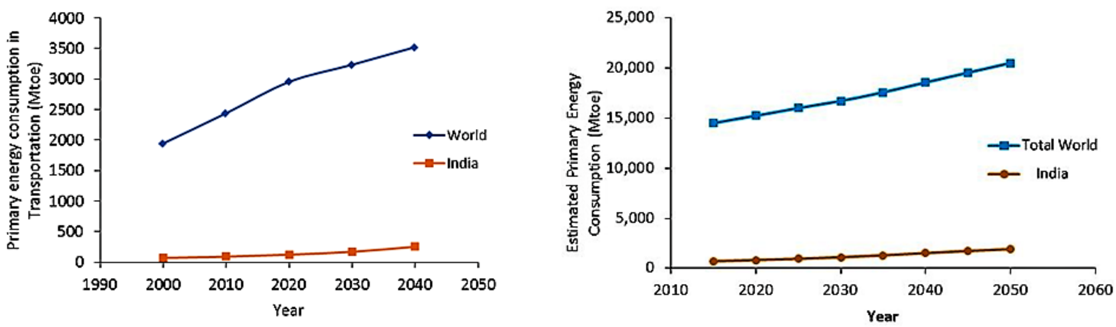


Figure 2. Increase in energy demand [7].

However, there is a good sign of shifting the energy dependency from fossil fuels to renewable fuels, which also shows how rising prosperity drives an increase in global energy demand and how that demand will be met over the coming decades through a diverse range of supplies, including oil, gas, coal and renewables [7]. Countries like Nigeria consumes a good amount (80%) of biomass and waste for their total primary energy need [8]. However, while most of the energy-dependent areas have seen a good transition from conventional to renewable energy, many sectors like transportation are still only at an introductory level in the use of renewable fuels [9]. Owing to high power density, internal combustion engines are extensively used in transportation and as a stationary power source. The emerging transport sector raises a big alarm for continuously depleting fossil fuels and increasing harmful emissions coming from vehicles.

Diesel Engine Emissions

NO_x, CO, HC, SO_x, particulates, soot and smoke are major exhaust emissions of IC engines. Out of these, CO and HC are common in SI engines, while NO and smoke (soot) are more common in diesel engines [11]. The rich air-fuel mixture creates a situation of lesser oxygen availability, where the reaction between carbon and oxygen becomes difficult, and it results in excess of CO and HC emission in the exhaust gases. In advanced combustion technologies, complete combustion of fuel hydrocarbons reduces the likelihood of CO and HC emission because diesel engines are lean-burn engines. The formation of oxides of nitrogen in diesel is mostly because of the nitrogen present in the air. Nitrogen exists in a stable diatomic form at low temperatures. At a temperature range of 2500-3000K, a significant amount of very reactive monoatomic nitrogen is generated [12]. The higher the combustion temperature, the more the monoatomic nitrogen will be formed by the dissociation of diatomic nitrogen, and hence more NO_x formation will occur. Improper combustion and high temperature conditions promote smoke. Many cities (like New Delhi in India) are gripped by heavy smoke, which is a big threat to our health and complete eco-system, in fact. Seven out of ten most polluted cities in the world are from India, with an average 113.5g/m^3 concentration of PM2.5 in Delhi [8]. Figure 3 shows that a significant amount of this particulate matter is from the transportation sector [10]. Many regions in New Delhi have recorded an Air Quality Index (AQI) up to 720 on regular days as compared to the good and satisfactory range of 0-50 and 51- 100 respectively which is a very serious concern (Figure 4).

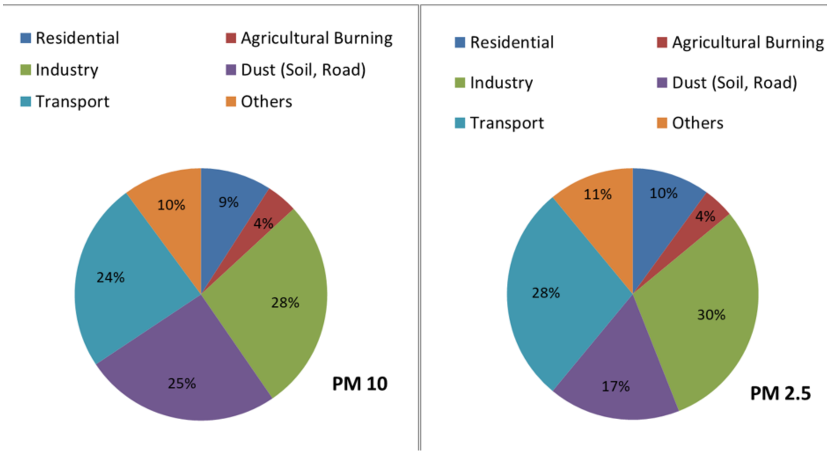


Figure 3. Sources of particulate matter in New Delhi sector wise [10].

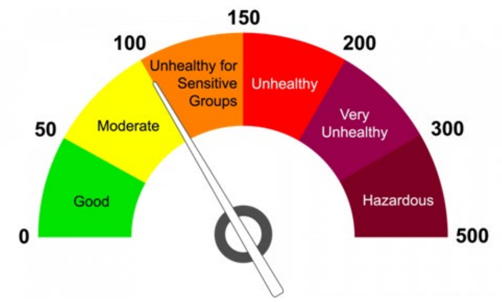


Figure 4. Various AQI Levels and their effects [13].

Mitigation of NO_x and Particulate Matter

As discussed in the above paragraph, the two important diesel emissions i.e., soot and oxides of nitrogen, could be controlled using various techniques. Mitigation of soot and NOx emissions together is not an easy task due to the process difference of their generation. By taking an example, the most common technique to reduce NOx emission is exhaust gas recirculation (EGR) but it results in increased PM emission [14]. Contrary to it, advancing the injection timing decreases the PM emissions with an increase in NO_x emission [15]. The high oxygen content of biodiesel fuel blends do normally generate less amount of carbon monoxide (CO), hydrocarbon (HC) and smoke (PM) emissions but its proximity to generate NO_x emission is more. However, various appropriate after-treatment technologies like diesel particulate filter (DPF) [16], diesel oxidation catalyst (DOC) [17] and catalytic converters [18] are successfully employed to curb both the emissions simultaneously with drawbacks like high cost, lower fuel economy and unnecessary maintenance. Hence, avoiding these drawbacks and expensive maintenance certain low-temperature combustion (LTC) techniques have been developed over the years, which address the problem of both NO_x and soot/particulate matter. The significant highlights of LTC involve lower temperature of combustion zone, better fuel atomisation and homogenisation, lower local equivalence ratios [19]. These features of LTC increase the potential to reduce the PM and NOx emissions together. A major problem has been found which is associated with LTC engines is its higher carbon monoxide (CO) and hydrocarbon (HC) emissions. However, HC and CO emissions remain within the prescribed limits, yet it has been suggested in the literature that it could be dealt with after-treatment devices like catalytic converters [20].

Low-Temperature Combustion Engine Fuels

Conventionally, the CI engines are fuelled with diesel fuel and sometimes with a small amount of biodiesel of low volatility, high viscosity and, moderate cetane number [21]. It does not let the air-fuel mixture become homogeneous before the beginning of combustion, and hence it tends to generate locally rich regions with high-temperature conditions

(Figure 5). It results in the emission of more PM and NOx emissions [22]. Thus, in LTC, the facility of increased air-fuel mixing do not let fuel rich regions to develop, which lowers down the temperature of the combustion zone and hence decreases both NOx and PM emissions, respectively [23,24]. Lower cetane number fuels were used by most of the researchers for LTC as it prolongs ignition delays and it allows more time for the homogeneous mixture to be developed [25,26]. Judit et al. [27] explained the LTC phenomenon in depth by studying the kinetics involved in the reactions during LTC. Water emulsified diesel fuel technique also works on the same principle, which improves thermal efficiency along with the decrease in emissions [28].

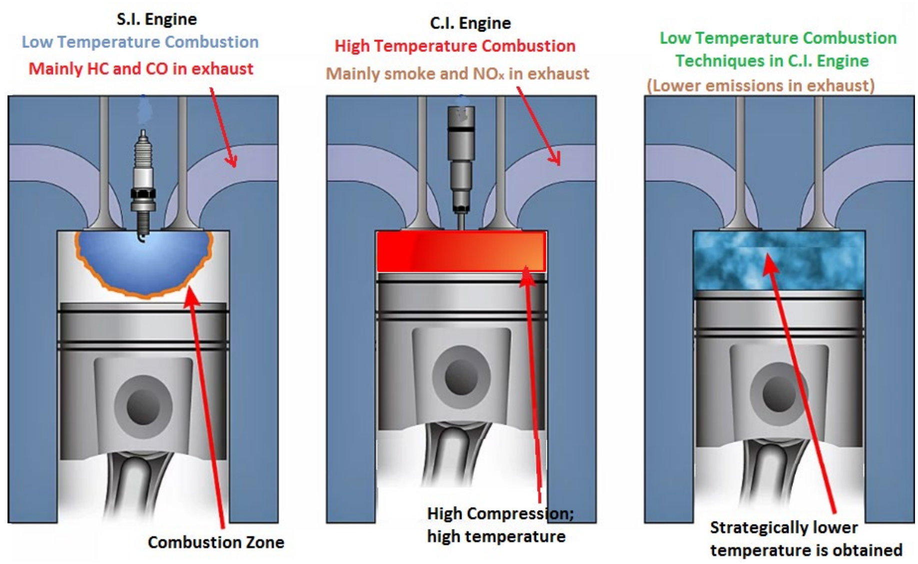


Figure 5. Effect of low-temperature combustion shown graphically.

This article is aimed to focus various LTC technologies and their effects on the performance parameters, combustion characteristics and exhaust emissions of the engine with conventional as well as non-conventional fuels. Agarwal et al. [29] Pachiannan et al. [15] have also reviewed the LTCs, but water emulsified diesel fuel technology is missing from them. Physicochemical properties of fuel influence the combustion quality and hence the combustion characteristics [30], hence these have also been discussed in detail for water emulsified diesel fuel. Because of the change in these properties, the effects it creates on the engine parameters have also been reviewed to understand the engine behaviour. Briefing all the important strategies of LTC, this paper provides a detailed review on the chemistry, preparation, performance, combustion and emission characteristics of water-in-diesel emulsion along with other biodiesels.

HCCI TECHNOLOGY

HCCI is referred to homogeneous charge compression ignition combustion, which is a process of combustion in which a homogeneous charge of air and fuel is fed to the cylinder and compressed as like in diesel engine so that at the end of the compression stroke, fuel gets auto-ignited. This process is considerably faster than either spark ignition or compression ignition combustion [31]. A comparative analysis in HCCI, CI, and SI combustion processes have been performed based on different parameters influencing the combustion is indicated in Table 1 and Table 2.

Table 1. Comparison of HCCI with SI engine [32].

Basis of comparison	Efficiency	Throttle losses	Compression ratios	Combustion duration	HC and CO emissions
SI engine	Less	More	Low	More	Comparatively more
HCCI engine	More	No	High	Less	Less

Table 2. Comparison of HCCI with CI engine [33].

Basis of comparison	Efficiency	Combustion temperatures	Cost	Combustion duration	PM and NOx emissions
Diesel engine	High	1900-2100 K	Comparatively high	More	More
HCCI engine	Equally high	800-1100 K	Less	Less	Less

HCCI combustion could improve the BTE while controlling the emissions and is applicable in both CI and SI engines after some modification. A range of alternative fuels could be used. Lean air-fuel mixtures are preferred in HCCI engines. The charge ignites automatically at several locations and unlike SI engine, combustion takes place without any visible flame of propagation [34]. It shows a high rate of heat release because of simultaneous burning of fuel in a very low combustion time [35]. Some advantages of HCCI combustion could be pointed as (i) along with meeting the stringent emissions standards, HCCI provides up to a 30-per cent fuel savings [36]. (ii) HCCI engines work on leaner air-fuel ratios which facilitate higher compression ratios like diesel (>15). It results in the attainment of higher efficiencies as compared to conventional spark-ignited petrol engines [37]. (iii) Homogeneous mixing of air and fuel emits lower emissions and hence cleaner combustion. Since, peak temperatures in typical spark-ignited engines are significantly lower, so NO_X levels are almost negligible. Moreover, lean premixed mixtures do not produce soot and smoke. HCCI engines can be fuelled with gasoline, diesel, or any other alternative fuels as like biodiesels.

Alternatively, there are also certain drawbacks to HCCI such as high peak pressures which may harm the engine with high diesel knock. Engine-wear increases because of the high rate of rise in pressure and high rate of heat release. Auto-ignition control is difficult in HCCI, which is not in the case of gasoline (SI) and diesel engines. The lower combustion duration and low in-cylinder temperatures, emissions like hydrocarbon (HC), carbon monoxide (CO) are higher than a usual spark-ignition engine [38].

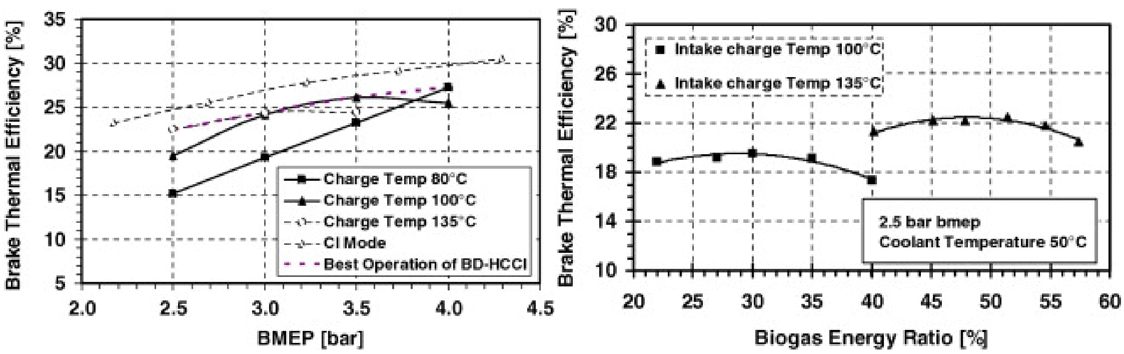
Principle of HCCI

HCCI is a combination of the two most common combustion phenomenon which utilise principles of SI and CI engines. Likewise, spark ignition, homogeneous charge of the fuel and oxidiser are fed together in the mixed form [39]. Whereas density and temperature of the charge in a diesel engine are increased by compression till the whole mixture reaches auto-ignition. Combustion initiates at the border of air-fuel mixing at the start of injection event, to initiate combustion [40].

During combustion with HCCI, simultaneous ignition occurs at several sites. There is no automatic combustion initiator. This makes it fundamentally difficult to control the process [39]. With the continuous advancements in microprocessors, HCCI can be operated with diesel like higher efficiency and gasoline-like lower emissions. In addition, it has been shown that HCCI engines produce extremely low levels of NO_X emissions without any after-treatment process like catalytic converter. Because of lower peak temperatures, Carbon monoxide emissions and unburned hydrocarbons are still high as in petrol engines and need to be handled to comply with automobile emissions regulations [33].

Performance and Emissions with HCCI

Most of the researchers [41,42] have observed the performance of HCCI engines is better in terms of thermal efficiency as compared to the conventional diesel engines. Swaminathan et al. [43] used biogas as a fuel in their study to compare and analyse the effect of HCCI engine with a conventional diesel engine. They used different intake temperatures and found that the thermal efficiency higher than a diesel engine at 135°C intake temperature. With hydrogen as a fuel Gomesantunes et al. [44] reported 45% higher thermal efficiency than diesel engines (Figure 6(a)). Moreover, on increasing the gaseous fuel content brake thermal efficiency increased in HCCI mode, as in Figure 6(b). Canacki et al. [45] also found similar results with gasoline as fuel. Alternatively, some researchers also got opposite trends [12,46,47]. This lower efficiency was attributed to improper mixture formation, quality of fuel etc. Since HCCI engines operate on lean air-fuel ratios, the in-cylinder gas temperature remains below the range of 2000-2100 K. This low temperature does not provide an atmosphere for NOx formation because NOx is formed at high temperature conditions [48]. In the literature, it is a finding of almost all the authors that NOx emissions become almost negligible in HCCI combustion as compared to normally operated CI engines [31,43,45,47,49,50]. Results of various other researches have been compared in the Table 3.



(a) (b)

Figure 6. Brake thermal efficiency of biogas-diesel HCCI operation (a) for the operation window, and (b) at BMEP=2.5 bar [43].

Table 3. Experimental work of different researchers on HCCI technology.

Ref	Engine set up	Operating condition	Fuel used	Performance		Exhaust emissions				Other
				BTE	BSFC	NOx	CO	HC	Soot	
[46]	Power-4.4 kW; CR=17.5:1; speed-1500 rpm; IP-200 bar	HCCI with external mixture formation	Diesel	↓12.6%	-	↓95%	↑7.5 g/kWh	-	-	
[51]	Single cylinder; CR=10.5:1 Direct and port injection	HCCI	Gasoline			Lower				Operating range of HCCI was expanded
[50]	Speed-1500-2500 rpm; CR=11:1; Direct injection	Gasoline bi-mode SI/ HCCI with a prototype catalyst	Gasoline		14% lesser	Up to 35-55% reduction	Up to 90-95% reduction	Up to 90-95% reduction		After treatment is performed
[52]	Single cylinder; CR=13:1; EGR=42%	HCCI	Gasoline + Methanol	High		Reduced using methanol stratifi-cation	Lower from stratified combust-ion			50% high IMEP
[53]	Two cylinder; CR=16.5:1; Speed=1500 rpm; Direct injection	HCCI Intake temperature =120-150ºC	Ethanol				High	High		-
[54]	Single cylinder; CR=17.5:1; power=7.4kW; speed=1800 rpm	HCCI multipoint injection	Diesel			Low		56% lower	24% lower	Compared to single point injection
[55]	four-stroke, single-cylinder, DI, air-cooled CI engine; CR=17:1	HCCI	Hydrogen	High	-	Low	0	-	0	CO and HC emissions are zero because of H_2 fuel

PARTIALLY PREMIXED COMPRESSION IGNITION

Various limitations of HCCI like high rate of pressure rise arose of shorter combustion duration, and difficulty in controlling the initiation of combustion have evolved a newer concept of PPCI combustion. An important difference between HCCI and PPCI combustion is the charge distribution of PPCI which is somewhat heterogeneous rather than HCCI. EGR is employed to achieve low combustion temperatures. In conventional diesel engine fuel is injected little before the top dead-center and ignition initiates before the complete injection. Thus, less fuel entered is premixed before the start of combustion. In PPCI, premixing of complete injected fuel is facilitated, even the fuel injected at the end.

With a high rate in rise of pressure in the cylinder, more knocking is observed. This imposes constraints on the required dilution and further increase in the CO and unburned HC. Zhang et al. [56] used gasoline and mineral diesel (dieseline) for their investigation for the partially premixed compression ignition (PPCI) system of combustion. For PPCI combustion, injection timings and EGR rates were varied to get different combinations. Up to 95% reduction in NOx and smoke emissions were observed with dieseline fuel PPCI as compared to combustion in a conventional diesel engine. Lewander et al. [57,58] conducted experiments to evaluate the single-injection PPCI operating area for three different fuels, viz. higher standard octane gasoline, diesel, and low-octane gasoline fuel with characteristics similar to diesel (Figure 7). Fuel with a high-octane number was found better for PPCI combustion as it elongates the ignition delay period, which significantly extended the operating region of PPCI in single injection mode. Musculus et al. [59] developed some conceptual models to explain the spray pattern, evaporation, charge formation, ignition, and combustion mechanisms which were found to be consistent with the experimental observations. It was found very useful to predict the premixed charge combustion behaviour. Kimura et al. [ref?] developed a new concept to lower down NOx and smoke emissions simultaneously. They called it Modulated Kinetics combustion and employed premixed combustion as a low temperature combustion strategy.

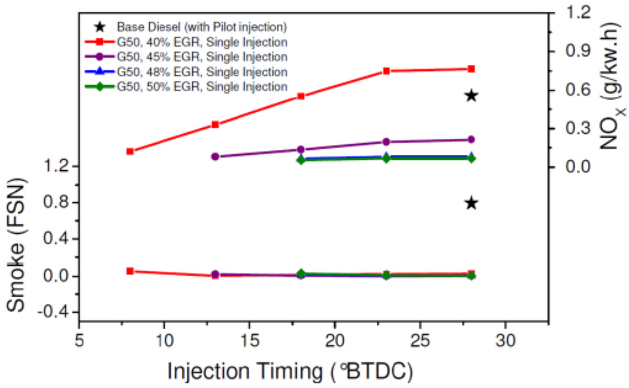


Figure 7. NO_x and Smoke variation in PPCI as compared to conventional diesel combustion [57].

EXHAUST GAS RECIRCULATION

To curb the NO_x emission especially, exhaust gases recirculation (EGR) is the most common and effective technology among various strategies. Up to 50% or even more of the exhaust gas can be re-circulated in CI engines but in SI engines, maximum EGR is limited to 20% [60]. However, in SI engines, NO_x reduction is achieved at the cost of poor combustion stability. In exhaust gas recirculation (EGR) a part from exhaust emissions is re-circulated back to the combustion chamber through externally made arrangements. EGR performs as a heat sink and reduces the amount of air intake (oxygen specifically) with diluents (carbon dioxide and water) to discourage the formation of NO_x. The diluents have high heat capacity which leads to lower rate of combustion resulting in low in-cylinder temperatures [14]. Ming et al. [61] employed EGR for biodiesel derived from Canola and yellow grease and observed simultaneous drop in NOx and particulate matter. It was achieved by elongation of ignition delay through more than 50% EGR at low load conditions.

Zheng et al. [62] comprehensively studied several ways of employing the EGR for reducing NO_X. They have aptly highlighted the importance of EGR. After analysis of EGR they proposed newer ways of EGR hydrogen reforming and EGR stream treatment. Although EGR gives lower NO_x emissions, it promotes HC, CO, soot emissions and poor performance of engine [63,64]. Ladomattos et al. performed a comprehensive experimental study for EGR impacts on the combustion process in a CI engine. In their experiments, they have found the effect of individual diluents such as CO_2, vaporised water and their combinations [65,66]. For this, they introduced them separately along with the intake air to carry out an exhaustive simulation of EGR [67]. In these experiments, it was found that the main factor that affected the variation in emission characteristics of NOx and soot was the dilution effect of individual additives. The displacement of oxygen intake with the implementation of exhaust gas recirculation leads to the reduction of the excess air proportion, which tends to increase the delay in ignition. This affects the temperature of the combustion zone and the formation of soot [68]. To overcome the dilution effect, few researchers used a turbocharger with a turbine having a variable area of nozzle to encourage additional EGR. Through this method, exhaust gases were pumped together and recycled with the induced air rather than replacing only a part of it. This extra charge leads to enhance heat inlet efficiency resulting in lower temperature of combustion and NOx emission. In fact, the level of inlet oxygen remains unaffected; thus, the process of soot oxidation will not become weak.

REACTIVITY CONTROLLED COMPRESSION IGNITION

With an objective to reduce EGR requirements in PPCI strategies, Inagaki et al. [69] investigated over dual-fuel mode PCI with directly injected diesel and premixed iso-octane. They operated conveniently up to 12 bar IMEP in the PCI mode in this study. They concluded that operating conditions differ with the change in fuel blends. For example, a fuel with a low cetane number performs better at higher loads and vice-versa. It generates the requirement of the system to be operated with different fuels and their blends that cover a range of fuel from bare gasoline to bare diesel. It could be facilitated by injecting low cetane number (high delay period/low reactive) fuel in the intake port and early cycle direct injection of high cetane number fuel (lower ignition delay) [70]. Hence, RCCI can be defined as a dual fuel combustion technology that works on in-cylinder fuel blending of different reactivity fuels and multiple injections to control the in-cylinder rate of combustion. Optimisation of combustion duration, phasing and rate is required. The process of RCCI involves the addition of a low-reactive agent/fuel into the cylinder to create a proper-mixed charge with re-circulated gases. Then, a fuel of high reactivity is directly injected in the combustion chamber before the ignition of premixed charge using single or multiple injections. As compared to strategies like dual fuel PCCI, dual fuel HCCI, and PPC, the RCCI technology has been found with better governing over combustion process, and this concept has demonstrated high thermal efficiencies of up to 60 per cent [15,71]. For safe, reliable and efficient operation of RCCI type methods, combustion phasing and control over heat release rates are very important. Moreover, close loop control of the delay period is also important because combustion temperature and EGR rates affect RCCI combustion very intensely [72].

LTC THROUGH FUEL ADDITIVES

The composition of fuel determines fuel combustion as it affects the duration of combustion, the delay in ignition and the auto-ignition temperature. The main effect of fuel additives is the LTR, due to which the beginning of the main reaction is affected. The density, lower heating value and latent heat of evaporation are the main properties of fuel which affect the physical delay period. While, the fuel's self-ignition and distillation properties affect the chemical delay [73]. Common ways of classifying fuels are based on the ease of self-ignition defined as CN or auto-ignition resistance [74]. A high number of cetane represents lesser self-ignition resistance, which includes straight chain paraffin. A high octane number includes branched chain paraffin which represents the resistance against auto-ignition. With high octane number, gasoline has almost no low-temperature reactions which cause combustion to start at about 950 K [15]. Mineral diesel like fuels exhibits major reactions at low temperatures from 750 K [75].

Starck et al. [76] conducted experiments to determine the effect of fuel properties on HCCI combustion and found that lower CN fuels are good HCCI fuels. EGR and timing for fuel injection were optimised to control the HCCI combustion. Therefore, optimum combustion speed and the fuel having a low cetane number could increase the combustion range of HCCI due to low-combustion speed, which allows more duration for homogenisation of charge and hence superior combustion during HCCI. Tanaka et al. [77] used a rapid compression machine (RCM) to analyse the influence of fuel chemistry and additives on HCCI combustion of pure HC fuels and their blend/mixtures. It was observed that saturated compound fuels show combustion in two stages while fuels with unsaturated hydrocarbon compounds exhibit single stage combustion. Aceves et al. [78] conducted a numerical analysis for fuels and additives in HCCI combustion. They carried out their work for a heavy-duty engine in which they selected a number of HCCI fuels and estimated acceptable operating range for CR, intake air temperature and equivalence ratio. The authors have experimentally investigated a large number of additives and enlisted the potential ones. In their experiments, adding a small quantity of additives (secondary fuels) could bring a significant effect over HCCI combustion characteristics which could regulate the combustion of HCCI in a better way. Through experimental work and numerical modelling, Mack et al. [79] studied the effect of the additive di-tertiary butyl peroxide (DTBP) on HCCI combustion. Small amounts of DTBP were mixed to 100% ethanol and DEE-mixed ethanol to conduct engine tests at a range of fuel injection times and load conditions. DTBP addition to the test fuel advances combustion timing in each condition. Experimental results were validated with numerical model analysis. Use of additives combustion timings for 100% ethanol and DEE-ethanol mixtures found to be advanced. In the case of DEE ethanol mixtures which confirmed the thermal and kinetic effects of the DTBP addition resulted in more advanced timing.

EMULSIFIED FUELS (WATER-IN-DIESEL EMULSION FUEL)

Out of the various strategies, water emulsion in diesel (WED) has been found as a prominent alternative fuel which could improve efficiency along with reducing pollution [80–84]. Emulsified diesel does not need any engine modification. Water-diesel emulsion has shown various advantages as fuel in the literature. Along with improvement in combustion efficiency, it lowers down various exhaust emissions such as CO, HC, NO_x, particulate matter and soot. Since the boiling point of diesel is more than that of water, when water-in-diesel emulsion enters the high temperature zone, the water droplets entrapped inside the diesel fuel evaporate first and break the surrounding diesel layer in a finer spray. This phenomenon can be called a micro-explosion [85]. The contact/surface area between air and fuel increased due to this dispersion which results in better combustion efficiency. Evaporated water takes away some heat which reduces peak combustion temperature in the form of latent heat of vaporisation. Better combustion and the reduction in peak temperature cut down the NO_x and PM emissions, respectively [86]. Aligning to this technology, Jhalani et al. [87] synthesised a new GMD emulsion which showed very attractive results for emission reduction as well as efficiency improvement. 15% cow-urine was added in the diesel to make the emulsion. It gave a remarkable 13.2% increase in BTE and up to 31.8% reduction in NO_x (Figure9 and Figure10). Optimisation of the engine operating parameters further improved the performance [88].

Brake Thermal Efficiency (BTE)

To analyse the performance of the engine, BTE is a prominent parameter to study and determine the impact of the tested fuel. Most of the studies have found that thermal efficiency improves with the use of water-in-diesel emulsion fuel [83,84]. Basha and Anand [90] found that the thermal efficiency to be increased up to 26.9% with emulsion fuel as compared to the bare diesel efficiency of 25.2%. Jhalani et al. [91] found a noticeable 9.28% increase in BTE with 23.89% efficiency as compared to 21.86% with neat diesel. A good relationship between the delay period and the micro-explosion phenomenon with an increase in the combustion efficiency was observed. The experimental results indicated that as the water in the emulsion fuel increases, both physical and chemical delay increases. Because of the increase in ignition delay, more diesel fuel accumulated, so sufficient time is available for the preparation of combustible charge for chemical reaction. It results in the rise of heat release rate [92]. The change in delay period is because of moisture present in the emulsion which slows down the process of physical and chemical reactions [19]. The water content of emulsion during the process of vaporisation forms latent heat. Emulsification increases the density and viscosity of the fuel. It results in an increase of physical delay. Further, water reduces the calorific value, which cause an increase in the chemical delay period. Thus, the physical and chemical delay results in elongation of overall ignition delay [93]. This delay period normally increases about 4 degree CA with water-in-diesel emulsion fuel, while in terms of time it increases around 0.2 ms as compared to diesel fuel. Though it was expected that the peak in-cylinder temperature would increase because of high heat release rates but it had been observed that due to the presence of water in the emulsion, the temperature decreases [94]. Most of the studies have observed increased diesel knock with the increase in ignition delay [95].

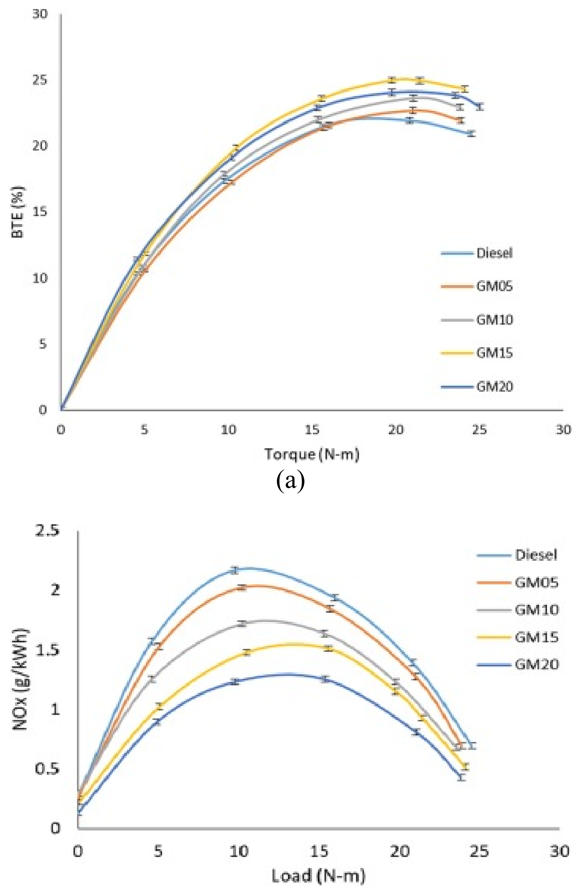


Figure 8. Variation in (a) BTE and (b) NO_x emission with the increase in the gomutra content [87].

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Nitrogen Oxide

Many studies have reported that the emission of oxides of nitrogen can be reduced by using water emulsified diesel fuel [96–99]. NO_x formation has been found to reduce by up to 50% in various studies. Attia and Kulchitskiy (2014) found up to 25% reduction in NO_x with use of water droplets of large size in the emulsion. Park et al. [99] observed up to 20% reduction with 20% water emulsified diesel. In addition, a strong relationship between the increases in the water percentage with the decrease in NOx emissions has also been reported. Many researchers agree that the reduction of NOx is directly related with increase in the proportion of water. Such temperature drop is due to the heat loss of latent heat caused by water evaporation in the emulsion. As per Jazair et al. [101], an endothermic reaction occurs because of a change in the phase of water into steam which decreases the temperature of the combustion zone. This decreases NOx formation in the combustion chamber. Further, Farfaletti et al. [102] explain the fall in combustion temperature because of the heat sink effect. The water content absorbs the heat from the combustion. It therefore, decreases the temperature of burning gas within the cylinder and thus limits the formation of NOx.

Soot and Particulate Matter

Particulate matter is an outcome of a complex phenomenon that happens from the reactions in diesel exhaust. It carries carcinogenic poly aromatic hydrocarbons which are very hazardous to human health [103]. These particles are very small in size which are therefore, can reach the smallest cavities of the lungs, which may cause health hazards. PM consists of mainly adsorbed hydrocarbons, elemental carbon, sulphates and inorganic compounds [104].

In CI engines, the measurement of emissions of particulate matter is a tedious task which requires much facilities and resources. From the experimental results, it has been shown that PM emissions are proportional to the smoke emissions [105,106]. Therefore, for simplicity, smoke emissions are generally measured to estimate the particulate matter and soot emissions in the engine exhaust. At low loads, the fuel-air combination remains lean. So, significant smoke is not emitted. On the other hand, higher emissions of smoke are prominent at top loads because the fuel-air ratio is more. Good air-fuel mixing conditions support lower smoke emissions. Hence due to the micro-explosion phenomenon, enhanced break-up of diesel occurs with water addition. It lowers down smoke [81]. Moreover, due to water part mixture becomes somewhat leaner, which also affects smoke emission. The addition of water enhances the proximity of presence of OH radicals

[28,107]. High OH radicals help the soot to get oxidised. As a result, smoke emission is reduced [108]. Particulate matter in the exhaust is mostly soot and ash which is the outcome of condensed unburned HC. This ash is formed due to the burning of lubricating oil. Instead, generation of soot is caused in the regions where fuel is rich inside cylinder when the fuel injection time is finished [3]. Again the observed reduction in the formation of particulate is due to the micro-explosion process which happens because of the volatility difference in diesel and water and then by a secondary break-up of fuel [109]. This violent disintegration encourages the mixture of fuel and air, improving the efficiency of combustion and eliminating soot and unburned HC formation. Hence, the combustion becomes better and homogeneous which reduces the particulate emission [110]. Honnery et al. [111] attributes the reduction in the formation of soot particles to high latent heat escaped out with the vaporised water. Hasannuddin et al. [112] estimated a trend of an average reduction in the particulate matter which is equal to double the mass fraction of water in the fuel emulsion. Results of various researches on emulsified fuels have been summarized in Table 4.

Table 3. Research work of different researchers on emulsified fuels.

Ref.	Engine set up	Operating condition	Fuel used	Performance	Exhaust Emissions			
				BTE	NOx	CO	HC	Soot
[113]	Single Cylinder CI; IT – 23° bTDC IP-200 bar;	100% load	Diesel+10% Water	3.21% ↑	27.90% ↓	9.0% ↑	13.30% ↑	25.1% ↓
[114]	Single Cylinder CI; IP-210 bar; CR – 19.3:1	90% load	Diesel+40% water	2.12% ↑	33.81% ↓	7.21% ↓	34.0% ↑	25.0% ↓
[115]	SAE J1995; IT - 13° bTDC IP-196 bar; CR – 19.3	90% load	Diesel+5% water	3.59% ↑	31.61% ↓	No significant variation	-	16.2% ↓
[116]	Single Cylinder CI; IT - 23° bTDC IP-210 bar; CR – 18;	75% load	Soybean biodiesel+ 10% water+ 100 ppm CNT	-	46.10% ↓	20.83% ↓	21.7% ↓	19.4% ↓
[117]	Constant speed DI engine (3500 rpm); CR – 19.3 IP-196 bar;	100% load	Diesel+10% Water	-	26.0% ↓	+12.0%	very high increase	62.9% ↓
[89]	Single Cylinder CI; CR – 17.5 IP-215 bar	100% load	Diesel+15% Water	6.70% ↑	24.71% ↓	25.0% ↓	10.8% ↑	29.4% ↓
[28]	Constant speed DI engine (80kW); CR – 17; IP – 245 bar	100% load	Diesel+20% Water with Oxygen enrichment	3.51% ↑	Significant reduction	-	-	75.0% ↓

CONCLUSION AND FUTURE SCOPE

In this review paper, various low-temperature combustion strategies have been reviewed to address the exhaust emission problems of diesel engines. The study of these LTC techniques shows that if the temperature of the combustion could be controlled by any means, it would result in lower NO_x emissions. The most important issue associated with the LTC is controlling the combustion. Limited operating range and higher HC and CO emissions are other difficulties stuck with LTC technology.

Specifically with the HCCI engines, high heat release rate and peak pressure problems are associated and hence it requires further research and development. However, premixed charge compression ignition overcomes the drawbacks of HCCI mode of combustion to some extent, yet it is needed to be addressed properly for its commercial viability. The exhaust gas recirculation technique is effective in lowering NO_x emission but it promotes HC and CO. This problem could be addressed by the after-treatment devices.

Out of the different strategies, the water in the diesel emulsion method is found to be a prominent technology that does not require any special arrangements or modifications in the engine. However, the issue of emulsion stability is a big drawback associated with it. Emulsification techniques are needed to be developed for longer emulsion stability.

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REFERENCES

[1] A. Nayyar, D. Sharma, SL. Soni, V. Gautam, C. Kumar, and M. Augustine, "Study of performance and emissions of a stationary DI variable compression ratio CI engine fueled with n-butanol/diesel blends using Taguchi technique: analytical and experimental analysis," *Energy Sources, Part A Recover Util. Environ. Eff.*, 2019, doi: 10.1080/15567036.2019.1666937.

[2] UITP India. India Will Implement Euro-Vi Emission Standard For Vehicles By 2020 2018. http://www.india.uitp.org/articles/euro-vi-emission-standards-by-2020 (accessed January 1, 2018).

[3] P. Kumar Sharma, D. Sharma, S. Lal Soni, and A. Jhalani, "Characterisation of the Nonroad Modified Diesel Engine Using a Novel Entropy-VIKOR Approach: Experimental Investigation and Numerical Simulation," *J. Energy Resour. Technol.*, 2019, vol. 141, doi: 10.1115/1.4042717.

[4] United Nations. World population prospects 2019. United Nations Dep. Econ. Soc. Aff. 2019.

[5] S. Nižetić, N. Djilali, A. Papadopoulos, and JJPC. Rodrigues, "Smart technologies for promotion of energy efficiency, utilisation of sustainable resources and waste management," *J. Clean Prod.*, 2019, vol. 231, pp. 565–591, doi: 10.1016/j.jclepro.2019.04.397.

[6] P.K. Sharma, D. Sharma, SL. Soni, A. Jhalani, D. Singh, and S. Sharma, "Characterisation of the hydroxy fueled compression ignition engine under dual fuel mode: Experimental and numerical simulation," *Int. J. Hydrogen Energy*, 2020, vol. 45, pp. 8067–8081, doi: 10.1016/j.ijhydene.2020.01.061.

[7] Centre for Energy Economics Research and Policy. BP Statistical Review of World Energy Statistical Review of World. 2019.

[8] J. Ben-Iwo, V. Manovic, and P. Longhurst, "Biomass resources and biofuels potential for the production of transportation fuels in Nigeria," *Renew. Sustain. Energy Rev.,* 2016, vol. 63, pp. 172–192, doi: 10.1016/j.rser.2016.05.050.

[9] EIA. International Energy Outlook 2017. US Energy Inf Adm 2017; IEO2017. https://doi.org/www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

[10] Mackintosh E. The perfect storm fueling New Delhi's deadly pollution. CNN 2019. https://doi.org/https://edition.cnn.com/2019/11/04/india/delhi-smog-pollution-explainer-intl/index.html.

[11] S. Sharma, D. Sharma, SL. Soni, D. Singh, and A. Jhalani, "Performance, combustion and emission analysis of internal combustion engines fuelled with acetylene – a review," *Int. J. Ambient Energy*, 2019, pp. 1–19, doi: 10.1080/01430750.2019.1663369.

[12] G. Singh, AP. Singh, and AK. Agarwal, "Experimental investigations of combustion, performance and emission characterisation of biodiesel fuelled HCCI engine using external mixture formation technique," *Sustain. Energy Technol. Assessments*, 2014, vol. 6, pp. 116–128, doi: 10.1016/j.seta.2014.01.002.

[13] Standard B. What is Air Quality Index (AQI). Bus Stand 2020. https://www.business-standard.com/about/what-is-air-quality-index (accessed May 30, 2020).

[14] J. Thangaraja, and C. Kannan, Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels - A review," *Appl. Energy,* 2016, doi: 10.1016/j.apenergy.2016.07.096.

[15] T. Pachiannan, W. Zhong, S. Rajkumar, Z. He, X. Leng, and Q. Wang, "A literature review of fuel effects on performance and emission characteristics of low-temperature combustion strategies," *Appl. Energy*, 2019, vol. 251, doi: 10.1016/j.apenergy.2019.113380.

[16] PK. Gupta, D. Sharma, SL. Soni, R. Goyal, and DK. Johar, "Experimental investigation of impact of diesel particulate filter on smoke and NOx emissions of a Euro-I compression ignition engine with active and off-board regeneration," *Clean Technol. Environ. Policy*, 2017, vol. 19, pp. 883–895, doi: 10.1007/s10098-016-1279-8.

[17] KS. Nagaprasad, NR. Banapurmath, D. Madhu, and TM. Yunus Khan, "Pre- and post-combustion emission reduction techniques for engine fuelled with diesel/DEE blends by three approaches," *Energy Sources, Part A Recover Util. Environ. Eff.*, 2019, pp. 1–18, doi: 10.1080/15567036.2019.1663304.

[18] I. Spassova, T. Tsontcheva, N. Velichkova, M. Khristova, and D. Nihtianova, "Catalytic reduction of NO with decomposed methanol on alumina-supported Mn-Ce catalysts," *J. Colloid Interface Sci.*, 2012, vol. 374, pp. 267–277, doi: 10.1016/j.jcis.2012.01.042.

[19] KA. Subramanian, and A. Ramesh, "A study on the use of water–diesel emulsions in a DI diesel engine. 2nd Int. SAE-India Mobil," Conf. IIT Madras, 2001, p. SAE paper no. 2001-28-0005; 2001.

[20] Y. Lee, and KY. Huh, "Analysis of different modes of low temperature combustion by ultra-high EGR and modulated kinetics in a heavy duty diesel engine," *Appl. Therm. Eng.,* 2014, doi: 10.1016/j.applthermaleng.2014.05.090.

[21] D. Singh, D. Sharma, SL. Soni, S. Sharma, and D. Kumari, "Chemical compositions, properties, and standards for different generation biodiesels: A review," *fuel,* 2019, vol. 253, pp. 60–71, doi: 10.1016/j.fuel.2019.04.174.

[22] B. Yang, M. Yao, WK. Cheng, Z. Zheng, and L. Yue, "Regulated and unregulated emissions from a compression ignition engine under low temperature combustion fuelled with gasoline and n-butanol/gasoline blends," *fuel*, 2014, vol. 120, pp. 163–170, doi: 10.1016/j.fuel.2013.11.058.

[23] J. Benajes, JM. García-Oliver, R. Novella, and C. Kolodziej, "Increased particle emissions from early fuel injection timing Diesel low temperature combustion," *fuel*, 2012, vol. 94, pp. 184–190, doi: 10.1016/j.fuel.2011.09.014.

[24] G. Kukkadapu, K. Kumar, CJ. Sung, M. Mehl, and WJ. Pitz, "Autoignition of gasoline surrogates at low temperature combustion conditions," *Combust Flame*, 2015, doi: 10.1016/j.combustflame.2015.01.025.

[25] S. Ciatti, and SN. Subramanian, "An Experimental Investigation of Low Octane Gasoline in Diesel Engines," *ASME 2010 Intern. Combust. Engine Div. Fall Tech. Conf., ASME*, 2010, pp. 329–339, doi: 10.1115/ICEF2010-35056.

[26] H. Wang, Z. Zheng, M. Yao, RD. Reitz, "An Experimental and Numerical Study on the Effects of Fuel Properties on the Combustion and Emissions of Low-Temperature Combustion Diesel Engines," *Combust. Sci. Technol*., 2014, vol. 186, pp. 1795–1815, doi: 10.1080/00102202.2014.920836.

[27] J. Zádor, CA. Taatjes, and RX. Fernandes, Kinetics of elementary reactions in low-temperature autoignition chemistry," *Prog. Energy Combust. Sci*, 2011, vol. 37, pp. 371–421, doi: 10.1016/j.pecs.2010.06.006.

[28] Y. Liang, G. Shu, H. Wei, and W. Zhang, "Effect of oxygen enriched combustion and water-diesel emulsion on the performance and emissions of turbocharged diesel engine," *Energy Convers. Manag.*, 2013, vol. 73, pp. 69–77, doi: 10.1016/j.enconman.2013.04.023.

[29] AK. Agarwal, AP. Singh, and RK. Maurya, "Evolution, challenges and path forward for low temperature combustion engines," *Prog. Energy Combust. Sci*. 2017, vol. 61, pp. 1–56, doi: 10.1016/j.pecs.2017.02.001.

[30] D. Singh, D. Sharma, SL. Soni. S. Sharma, P. Kumar Sharma, and A. Jhalani, "A review on feedstocks, production processes, and yield for different generations of biodiesel," *fuel*, 2020, vol. 262, 116553, doi: 10.1016/j.fuel.2019.116553.

[31] S. Gan, HK. Ng, and KM. Pang, "Homogeneous Charge Compression Ignition (HCCI) combustion: Implementation and effects on pollutants in direct injection diesel engines," *Appl. Energy* 2011, doi: 10.1016/j.apenergy.2010.09.005.

[32] NK. Noran, NK, P. Naveenchandran, and AR. A. Aziz, "Comparison of HCCI and SI Combustion of Direct Injected CNG at Low Load Condition," 2011, doi: 10.4271/2011-01-1180.
[33] M. Yao, Z. Zheng, and H. Liu, "Progress and recent trends in homogeneous charge compression ignition (HCCI) engines," *Prog. Energy Combust. Sci.*, 2009, doi: 10.1016/j.pecs.2009.05.001.
[34] SC. Kong, CD. Marriott, RD. Reitz, and M. Christensen, "Modeling and experiments of HCCI engine combustion using detailed chemical kinetics with multidimensional CFD," S*AE Tech. Pap*., 2001, doi: 10.4271/2001-01-1026.
[35] S. Soylu, "Examination of combustion characteristics and phasing strategies of a natural gas HCCI engine," *Energy Convers. Manag.,* 2005, doi: 10.1016/j.enconman.2004.02.013.
[36] JH. Mack, SM. Aceves, and RW. Dibble, "Demonstrating direct use of wet ethanol in a homogeneous charge compression ignition (HCCI) engine," *energy*, 2009, doi: 10.1016/j.energy.2009.02.010.
[37] J. Warnatz, U. Maas, and RW. Dibble, "Combustion: Physical and chemical fundamentals, modeling and simulation, experiments, pollutant formation," 2006, doi: 10.1007/978-3-540-45363-5.
[38] AA. Hairuddin, AP. Wandel, and T. Yusaf, "An introduction to a homogeneous charge compression ignition engine," *J. Mech. Eng. Sci.,* 2014, doi: 10.15282/jmes.7.2014.3.0101.
[39] H. Bendu, and S. Murugan, "Homogeneous charge compression ignition (HCCI) combustion: Mixture preparation and control strategies in diesel engines," *Renew Sustain Energy Rev*., 2014, doi: 10.1016/j.rser.2014.07.019.
[40] GE. Bogin, JH. Mack, and RW. Dibble, "Homogeneous charge compression ignition (HCCI) engine," *SAE Int. J. Fuels Lubr.* 2009, doi: 10.4271/2009-01-1805.
[41] RH. Stanglmaier, PJ. Dingle, and DW. Stewart, "Cycle-Controlled Water Injection for Steady-State and Transient Emissions Reduction From a Heavy-Duty Diesel Engine," *J. Eng. Gas Turbines Power*, 2008, vol. 130, 032801, doi: 10.1115/1.2830856.
[42] P. Venkataramana, "Homogeneous Charge Compression Ignition," *Int. J. Eng. Res. Technol*., 2013.
[43] S. Swami Nathan, JM. Mallikarjuna, and A. Ramesh, "An experimental study of the biogas–diesel HCCI mode of engine operation," *Energy Convers. Manag.,* 2010, vol. 51, pp. 1347–1353, doi: 10.1016/j.enconman.2009.09.008.
[44] J. Gomesantunes, R. Mikalsen, and A. Roskilly, "An investigation of hydrogen-fuelled HCCI engine performance and operation," *Int. J. Hydrogen Energy*, 2008, vol. 33, pp. 5823–5328, doi: 10.1016/j.ijhydene.2008.07.121.
[45] M. Canakci, "An experimental study for the effects of boost pressure on the performance and exhaust emissions of a DI-HCCI gasoline engine," *Fuel* 2008, vol. 87, pp. 1503–1514, doi: 10.1016/j.fuel.2007.08.002.
[46] D. Ganesh, and G. Nagarajan, "Homogeneous charge compression ignition (HCCI) combustion of diesel fuel with external mixture formation," *energy*, 2010, vol. 35, pp. 148–157, doi: 10.1016/j.energy.2009.09.005.
[47] J. Ma, X. Lü, L. Ji, and Z. Huang, "An experimental study of HCCI-DI combustion and emissions in a diesel engine with dual fuel," *Int. J. Therm. Sci*., 2008, vol. 47, pp. 1235–1242, doi: 10.1016/j.ijthermalsci.2007.10.007.
[48] H. Guo, V. Hosseini, WS. Neill, WL. Chippior, and CE. Dumitrescu, "An experimental study on the effect of hydrogen enrichment on diesel fueled HCCI combustion," *Int. J. Hydrogen Energy*, 2011, doi: 10.1016/j.ijhydene.2011.07.143.
[49] J. Thangaraja, and C. Kannan, Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels - A review," *Appl. Energy*, 2016, vol. 180, pp. 169–184, doi: 10.1016/j.apenergy.2016.07.096.
[50] AO. Hasan, A. Abu-Jrai, AH. Al-Muhtaseb, A. Tsolakis, H. Xu, "HC, CO and NOxemissions reduction efficiency of a prototype catalyst in gasoline bi-mode SI/HCCI engine," *J. Environ. Chem. Eng.*, 2016, vol. 4, pp. 2410–2416, doi: 10.1016/j.jece.2016.04.015.
[51] K. Lee, S. Cho, N. Kim, and K. Min, "A study on combustion control and operating range expansion of gasoline HCCI," *energy*, 2015, vol. 91, pp. 1038–1048, doi: 10.1016/j.energy.2015.08.031.
[52] D. Yang, Z. Wang, J-X. Wang, S. Shuai, "Experimental study of fuel stratification for HCCI high load extension," *Appl. Energy*, 2011, vol. 88, pp. 2949–2954, doi: 10.1016/j.apenergy.2011.03.004.
[53] RK. Maurya, and AK. Agarwal, "Experimental study of combustion and emission characteristics of ethanol fuelled port injected homogeneous charge compression ignition (HCCI) combustion engine," *Appl. Energy*, 2011, vol. 88, pp. 1169–1180, doi: 10.1016/j.apenergy.2010.09.015.
[54] K. Mathivanan, J. M. Mallikarjuna, and A. Ramesh, Influence of multiple fuel injection strategies on performance and combustion characteristics of a diesel fuelled HCCI engine – An experimental investigation," *Exp. Therm. Fluid Sci.*, 2016, vol. 77, pp. 337–346, doi: 10.1016/j.expthermflusci.2016.05.010.
[55] J. Gomes Antunes, R. Mikalsen, A. Roskilly, "An investigation of hydrogen-fuelled HCCI engine performance and operation," *Int. J. Hydrogen Energy*, 2008, vol. 33, pp. 5823–5828, doi: 10.1016/j.ijhydene.2008.07.121.
[56] F. Zhang, H. Xu, S. Zeraati Rezaei, G. Kalghatgi, S-J. Shuai, "Combustion and Emission Characteristics of a PPCI Engine Fuelled with Dieseline," *SAE Tech. Pap*., 2012, doi: 10.4271/2012-01-1138.
[57] M. Lewander, K. Ekholm, B. Johansson, P. Tunestål, N. Milovanovic, N. Keeler et al., "Investigation of the combustion characteristics with focus on partially premixed combustion in a heavy duty engine," *SAE Int. J. Fuels Lubr.* 2009, doi: 10.4271/2008-01-1658.
[58] CM. Lewander, B. Johansson, and P. Tunestal, "Extending the operating region of multi-cylinder partially premixed combustion using high octane number fuel," *SAE Tech. Pap*., 2011.
[59] MPB. Musculus, PC. Miles, and LM. Pickett, "Conceptual models for partially premixed low-temperature diesel combustion," *Prog. Energy Combust. Sci*., 2013, vol. 39, pp. 246–283, doi: 10.1016/j.pecs.2012.09.001.
[60] E. Sher, "Environmental Aspects of Air Pollution. Handb. Air Pollut. From Intern," *Combust. Engines*, Elsevier; 1998, pp. 27–41, doi: 10.1016/B978-012639855-7/50041-7.
[61] M. Zheng, MC. Mulenga, GT. Reader, M. Wang, DSK. Ting, and J. Tjong, "Biodiesel engine performance and emissions in low temperature combustion," *Fuel* 2008, doi: 10.1016/j.fuel.2007.05.039.
[62] M. Zheng, GT. Reader, and JG. Hawley, Diesel engine exhaust gas recirculation - A review on advanced and novel concepts," *Energy Convers. Manag*., 2004, doi: 10.1016/S0196-8904(03)00194-8.
[63] Handbook of Air Pollution From Internal Combustion Engines. Elsevier; 1998, doi: 10.1016/B978-0-12-639855-7.X5038-8.
[64] N. Ladommatos, S. Abdelhalim, H. Zhao, "The effects of exhaust gas recirculation on diesel combustion and emissions," *Int. J. Engine Res*. 2000, doi: 10.1243/1468087001545290.
[65] N. Ladommatos, SM. Abdelhalim, H. Zhao, and Z. Hu, "The dilution, chemical, and thermal effects of exhaust gas recirculation on diesel engine emissions - Part 3: Effects of water vapour," *SAE Tech. Pap*., 1997, doi: 10.4271/971659.

[66] N. Ladommatos, SM. Abdelhalim, H. Zhao, Z. Hu, "The effects of carbon dioxide in exhaust gas recirculation on diesel engine emissions," *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.,* 1998, doi: 10.1243/0954407981525777.

[67] N. Ladommatos, S. Abdelhalim, and H. Zhao, Control of oxides of nitrogen from diesel engines using diluents while minimising the impact on particulate pollutants," *Appl. Therm. Eng*., 1998, vol. 18, pp. 963–980, doi: 10.1016/S1359-4311(98)00031-3.

[68] N. Ladommatos, S. Abdelhalim, H. Zhao, and Z. Hu, "The Dilution, Chemical, and Thermal Effects of Exhaust Gas Recirculation on Disesel Engine Emissions - Part 4: Effects of Carbon Dioxide and Water Vapour," *SAE Tech. Pap*., 1997, doi: 10.4271/971660.

[69] K. Inagaki, T. Fuyuto, K. Nishikawa, K. Nakakita, and I. Sakata "Dual-Fuel PCI Combustion Controlled by In-Cylinder Stratification of Ignitability," *SAE Tech. Pap*., 2006, doi: doi: 10.4271/2006-01-0028.

[70] S. Kokjohn, R. Hanson, D. Splitter, J. Kaddatz, RD. Reitz, "Fuel Reactivity Controlled Compression Ignition (RCCI) Combustion in Light- and Heavy-Duty Engines," *SAE Int. J. Engines*, 2011, vol. 4, 2011, doi: 10.4271/2011-01-0357.

[71] ML. Wissink, JH. Lim, DA. Splitter, RM. Hanson, and RD. Reitz, Investigation of injection strategies to improve high efficiency rcci combustion with diesel and gasoline direct injection," *ASME 2012 Intern. Combust. Engine Div. Fall Tech. Conf. ICEF* 2012, 2012, doi: 10.1115/ICEF2012-92107.

[72] A. Paykani, A. Garcia, M. Shahbakhti, P. Rahnama, and RD. Reitz, reactivity controlled compression ignition engine: Pathways towards commercial viability," *Appl. Energy*, 2021, vol. 282, 116174, doi: 10.1016/j.apenergy.2020.116174.

[73] N. Sharma, RA. Agarwal, AK. Agarwal, "Particulate Bound Trace Metals and Soot Morphology of Gasohol Fueled Gasoline Direct Injection Engine," *J. Energy Resour. Technol.,* 2018, vol. 141, 022201, doi: 10.1115/1.4040580.

[74] KE. Niemeyer, SR. Daly, WJ. Cannella, and CL. Hagen, "A Novel Fuel Performance Index for Low-Temperature Combustion Engines Based on Operating Envelopes in Light-Duty Driving Cycle Simulations," *J. Eng. Gas Turbines Power*, 2015, vol. 137, doi: 10.1115/1.4029948.

[75] AK. Agarwal, RA. Agarwal, T. Gupta, and BR. Gurjar, "Introduction to Biofuels," *Green Energy Technol*., 2017, pp. 3–6, doi: 10.1007/978-981-10-3791-7_1.

[76] L. Starck, B. Lecointe, L. Forti, and N. Jeuland, Impact of fuel characteristics on HCCI combustion: Performances and emissions," *Fuel* 2010, doi: 10.1016/j.fuel.2010.05.028.

[77] S. Tanaka, F. Ayala, and JC. Keck, "A reduced chemical kinetic model for HCCI combustion of primary reference fuels in a rapid compression machine," *Combust Flame* 2003, doi: 10.1016/S0010-2180(03)00057-9.

[78] SM. Aceves, DL. Flowers, J. Martinez-Frias, JR. Smith, CK. Westbrook, WJ. Pitz WJ, et al. "A Sequential Fluid-Mechanic Chemical-Kinetic Model of Propane HCCI Combustion," *SAE Tech. Pap*., 2001, doi: 10.4271/2001-01-1027.

[79] JH. Mack, RW. Dibble, BA. Buchholz, DL. Flowers, "The Effect of the Di-Tertiary Butyl Peroxide (DTBP) additive on HCCI Combustion of Fuel Blends of Ethanol and Diethyl Ether," *SAE Tech. Pap*., 2005, doi: 10.4271/2005-01-2135.

[80] AM. Ithnin, H. Noge, HA. Kadir, and W. Jazair, "An overview of utilising water-in-diesel emulsion fuel in diesel engine and its potential research study," *J. Energy Inst*. 2014, vol. 87, pp. 273–288, doi: 10.1016/j.joei.2014.04.002.

[81] PK. Mondal, and BK. Mandal, "A comprehensive review on the feasibility of using water emulsified diesel as a CI engine fuel," *Fuel* 2019, vol. 237, pp. 937–960, doi: 10.1016/j.fuel.2018.10.076.

[82] Debnath BK, Saha UK, Sahoo N. A comprehensive review on the application of emulsions as an alternative fuel for diesel engines. Renew Sustain Energy Rev 2015;42:196–211. https://doi.org/10.1016/j.rser.2014.10.023.

[83] A. Jhalani, D. Sharma, SL. Soni, PK. Sharma, S. Sharma, "A comprehensive review on water-emulsified diesel fuel: chemistry, engine performance and exhaust emissions," *Environ. Sci. Pollut. Res*., 2019, doi: 10.1007/s11356-018-3958-y.

[84] S. Vellaiyan, and KS. Amirthagadeswaran, "The role of water-in-diesel emulsion and its additives on diesel engine performance and emission levels: A retrospective review," *Alexandria Eng. J*., 2016, vol. 55, pp. 2463–2472, doi: 10.1016/j.aej.2016.07.021.

[85] M. Saravanan, A. Anbarasu, and BM. Gnanasekaran, "Study of performance and emission characteristics of IC engines by using diesel-water emulsion," *Int. J. Adv. Manuf. Technol.,* 2013, vol. 69, pp. 2531–2544, doi: 10.1007/s00170-013-5132-5.

[86] F. Bedford, C. Rutland, P. Dittrich, A. Raab, and F. Wirbeleit, "Effects of Direct Water Injection on DI Diesel Engine Combustion," *SAE Tech. Pap*., 2000, doi: 10.4271/2000-01-2938.

[87] A. Jhalani, D. Sharma, S. Soni, PK. Sharma, and D. Singh, "Feasibility assessment of a newly prepared cow-urine emulsified diesel fuel for CI engine application," *Fuel* 2021, vol. 288, 119713, doi: 10.1016/j.fuel.2020.119713.

[88] A. Jhalani, D. Sharma, SL. Soni, PK. Sharma, and D. Singh, "Experimental studies on combustion duration and ignition delay period for a newly synthesised gomutra emulsified diesel," *Int. J. Environ. Sustain. Dev.,* 2021, vol. 20, pp. 216, doi: 10.1504/IJESD.2021.116852.

[89] JS. Basha, and RB. Anand, "An Experimental Study in a CI Engine Using Nanoadditive Blended Water–Diesel Emulsion Fuel," *Int. J. Green Energy,* 2011, vol. 8, pp. 332–348, doi: 10.1080/15435075.2011.557844.

[90] JS. Basha, and RB. Anand, "Effects of nanoparticle additive in the water-diesel emulsion fuel on the performance, emission and combustion characteristics of a diesel engine," *Int. J. Veh. Des.,* 2012, vol. 59, pp. 164, doi: 10.1504/IJVD.2012.048692.

[91] A. Jhalani, D. Sharma, SL. Soni, and PK. Sharma, "Effects of process parameters on performance and emissions of a water-emulsified diesel-fueled compression ignition engine," *Energy Sources, Part A Recover Util. Environ. Eff.,* 2019, doi: 10.1080/15567036.2019.1669739.

[92] AE. Dhole, RB. Yarasu, and DB. Lata, "Investigations on the combustion duration and ignition delay period of a dual fuel diesel engine with hydrogen and producer gas as secondary fuels," *Appl. Therm. Eng*., 2016, vol. 107, pp. 524–532, doi: 10.1016/j.applthermaleng.2016.06.151.

[93] JGT. Reyes, and EN. Quiros, "Determination of the Start and End of Combustion in a Direct Injection Diesel Engine using the Apparent Heat Release Rate," *Proc. ASME 2017 Power Conf. Jt. With ICOPE-17*, North Carolina: ASME; 2017, pp. 1–6.

[94] MR. Seifi, SR. Hassan-Beygi, B. Ghobadian, U. Desideri, and M. Antonelli, "Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions," *Fuel* 2016, vol. 166, pp. 392–399, doi: 10.1016/j.fuel.2015.10.122.

[95] M. Nour, H. Kosaka, AK. Abdel-Rahman, and M. Bady, "Effect of Water Injection into Exhaust Manifold on Diesel Engine Combustion and Emissions," *Energy Procedia* 2016, vol. 100, pp. 178–187, doi: 10.1016/j.egypro.2016.10.162.

[96] P. Baskar, and A. Senthil Kumar, "Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air," *Alexandria Eng. J.* 2017, vol. 56, pp. 137–146, doi: 10.1016/j.aej.2016.09.014.

[97] V. Suresh, and KS. Amirthagadeswaran, "Combustion and Performance Characteristics of Water-in-diesel Emulsion Fuel," *Energy Sources, Part A Recover Util. Environ Eff*. 2015, vol. 37, pp. 2020–2028, doi: 10.1080/15567036.2015.1072605.

[98] PS. Kumar, B. Venkatesh, and SPS. Khan, "Emission control by using water emulsified diesel in single cylinder diesel engine," *Int. J. Adv. Eng. Technol.,* 2013, vol. 5, pp. 263–273.

[99] JW. Park, KY. Huh, and JH. Lee, "Reduction of NOx, smoke and brake specific fuel consumption with optimal injection timing and emulsion ratio of water-emulsified diesel," *Proc. Inst. Mech. Eng. Part D-Journal Automob. Eng*. 2001, vol. 215, pp. 83–93, doi: 10.1243/0954407011525476.

[100] AMA. Attia, and AR. Kulchitskiy, "Influence of the structure of water-in-fuel emulsion on diesel engine performance," *Fuel*, 2014, vol. 116, pp. 703–708, doi: 10.1016/j.fuel.2013.08.057.

[101] W. Jazair, and M. Azrin, "Combustion performance and exhaust emission of DI diesel engine using various sources of waste cooking oil," *Combust. Altern. Fuel*, Malaysia: 2010.

[102] A. Farfaletti, C. Astorga, G. Martini, U. Manfredi, A. Mueller, M. Rey et al. Effect of water/fuel emulsions and a cerium-based combustion improver additive on HD and LD diesel exhaust emissions," *Environ. Sci. Technol*., 2005, vol. 39, pp. 6792–6799, doi: 10.1021/es048345v.

[103] Y. Wang, H. Liu, CFF. Lee, "Particulate matter emission characteristics of diesel engines with biodiesel or biodiesel blending: A review," *Renew. Sustain. Energy Rev.,* 2016, vol. 64, pp. 569–581, doi: 10.1016/j.rser.2016.06.062.

[104] R. Stein, B. Boucsein, K. Fahl, T. Garcia de Oteyza, J. Knies, and F. Niessen, "Accumulation of particulate organic carbon at the Eurasian continental margin during late Quaternary times: controlling mechanisms and paleoenvironmental significance," *Glob Planet Change* 2001, vol. 31, pp. 87–104, doi: 10.1016/S0921-8181(01)00114-X.

[105] J. Merkisz, and J. Pielecha, "Analysis of Particle Concentrations and Smoke in Common-Rail Diesel Engine," *Sae Tech. Pap*., 2008, doi: 10.4271/2008-01-1743.

[106] Y. Sung, G. Jung, J. Park, B. Choi, and MT. Lim, "Relation between particulate emissions and exhaust smoke level in premixed charge compression ignition engine," *J. Mech. Sci. Technol.,* 2014, vol. 28, pp. 783–787, doi: 10.1007/s12206-013-1144-1.

[107] N. Samec, B. Kegl, and RW. Dibble, "Numerical and experimental study of water/oil emulsified fuel combustion in a diesel engine," *Fuel* 2002, vol. 81, pp. 2035–2044, doi: 10.1016/S0016-2361(02)00135-7.

[108] P. Roth, O. Brandt, and SVON. Gersum, "High Temperature Oxidation of Suspended Soot Particles Verified by CO and CO2 Measurements," *Symp. Combust*., 1990, vol. 23, pp. 1485–1491, doi: 10.0.3.248/S0082-0784(06)80417-0.

[109] T. Kadota, and H. Yamasaki, "Recent advances in the combustion of water fuel emulsion," *Prog. Energy Combust. Sci*., 2002, vol. 28, pp. 385–404, doi: 10.1016/S0360-1285(02)00005-9.

[110] A. Lif, and K. Holmberg, "Water-in-diesel emulsions and related systems," *Adv. Colloid. Interface Sci*., 2006, vol. 123–126, pp. 231–239, doi: 10.1016/j.cis.2006.05.004.

[111] DR. Honnery, M. Tappe, and JH. Kent, "Two Parametric Models of Soot Growth Rates in Laminar Ethylene Diffusion Flames," *Combust. Sci. Technol*., 1992, vol. 83, pp. 305–321, doi: 10.1080/00102209208951838.

[112] AK. Hasannuddin, JY. Wira, S. Sarah, MI. Ahmad, SA. Aizam, MAB. Aiman, et al., "Durability studies of single cylinder diesel engine running on emulsion fuel," *Energy* 2016, vol. 94, pp. 557–568, doi: 10.1016/j.energy.2015.10.144.

[113] R. Vigneswaran, K. Annamalai, B. Dhinesh, and R. Krishnamoorthy, "Experimental investigation of unmodi fi ed diesel engine performance, combustion and emission with multipurpose additive along with water-in- diesel emulsion fuel," *Energy Convers. Manag*., 2018, vol. 172, pp. 370–380, doi: 10.1016/j.enconman.2018.07.039.

[114] KA. Subramanian, "A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions," *Energy Convers. Manag*., 2011, vol. 52, pp. 849–857, doi: 10.1016/j.enconman.2010.08.010.

[115] AM. Ithnin, WJ. Yahya, MA. Ahmad, NA. Ramlan, H. Abdul Kadir, NAC. Sidik, et al., "Emulsifier-free Water-in-Diesel emulsion fuel: Its stability behaviour, engine performance and exhaust emission," *fuel*, 2018, vol. 215, pp. 454–462, doi: 10.1016/j.fuel.2017.11.061.

[116] S. Vellaiyan, "Enhancement in combustion, performance, and emission characteristics of a biodiesel-fueled diesel engine by using water emulsion and nanoadditive," *Renew. Energy* 2020, vol. 145, pp. 2108–2020, doi: 10.1016/j.renene.2019.07.140.

[117] AK. Hasannuddin, WJ. Yahya, S. Sarah, AM. Ithnin, S. Syahrullail, NAC. Sidik, et al., "Nano-additives incorporated water in diesel emulsion fuel: Fuel properties, performance and emission characteristics assessment," *Energy Convers. Manag*., 2018, vol. 169, pp. 291–314, doi: 10.1016/j.enconman.2018.05.070.