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Current Challenges and Future Perspectives

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Meet the editor

Prof. Dr. Hasan Koten obtained a Ph.D. with honors from the Mechanical Engineering Department, Marmara University, Turkey. During his Ph.D. study, he was a visiting scholar at the Center for Automotive Research, The Ohio State University, USA. He was also a researcher for the first full geometry engine design project of The Scientific and Technological Research Council of Turkey (TUBITAK). He was awarded first place by the TÜBİTAK 2238 – Entrepreneurship and Innovation Competition Program. In 2018, he was a post-doctorate researcher at the College of Engineering, Design and Physical Sciences (CEDP), Brunel University London. He has led several projects, supervised MSc and Ph.D. theses, and presented more than 150 conference proceedings. He has also published around 100 journal articles. He was a visiting professor at the Clean Combustion Research Center (CCRC), King Abdullah University of Science and Technology (KAUST), Saudi Arabia, and the University of Applied Sciences, Germany. He has many patents in the field of combustion engines. He is the head of the Mechanical Engineering Department, Istanbul Medeniyet University, Turkey. Dr. Koten participates in Turkey's largest TÜBİTAK-funded project on the production of 400-HP, 16- and 8-cylinder engines.

Contents

Preface

Although there is debate surrounding internal combustion engines because of their negative effects on the environment, diesel engines will likely remain indispensable in industry today and in the future.

Diesel engines are among the most indispensable internal combustion engines, especially in terms of high traction torque and efficiency. Gasoline engines are preferred for speed and jet engines for thrust, while diesel engines are widely used in heavy-duty machines, trains, ships, unmanned aerial vehicles, tanks, and other vehicles.

Although new clean technologies are sought in zero carbon, zero-emission, and decarbonization studies, diesel engines can be redeveloped to meet emissions requirements via various in-engine and after-treatment options.

This book discusses artificial intelligence, alternative fuels, and other technological advancements as they relate to diesel engines. It also discusses applications of hydrogen-fueled diesel engines. The book emphasizes that clean combustion can be achieved with alternative applications in diesel engines, as well as examines the current and future situations of these internal combustion engines.

We see that these high-performance diesel engines, which include alternative combustion technologies with ultra-high pressure injection systems, will continue to exist in the future.

This book is an interesting and useful resource for research centers, universities, and engine-producing companies.

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Chapter 1

Artificial Intelligence in Diesel Engines

Hasan Koten and Mohammad Mostafa Namar

Abstract

The use of artificial intelligence in different parts of human life is becoming inevitable and it is expected that in the near future, the range of artificial intelligence applications will include all service, industrial, research, and educational activities. Providing a solution or performance enhancement in research and industrial activities, considering that these activities contain lots of dependent parameters with formulated/non-formulated correlations, is always a challenge for researchers. The recent approach of researchers in using statistical data and applying techniques based on artificial intelligence is a promising solution that provides the desired answers more quickly and accurately. The automobile industry and internal combustion engines have also benefited from the advantages of artificial intelligence in order to improve their performance and efficiency. Among the most important developments and achievements of this approach, we can mention real-time modeling, optimization and intelligent control, new fuel combinations, fault detection systems, and self-driving vehicles. Therefore, in this chapter, the recent research and industrial achievements of diesel engines due to the use of artificial intelligence techniques will be discussed.

Keywords: artificial intelligence, machine learning, deep learning, diesel engine, automotive industry

1. Introduction

Nowadays, the applications of Artificial Intelligence (AI) are noticeably extending in the wide range of research and industries. It seems that industrial products are competing in equipping themselves with artificial intelligence. Diesel engines also use this concept to improve their performance, usability, and viability in this competition. Consequently, in this chapter, the development of diesel engines via artificial intelligence will be discussed. First, the fundamentals of artificial intelligence, classifications, and applications are briefly illustrated, then a short review about employing artificial intelligence in internal combustion engines is presented, and finally, the recent trends, achievements, and challenges of using artificial intelligence in diesel engines are discussed.

2. Artificial intelligence

Artificial intelligence is considered as an effort to persuade a computer, robot, or other piece of technology to think and process data just similar to human's brain. So, artificial intelligence has to find how the human brain thinks, learns, and makes decisions during processes like solving a problem or executing a task. The aim of AI is to develop products by adding functionality related to human acts of reasoning, learning, and problem-solving [1].

2.1 Types of artificial intelligence

While artificial intelligence can be divided into various types, there are two main classifications which are based on its capability and functionally and are shown in **Figure 1**. Based on the capabilities, it is divided into three types namely; Narrow, General, and Super AI. The most common and available type of AI is Narrow type which is able to perform a dedicated task with intelligence. It is only trained for a specific task and could fail in unpredictable ways if it goes beyond its limits. Apple Siriis, self-driving cars, and speech/image recognition are the most well-known examples of Narrow AI. General AI could perform intellectual tasks with efficiency like a human and Super AI is an upper-level of human Intelligence. It is able to perform any task better than humans with cognitive properties. Up to now, there is no executed example of General and Super AIs and researchers are working on the General level of AI [2].

The other classifications of AI systems are based on their function. In this approach, it is divided into four classes namely; Reactive Machines, Limited Memory, Theory of Mind, and Self Awareness. The simplest AI in this approach is the Reactive machine which reacts based on the current scenario and best possible action. It does not use previous experiences to make decisions. Limited Memory AI could store and use previous experiences and or some data for a limited short period of time to

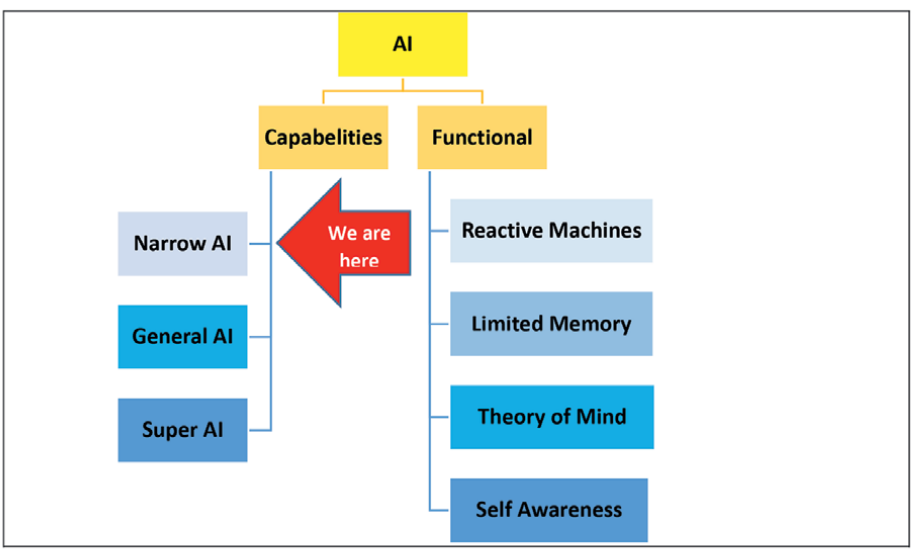

Figure 1.
Classifications of artificial intelligence.

make decisions. The most famous example is self-driving cars which store the recent speed of nearby cars, the distance of other cars, speed limit, and other information to navigate the road. Theory of Mind AI is able to understand human emotions and beliefs like humans, and Self Awareness AI which is known as the future of artificial intelligence and will be smarter than the human mind. Both of them do not exist in reality and researchers are working on them [2].

2.2 AI vs. machine learning

One of the common mistakes in artificial intelligence subject is using AI, Machine Learning (ML), and Deep Learning interchangeably. These terms are actually distinct but related concepts and have meaningful differences. Simply, AI could be considered as computer software that imitates humans thinking, analyzing, reasoning, and learning processes in order to handle complex duties. Machine learning as the subset of AI is actually the model producer using special learning algorithms based on data which makes AI able to perform such complex tasks. Up to now, most applied AIs are provided using machine learning, so it is the main reason for using them synonymously. However, AI refers to the comprehensive concept of making human-like perceptions by computer software, while machine learning refers to only one method or model of doing that. **Figure 2** indicates the relations between Al and ML [3].

2.3 The applications of AI

The usage of products and services that are using AI is such a common that one may not be aware of engaging with AI during his daily life. In fact, AI-powered products and services have been increasingly intertwined with human daily life. Banking applications that checks shady transactions, spam detectors that keeps our inbox free of virus, and video-streaming platforms which recommend us to watch an attractive movie are just some examples of our daily routines which are equipped with AI. There is no doubt that one of the most valuable achievements of AI is the development

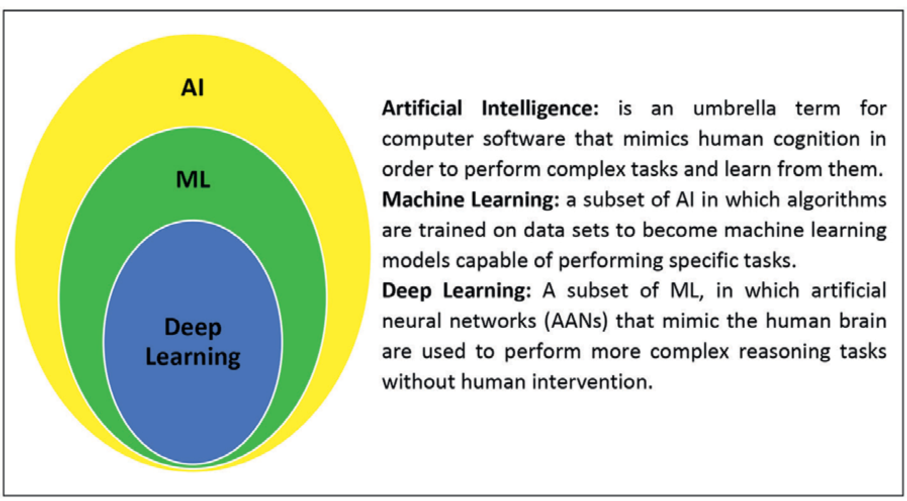

Figure 2.
AI vs. ML.

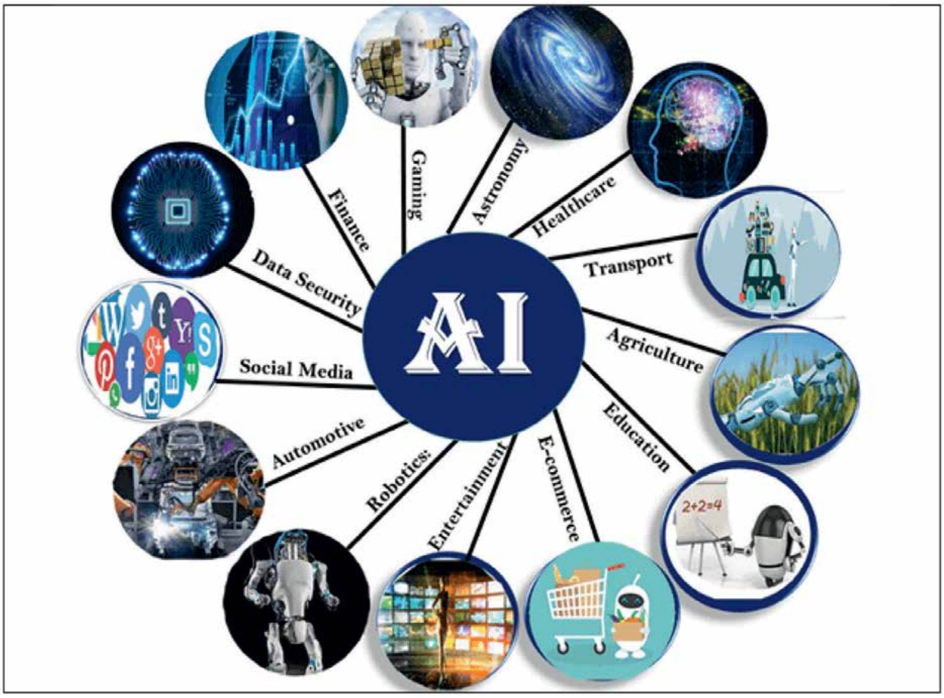

Figure 3.
Top applications of AI.

of services in health care. ML models capable of analyzing the medical pictures for cancerous growths, smartphone applications which provide personalized treatment schedules, and automation systems which efficiently allocate hospital resources are just some of the achievements in this subject. Furthermore, AI has had a significant impact on the world-class business. It has been used to reduce the costs using automation and to produce actionable insights via analyzing big data sets [4]. Some of the most applications of AI in our daily life are shown in **Figure 3**.

3. AI in internal combustion engines

It could be asserted that the world is experiencing the midst of a third wave of artificial intelligence algorithm development, after the first and second ones in the 1970s and 2000s [5]. Besides the conventional ways to improve engine performance, its numerous challenges and the competition between the producers lead the researchers to develop artificial intelligence algorithm and apply them in the engine industry. Using conventional methods to regulate, anticipate, and optimize the hardly nonlinear and complex events of an ICE such as 2D and 3D mapping of the engine characteristics, large number of nonlinear combustion chemical reactions, pressure and temperature gradients, multi-phase flow interactions, and formation of particulate matters is a challenging issue. So, the models based on AI could estimate the engine performance ignoring such hard phenomena and just based on the experimental data.

Furthermore, there are some ignored issues in conventional ICE management systems such as regulating stochastic cyclic variability that brings poor performance for the engine management systems. More powerful and efficient control models are provided using artificial intelligent algorithms in various ICE combustion modes such as homogeneous charge compression ignition or reactivity-regulated compression ignition. The rapid rise of employing and applying big data, make us able to provide ever-more sufficient and smart management system using a large amount of details and countless information from the engine such as speed, load, indicated torque, temperature, pressure, fuel injection, fuel consumption, etc. It is obvious that such an enormous amount of data needs a powerful analyzing tool and artificial intelligence algorithms are the best choice considering efficiency, time consumption, errors, and cost for engine management. In addition, AI technology using the data adopted from noticeable comparable ICEs connected to a network could provide a real-time smart engine management system.

3.1 Recent trend

The ever-increasing growth of human societies, continuous change of customer desirers and the mechanization of traditional common methods besides fossil fuel resource limitations, environmental pollutants concerns, and design considerations lead researchers to have non-stop efforts developing the performance of internal combustion engines. Extended works have been carried out by researchers to have more efficient and cleaner engines [6–8]. These efforts contain a vast variety of approaches from engine design [9, 10] to fuel development [11, 12] and combustion control [13, 14].

Among these extended subjects, applying AI to internal combustion engines is a new approach on which researchers are working [15, 16]. Although the most of efforts have been devoted to the control approaches [17, 18], the range of employing AI in engine performance development is still wide from the optimized redesign [19, 20] to fuel/charge mixture [21, 22] and combustion characteristics [23, 24]. Furthermore, due to the strong research background in this field, it can be asserted that AI technology is simultaneously applied to all known combustion modes, from spark ignition engines [25, 26] to diesel [27, 28] and low-temperature combustion ones [29, 30]. Most of the efforts are based on the Artificial Neural Network (ANN) to simulate the engine performance and then use such a model for control approaches or optimization. Indeed, engine general performance such as power, torque, and emission based on its operating conditions and input parameters such as valve timing, ambient pressure/temperature, and equivalence ratio could be estimated using machine learning and deep learning techniques. In such models, based on the engine data set, some predictive correlations will be produced and used to estimate the target values based on the input ones. For example in Ref. [30], the start of combustion has been estimated based on the ambient pressure, ambient temperature, inlet valve closing, equivalence ratio, engine speed, and compression ratio via a simple linear correlation suggested by ML regression models for methane fueled homogeneous charge compression ignition engines. Such a correlation is useful to control the engine combustion stability in the real-time application. Or, in Ref. [29] the combustion noise level of a converted-diesel homogeneous charge compression ignition engine is estimated by the ANN model using engine experimental data. This real-time predictor is able to predict the noise level with 5% accuracy, so applying it to the engine control strategy may protect the engine from intense ringing. Although a huge number of works in this field are presented in the literature, generally they can be categorized into four section namely; performance simulation, control approaches, fault diagnosis, and optimization as shown in **Figure 4**.

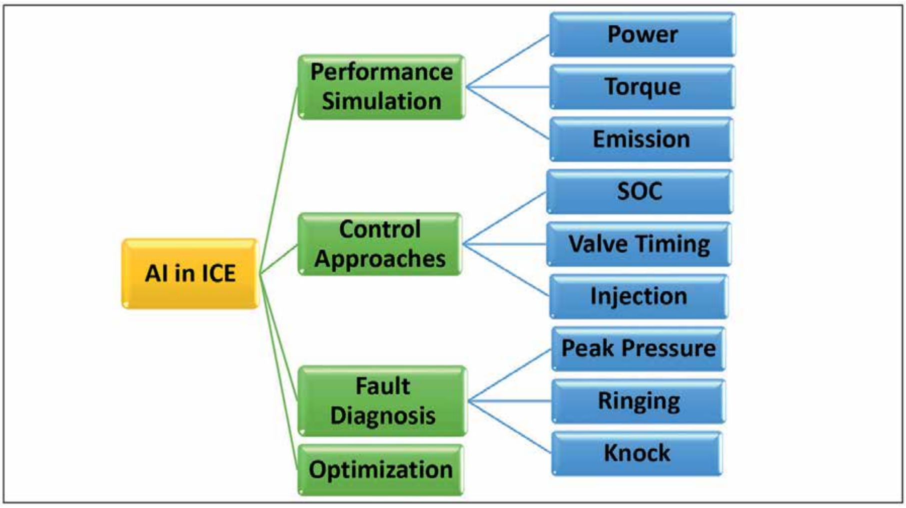

Figure 4.
AI technology in internal combustion engines.

4. AI in diesel engines

Having more intelligent vehicles supervised, unsupervised, and reinforcement learning techniques are employed by machine learning algorithms and deep learning models. Both supervised and unsupervised learning techniques, such as regression, classification, detection, segmentation, dimensionality reduction, and clustering use the data obtained from various sensors located in different parts of engines to analyze the factors affecting fuel consumption, emissions, fault detection, maintenance, understanding the driver's behavior, automated driver assistance systems, and self-driving. For autonomous vehicles, considering the decision-making process based on the environmental condition, path planning, object detection, and decision-making control, it is more common to use semi-supervised learning, reinforcement learning, and deep learning techniques. The domain of efforts employing these artificial intelligence techniques on diesel engines is categorized into five classes namely; fuel construction, engine performance, fault diagnosis, engine control, and optimization which are illustrated here. It should be noted that the research at this level can be considered in primary steps since just some AI techniques have been employed to develop diesel engines as shown in **Figure 5**.

4.1 Fuel construction

Fossil fuels play an important role in providing the demanded energy for almost all sectors of life after the globalization of the world and the industrial revolution. However, there are extended efforts to find other sources of energy due to their detrimental impact on the global ecosystem. For the transportation sector, biodiesel as a promising replacement for fossil fuel-based diesel is becoming more popular as its performance is known more. As the recent achievements, a huge number of techniques have been provided to efficiently extract biodiesel from different oils/fats. Using AI approaches, we are able to estimate the efficiency of biodiesel production techniques, optimize such a process, and minimize process costs. The AI-powered

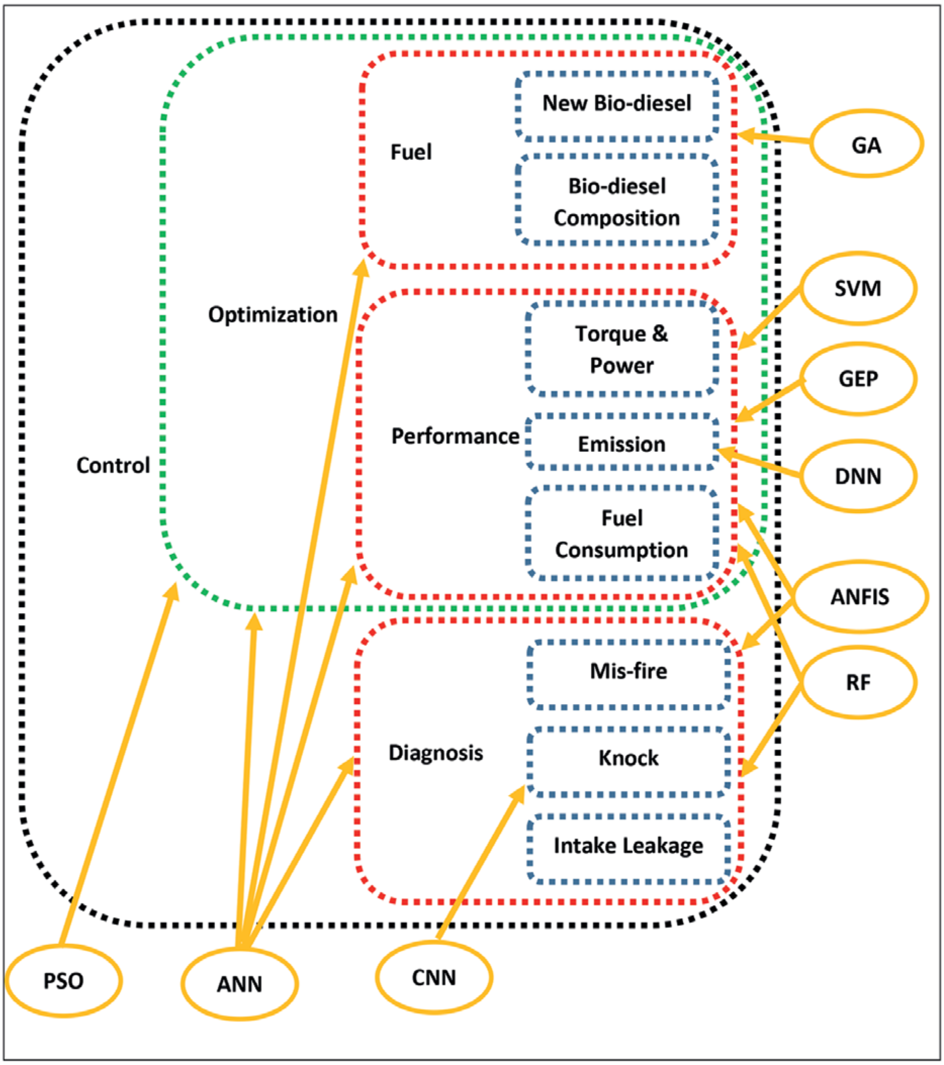

Figure 5.
AI in diesel engines.

biodiesel performance prediction models have several stages namely; data collection, data preprocessing, developing, applying ML algorithm on biodiesel data, and finally predicting the target values such as unknown biodiesel characteristics and properties. Consequently, the main achievements of using AI in the biodiesel production process could be reported as the improvement of the process optimization, development of the fuel properties predictor models, and ultimately cost reduction [31].

4.2 Engine performance

It can be asserted that one of the most focused sections of AI applications in diesel engines is the engine performance estimation using the engine simulator models. Based on the target of research, the engine outputs such as fuel consumption, exhaust emission, brake torque, and power could be estimated using AI techniques due to the engine inlet parameters. Although most of this research is carried out by the ANN, there are some other efforts employing different methods such as Adaptive-Neuro Fuzzy Inference System (ANFIS) [32] and Gene Expression Programming (GEP) [33, 34] to compare the accuracy and comprehensibility of AI techniques on the performance prediction of diesel engines.

4.2.1 Fuel consumption

Fuel consumption, as a key factor of vehicles especially for heavy-duty ones, directly affects on overall operational cost of vehicles. The fuel economy standards of vehicles are regulated by the Corporate Average Fuel Economy (CAFE) standards of the National Highway Traffic Safety Administration (NHTSA) of the United States. It is obvious that noticeable savings in the transportation industry are achievable by improving fuel efficiency and reducing fuel consumption, so applying AI techniques could create a huge revolution on this issue. Several research and studies have been carried out to model the fuel consumption/fuel efficiency of diesel engines based on statistical and other AI approaches. Furthermore, estimating the fuel efficiency could help the transportation fleet management and for diagnostic targets wherever we are facing with high level of fuel consumption. While the statistical and physics-based approaches are time-consuming, AI and machine learning methods have high speed and are more accurate for such modeling. In consequence, several studies have been performed to predict fuel consumption in vehicles using machine learning and deep learning techniques such as Support Vector Machine (SVM) [35], Random Forest (RF) [36], and ANN [37–39].

4.2.2 Exhaust emission

Emission reduction has been significantly focused on by the automotive industries since the emission regulations for transportation sectors were published. The standards of environmental protection and emission inventories could be developed by emission efficiency estimation. Considering the challenges of physics-based models, the research and development section of companies prefer to use data-driven approaches to estimate emissions and in the next step to reduce the emissions. Previous research for analysis and estimation emissions in diesel engines such as carbon monoxide, carbon dioxide, nitrogen oxides, hydrocarbon, and particulate matter based on machine learning and AI techniques have proved the power of AI in emissions data investigations [40–42]. These studies have motivated the use of artificial intelligence techniques such as ANN, ANFIS, SVM, RF, and Deep Neural Networks (DNN) [43] in analyzing and estimating of emissions for diesel engines.

4.3 Fault diagnosis

Any computerized or even manual evaluation to detect potential issues leading to any malfunction such as misfire or knock is defined as engine diagnosis in the literature. Misfire is considered a common failure situation of diesel engines which could bring a significant reduction in the brake torque, power, and economic performance, so numerous research is devoted to this challenge. It could occur in diesel engines due to poor fuel quality, unfavorable fuel injection, and electro-mechanical failure. Indeed, misfires might cause irregular pollution and operation in diesel engines. Therefore, researchers are continuously working to provide real-time and accurate misfire detection models [44] using ANN [45] and RF [36] techniques. Even if modern diesel engines are equipped by semi-intelligent electronic control units that are using AI techniques based on the data driven from numerous sensors, misfire occurrences are still hard to identify using a simple algorithm or reasoning. Both of electrical or mechanical component failures such as injection nozzle blockage, solenoid drive failure, and unfavorable air-fuel mixing injection may cause misfires in diesel engines which are pretty hard to detect and manage.

Engine knock, as the other engine fault, is a tapping-pinging sound due to the unwanted auto-ignition of the air-fuel mixture that gets louder as the driver requests more acceleration by pushing the throttle pedal. The result of such an unpunctual combustion is a shock wave which causes the in-cylinder pressure to rise quickly and if a significant knock is not removed and managed soon, the engine will experience damage to rings, pistons, and exhaust valves. Consequently, extended research are devoted to knock detection-based AI techniques such as Convolutional Neural Network (CNN) [46] and RF learning [47]. Furthermore, there are some efforts to detect the intake system leakage [48] and oxygen [49] as the other faults of diesel engines are mainly based on ANN.

4.4 Engine control

Other approach to improve the performance of diesel engines is applying efficient controller and controlling the operating parameters. Having better control of automobiles and improving engine performance, the electronic systems could be integrated with vehicle operation and control. In this approach, the control process of the vehicle operation will be carried out automatically using several sensors and associated electronic transducer systems. One of the recent achievements in this field could be reported Diesel Particulate Filter (DPF) device which is designed to remove diesel PM or soot from the exhaust gases of diesel engines. In addition, an electronic diesel injection controller designed for precise metering and fuel delivery to the combustion chamber could be found in recent trucks and cars using diesel engines.

Despite extensive research [50, 51] carried out in this domain, it seems that more investigations are still needed in two main areas namely; modeling of engine performance under a wide range of operating conditions and development of an intelligent vehicle control system incorporating such a model to improve vehicle overall performance.

4.5 Optimization

The other applications of AI techniques include ANN, Fuzzy, Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) in diesel engines is employing them to optimize the engine operating conditions to achieve the desired target values. Extended research has been carried out in this field, and researcher are continuously developing the optimization techniques as well as the engine performance. It can be asserted that optimization research is applied to almost all aspects of diesel engines and experiencing nonstop development. Indeed, it seems that intelligence optimization is entering into a new phase of developing the real-time optimization. In this approach, the target values may change during the time, thus the optimum values will be continuously updated. Researcher are not stopped at this point and are trying to apply such an approach to diesel engine calibration [52], but it should be noted that this is still of the primary steps and lots of effort are needed to have fully smart engine.

5. Conclusion

In this chapter, the fundamentals of artificial intelligence, the recent trends of using artificial intelligence in internal combustion engines, focused on diesel engines, achievements, and challenges have been discussed. To conclude the subject, it is better to look in more detail at the current technology and the basic definition of artificial intelligence.

As we are able to find in the literature, the current technology and research are focused on the modeling state and we are trying to apply the results to control approaches. As an example, when we introduce a semi-empirical correlation to estimate the out power of the engine based on AI/ML techniques, the main question is about intelligence! What is the difference between these correlations and other physics-based simulation results adopted from a 3-dimensional computational fluid dynamic or a quasi-dimensional thermodynamic model? If just the computational speed/limitations are the difference, where is the intelligence? Or when just the optimized condition is defined as a target, using AI-based optimization cannot mean the intelligence! The intelligence means the target may be updated due to the new condition or engine by the engine.

Looking at more details on the engine control unit, we are able to find some primary levels of intelligence. There are lots of calibration tables for operating ranges of the engine that the engine control unit uses to calculate the needed, for example, fuel to be injected based on the working condition and driver request. Based on the data adopted from the sensors (engine speed, manifold pressure and temperature, the angle of throttle, etc.) the coefficients of fuel mass flow rate correlation is found from the related calibration tables, and after applying the modification coefficients (liquid film loss) the demanded fuel mass flow rate to be injected and will be calculated. There are some other correlations and modifications based on the voltage of the battery to convert the demanded mass flow rate to the millisecond needed to open the injector. Finally, the feedback of such a process can be achieved using oxygen sensor by calculating the equivalence ratio. The schematic of the sensors and actuators for the fuel system is shown in **Figure 6**.

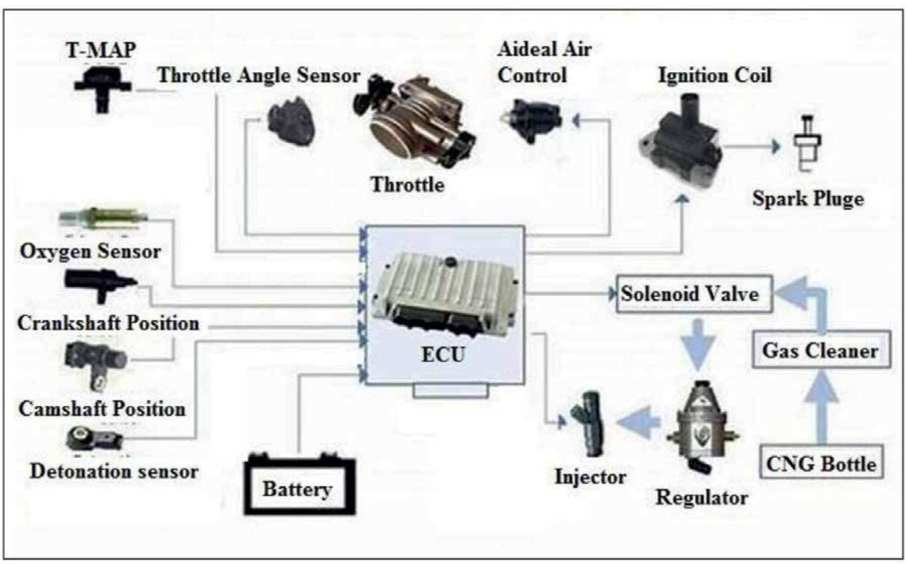

Figure 6.
The schematic of the fuel system.

This is an example of the primary level of artificial intelligence used in engines, the engine is able to find the needed inputs and apply them to achieve the target values. However, it is not the desired definition of a smart engine! The main issue is the process of these calculations which are mainly based on the calibration coefficients that had been defined during the experimental tests of engine in the test cell, and the engine configuration may change during the usage period or due to maintenance operations. So how the engine is able to detect such changes, and how it can find the new best target values, correlations, and their coefficients? In my idea, the right place of “intelligence” is exactly here. As the future development step, the engine control unit could be powered by AI to detect new conditions (engine by engine and even situation by situation), to define new best values of the targets (performance, emission, and faults), and to update the correlations for new values. In this case, we will be able to assert that we have a really smart engine!

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Chapter 2

Ammonia as Fuel for Future Diesel Engines

Zhichao Hu, Zenghui Yin, Yanzhao An and Yiqiang Pei

Abstract

Ammonia (NH_3) is one of the important ways for diesel engines to achieve carbon neutrality. Ammonia's energy density by volume is nearly double that of liquid hydrogen, making it easier to ship and distribute. Ammonia has a well-developed infrastructure and can also be used as a hydrogen energy carrier. However, it was discovered that using pure ammonia as fuel was impracticable, prompting researchers to create concepts for dual-fuel systems or innovative combustion techniques. Therefore, a detailed literature review was conducted on applying ammonia in diesel engines. Firstly, the development of ammonia as a fuel, green ammonia production, ammonia's physicochemical characteristics, and challenges were discussed. Then, using ammonia as fuel in a dual-fuel compression ignition engine was emphasized, with secondary fuels such as diesel, dimethyl ether, hydrogen, and other alternative fuels. Advanced injection strategies help improve engine combustion performance and reduce emissions. Due to the low flame velocity, long quenching distance, and fuel-bound nitrogen of ammonia, there are high levels of NO_x and unburned NH_3 in the exhaust, which makes it necessary to use after-treatment systems downstream. The NH_3-H_2 homogeneous charge compression ignition mode and ammonia cracking are also presented.

Keywords: green ammonia, dual-fuel engines, injection strategy, ammonia cracking, advanced combustion technologies

1. Introduction

With the widespread usage of fossil fuels, environmental issues such as the greenhouse effect have become more serious. Aiming to achieve net zero greenhouse gas emissions in the second half of this century, the Paris Agreement was ratified by over 200 parties to the United Nations Framework Convention on Climate Change in 2015 [1]. In order to achieve the above targets, it is essential to replace a significant percentage of fossil fuels with renewable energy sources. However, the majority of renewable energy sources, like wind, wave, tidal, and solar, produce energy intermittently. As a result, storing the energy in batteries or chemical form is important to mitigate the consequences of fluctuations in energy output [2]. Chemical storage is more economical in comparison to batteries. Chemical storage systems, which have a lower levelized cost of energy storage and allow for the storage of energy produced from renewable sources by converting it into fuel (power-to-fuel), can be used to store energy for longer periods of time and in larger amounts [3]. Therefore, hydrogen and ammonia are proposed as alternative energy sources available in chemical form.

As the main source of greenhouse gas (GHG) in transportation, internal combustion engines face a major challenge and opportunity [4]. The most practical way to minimize GHG emissions is to use carbon-free alternative fuels. Recently, green hydrogen produced by water electrolysis (using electricity from renewable energy sources) has drawn a lot of interest as the future fuel, but its implementation has been constrained by problems with hydrogen storage and delivery [5]. Ammonia has been highlighted as an energy carrier for the green energy (zero-emission) cycle because of its ability to act as a hydrogen energy carrier for the storage and transit of green hydrogen [6]. The findings of recent research, which showed that GHG emissions from ammonia-fueled engines are less than one-third of those from traditional engines fueled with fossil fuels, demonstrate the potential of ammonia to serve as a power-to-fuel for sustainable energy future [7].

Compression ignition (CI) engines have a higher installed capacity and higher thermal efficiency than spark ignition (SI) engines in the transportation and power generation sectors [8]. The shipping industry uses over 330 million metric tons of fossil fuels a year, which increases the amount of hazardous exhaust emissions that contaminate the environment [9]. The International Maritime Organization's implementation of rigorous emission limits for the shipping industry's decarbonization prompted a search for alternative fuels, and ammonia caught the attention of researchers as a carbon-free fuel [10]. This work aims to provide a comprehensive analysis of historical and present research activity on ammonia applications in CI engines. The chapter's organization is as follows: Section 1 provides an overview of the evolution of ammonia as a fuel, the production of green ammonia, the physical and chemical characteristics of ammonia, and the difficulties when ammonia is used as a fuel in CI engines. Section 2 contains a detailed literature review of ammonia-fueled CI engines' performace, with Sections 2.1, 2.2, 2.3, and 2.4 covering the single-fuel combustion of ammonia and the dual-fuel combustion of ammonia with diesel, dimethyl ether (DME), and other fuels, respectively. Section 3 introduces advanced combustion technologies for ammonia CI engines, including homogeneous charge compression ignition (HCCI) (3.1) and ammonia cracking for hydrogen production (3.2). Section 4 lists the after-treatment measures for the ammonia CI engine's emissions. Section 5 provides a summary of the literature review.

1.1 Development of ammonia fuel

As illustrated in **Figure 1**, the use of ammonia as a fuel for transportation dates back to the early 1800s. Small locomotives and trams were the primary use for ammonia during this period. Privately owned ammonia-powered vehicles first appeared in the early to mid-1900s, going through propulsion technology with NASA's X-15 program in 1965. The most recent advancements in ammonia-fueled vehicles happened in the 2010s, with the most current usage in a sports car [11].

The study of ammonia as a fuel for internal combustion engines was undertaken in two stages, each with a distinct goal. The initial phase of research took place during the 1960s and 1970s, following the Second World War, with the goal of addressing the oil and logistical crises. The major goal of the second phase of ammonia fuel research, which began in the new century, was to reduce greenhouse gas emissions through the creation of carbon-free fuels [12].

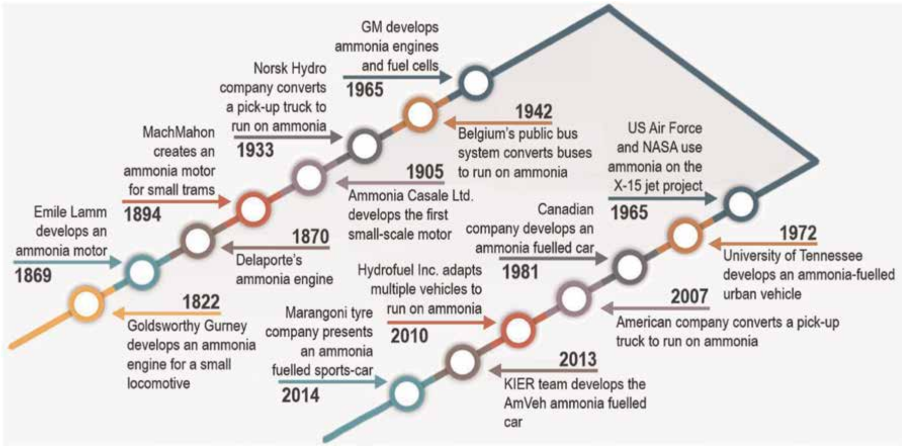

Figure 1.
The development of ammonia as a fuel for internal combustion engines, reprinted from [11].

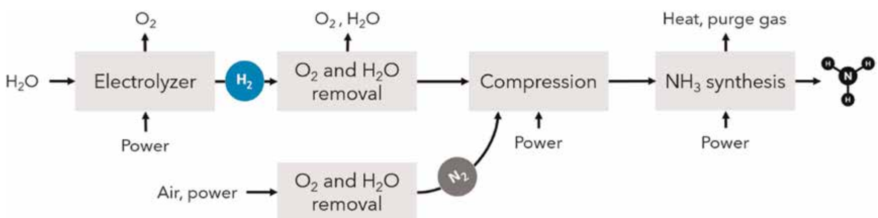

Figure 2.
Schematic for green ammonia synthesis combined with electrolysis-based hydrogen production, reprinted from [13].

1.2 Production process of green ammonia

Ammonia production may be classified into three categories based on its manufacturing process: brown ammonia, produced exclusively from fossil fuels, which is the highest carbon-emitting process; blue ammonia, low-carbon ammonia whose production is still fossil fuel-based, but carbon capture and storage technology is added to the process; and green ammonia, carbon-free ammonia produced exclusively via sustainable electricity, water, and air [11]. Green ammonia production is possible by combining a standard ammonia synthesis loop with electrolysis-based hydrogen, as shown in **Figure 2**. The electricity used throughout the entire process is generated from renewable energy sources such as wind and solar energy.

Green ammonia is produced by the Haber-Bosch process, where hydrogen (from water electrolysis) is combined with nitrogen (from the air separation unit) at high temperature (400–600°C) and pressure (200–400 bar) [14]. The reaction process for ammonia synthesis is shown in Eq. (1):

$$N_2 + 3H_2 \rightarrow 2NH_3 \ (\Delta H = -92.4 kJ/mol) \tag{1}$$

Ammonia is an important hydrogen energy carrier in the development of green ammonia and green hydrogen production. Major countries have proclaimed policies and incentives for the development of cost-effective and creative technologies for green ammonia production, recognizing the ease of storing and delivering hydrogen energy in the form of green ammonia using their well-established infrastructure. Since 2014, Japan has launched the Energy Carriers technology development consortium, which is supported by the Cross-ministerial Strategic Innovation Promotion Program, emphasizing ammonia's central role in the hydrogen economy as a carrying energy vector. The first small-scale green ammonia concept plant consists of a 30 kW electrochemical reactor created in Oxford, UK. This machine produces roughly 30 kg of green ammonia per day as a consequence of a collaboration between Siemens and the Universities of Oxford and Cardiff [15]. In addition to Siemens, other large corporations have already established research and development guidelines for the synthesis of carbon-free ammonia supported by renewable energy sources for use in transportation, chemical fertilization, and large-scale power production. These corporations include MAN Energy Solutions [16] and ThyssenKrupp [17].

1.3 Physical and chemical properties of ammonia

The complete combustion reaction of ammonia is shown in Eq. (2)

$$NH_3 + \frac{3}{4}(O_2 + 3.76N_2) \rightarrow \frac{3}{2}H_2O + 3.32N_2 \tag{2}$$

There are no emissions of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC), or soot from ammonia combustion since it does not contain any carbon atoms. **Table 1** compares the thermodynamic characteristics of ammonia and other conventional or alternative fuels in detail. Ammonia is a colorless gas with a strong odor. Its molecular structure consists of one nitrogen atom and three hydrogen atoms. It is lighter than air and alkaline in nature. Ammonia may be erosive to some

Property	Units	Ammonia	Hydrogen	Methane	Gasoline	Diesel
Density at 1 bar, 25°C	kg/m^3	0.718	0.0837	0.667	736	849
Lower heating value	MJ/kg	18.8	120	50	44.5	45
Latent heat of vaporization	kJ/kg	1370	455	511	348.7	232.4
Boiling point	°C	−33.34	−252.7	−161.5	35–200	282–338
Specific heat capacity Cp	kJ/(kg K)	2.19	14.30	2.483	2.22	1.75
Volumetric energy density at 1 bar, 25°C	GJ/m3	11.3	4.7	9.35	33	36.4
Octane number (RON)		130	>100	120	90–98	8–15
Autoignition temperature	°C	657	500–577	586	230	254–285
Laminar flame speed	cm/s	7	351	38	58	86
Flammability limit (φ)		0.63–1.4	0.1–7.1	0.5–1.7	0.55–4.24	0.8–6.5
Stoichiometric air-fuel ratio by mass		6.05	34.6	17.3	15	14.5
Adiabatic flame temperature	°C	1800	2110	1950	2138	2300

Table 1.
Physical and chemical properties of ammonia and other common fuels [18].

materials. Ammonia has a larger potential as an energy carrier since it can liquefy at a temperature of 33.34°C under atmospheric pressure, while hydrogen must liquefy at a very low temperature of 252.7°C. Another benefit of using ammonia as fuel is that it can be transported safely in huge amounts because of well-established documented protocols and widespread infrastructure for pipes, roads, and rails. Additionally, ammonia is less dangerous in unintentional fires or explosions than other fuels due to its low reactivity. However, ammonia has certain limitations for engine applications, such as high autoignition temperature, low flame propagation speed, and narrow flammability limits, which make it difficult to utilize as a single fuel in engines. Ammonia's great latent heat of vaporization restricts its use as a liquid fuel since it requires more energy to vaporize, lowering the in-cylinder temperature and affecting the engine combustion characteristics.

1.4 Challenges of ammonia combustion in CI engines

The physicochemical properties of ammonia determine the following challenges for its application in engines:

- Security and compatibility
- Low reactivity
- High-fuel nitrogen oxide (NO_x) emissions

Both gaseous and liquid ammonia are dangerous to human health. Ammonia inhalation or direct contact causes lung infections, eye discomfort, and skin damage [19]. Considering ammonia is poisonous, it is important to eliminate leaks in the combustion system and remove unburned ammonia from the exhaust gases after combustion. Corrosion is caused when ammonia exposes to metals, including copper, zinc, aluminum, and their alloys. Steel has been used to store ammonia as a replacement. Ammonia can be used as a fuel in a typical internal combustion engine without significantly changing the engine's geometrical characteristics [20]. The ammonia fuel container and supply system are the main alterations that most typically increase the total area required and weight of the engine system.

To address the inherent drawbacks of the ammonia oxidation process, a variety of highly reactive fuels, such as diesel, biodiesel, hydrogen, and DME, are frequently chosen for co-combustion with ammonia in CI engines. On the other hand, the strategy of combining NH_3 with other fuels as combustion boosters would significantly lessen the requirement for dramatic engine changes [21]. To give maximum power and minimal emissions for each unique fuel, the best blend of ammonia, fuel, and air must be devised [12]. Related studies have succeeded in demonstrating effective operation using NH_3 with no or little design modifications while often deteriorating NO_x emissions. Because the presence of fuel-bound nitrogen in ammonia causes massive NO_x generation during the pyrolysis process in the combustion zone, a better knowledge of NO_x chemistry during ammonia combustion is essential for the development of effective abatement strategies and technologies. Several methods have been presented to minimize NO_x emissions in the combustion system, including moderate or intense low-oxygen dilution combustion, two-stage rich-lean combustion, selective catalytic reduction, or steam addition [22].

2. Ammonia-fueled CI engines

The results of the early-year study on ammonia were unsatisfactory for CI engines due to its high autoignition temperature, low flame speed, narrow flammability limits, and high heat of vaporization [23]. Only the engines designed with extremely high compression ratios (CR) ranging from 35:1 to 100:1 showed successful ammonia operation under CI conditions [24]. Higher CRs are unfeasible in conventional engines since the allowable CR in real-world applications ranges from 12:1 to 24:1 [25]. Therefore, the failed surgery during the first phase might explain the long-term blank observed in the literature. During the second stage, the research aims are primarily focused on reducing greenhouse emissions by partially substituting diesel with ammonia in a dual-fuel operation [26]. Combustion of ammonia in dual-fuel mode with a secondary fuel as a combustion promoter would be feasible for ammonia combustion in CI engines [27].

2.1 Ammonia as a single fuel for CI engines

Gray et al. [28] could only perform ammonia CI combustion at a condition with a CR of 35:1 and an intake gas temperature over 150°C. High-temperature glow coils were proven to be superior ignition sources. The fuel injection system was changed in Ref. [29] to allow for liquid ammonia injection. In a recent study, Lee and Song proposed a new combustion strategy for CI engines fueled with pure ammonia, where a small amount of ammonia (corresponding to equivalence ratios of 0.1–0.3) was pilot injected during the intake process to form a homogeneous lean mixture with air and undergoes autoignition during the compression stroke [30]. This will raise the pressure and temperature within the cylinder to the point where the primary ammonia spray injection will ignite. The specific combustion strategy is shown in **Figure 3**. A parametric analysis was carried out with the assistance of simulations to examine the engine performance using the suggested combustion approach. Despite the intriguing approach, the authors emphasize that additional work is

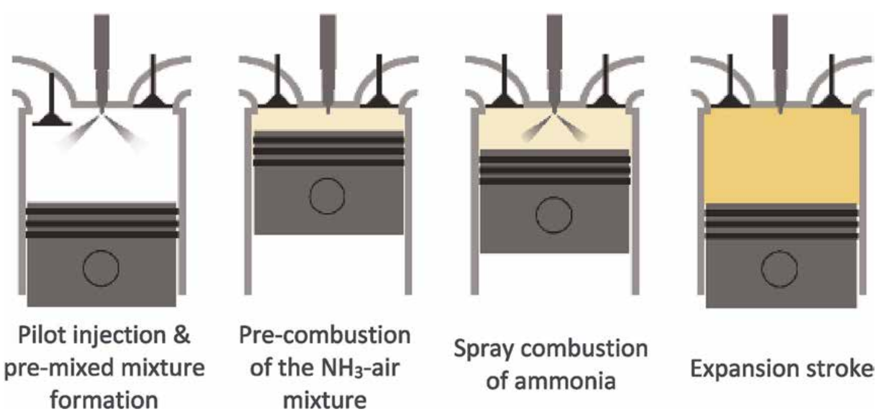

Figure 3.
Schematic describing the combustion strategy for pure ammonia combustion, reprinted from [30].

required. However, the adoption of pure ammonia in CI engines is difficult due to the extraordinarily high CRs required.

2.2 Ammonia-diesel dual-fuel operation

There are two strategies for ammonia-diesel dual-fuel operation: low-pressure injection dual-fuel (LPDF) mode and high-pressure injection dual-fuel (HPDF) mode. In LPDF mode, ammonia and air are mixed during the intake stroke, and diesel is typically injected into the combustion chamber at the end of the compression stroke to induce the combustion process. According to the experience of LPDF engines using methane as the main fuel, the valve overlap and quenching effects will result in methane slipping into the exhaust gas [31]. The use of ammonia as the main fuel can also result in corresponding situations. For the LPDF mode, the maximum ammonia ratio of roughly 80% by energy is advised, and increasing the diesel replacement ratio will induce the risk of misfire [32].

In comparison to LPDF, the high-pressure direct injection of liquid ammonia not only delivers enough ammonia into a cylinder in less time but also has no volumetric efficiency loss. For the HPDF engines, the high-reactivity pilot diesel fuel is injected into the combustion chamber at the end of the compression stroke and acts as an ignition source for the subsequently injected low-reactivity main fuel of ammonia. Similar to diesel engines, the in-cylinder combustion process is controlled by fuel-air mixing in the HPDF mode. The high CR can be used on the HPDF engine to increase the thermal efficiency without knocking. Furthermore, the diffusive flame combustion process is complete and stable, which reduces unburned fuel slip and broadens the working condition, with the potential to attain a 97% diesel replacement ratio [32]. **Figure 4** shows a schematic of engine bench setup with an ammonia-diesel dual direct injection system.

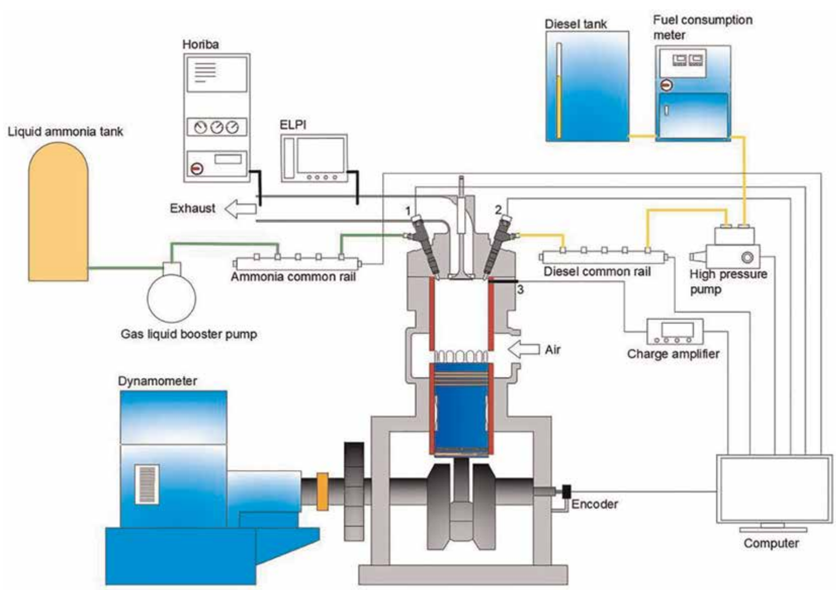

Figure 4.
Schematic of engine bench setup with an ammonia-diesel dual direct injection system, reprinted from [33].

2.2.1 Low-pressure injection dual-fuel mode

Research into the LPDF mode first began in the 1960s. The diesel pilot injection and gaseous ammonia intake port injection were used in a two-cylinder engine with a CR of 18.6:1 [29]. Pearsall performed experiments to examine the effects of changing the amount of diesel delivered to engine in-cylinder while keeping all other factors constant. In comparison to the case where the engine was operating at richer conditions (equivalence ratio = 0.85), it was discovered that when the engine was operating at relatively lean conditions (equivalence ratio = 0.64), increasing the amount of diesel produced a more pronounced increase in power output and decreased brake specific fuel consumption. According to the research [29], a naturally aspirated ammonia-only SI engine could easily produce as much power as a supercharged diesel-ammonia engine. Bro and Pedersen [34] examined the feasibility of premixed ammonia gas compared to methanol, ethanol, and methane in a dual-fuel CI engine in 1977. According to **Figure 5**, ammonia is the least preferable alternative fuel for dual-fuel combustion in CI engines because of its slow burning velocity, high ignition delay time, and unburned ammonia. Following this study, research into ammonia-fueled CI engines was suspended for a period of time.

With increasing attention to GHG emissions, research on the combustion and emission characteristics of LPDF engines has been revived in recent years. In 2008, Reiter and Kong demonstrated the performance of ammonia-powered CI engines in dual-fuel mode [20]. The engine air intake system was injected with ammonia through stainless steel tubing, and the diesel injection system remained unmodified. They explored the influence of changing the ammonia replacement (energy share ratios) on combustion performance and emission characteristics. The engine successfully ran at a maximum energy share of 95%. For ammonia ratios ranging from 40 to 80%, reasonable fuel economy with a combustion efficiency of roughly 95% was obtained, and the brake thermal efficiency was around 33–38%. When diesel was

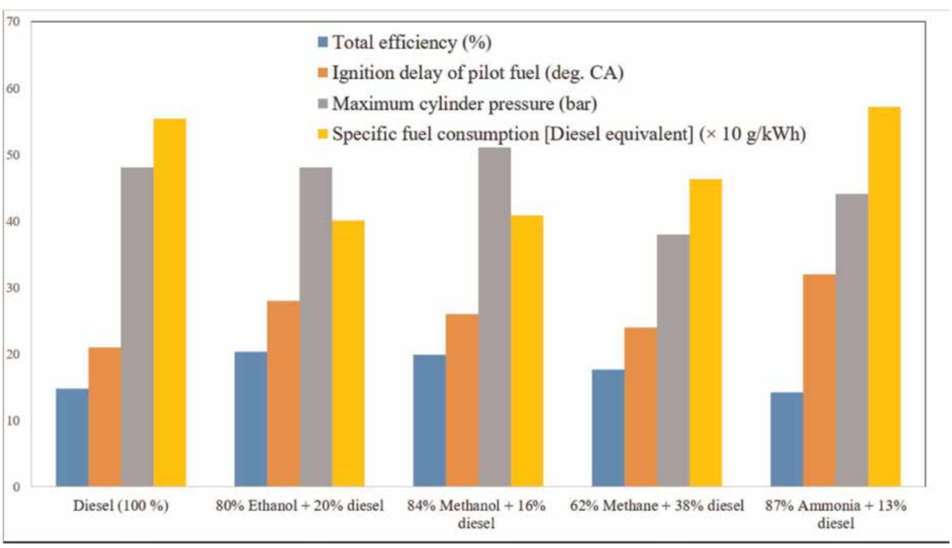

Figure 5.
Results of comparative study on alternate fuels for diesel dual-fuel combustion at 1500 rpm and 1.6 kW, reprinted from [12].

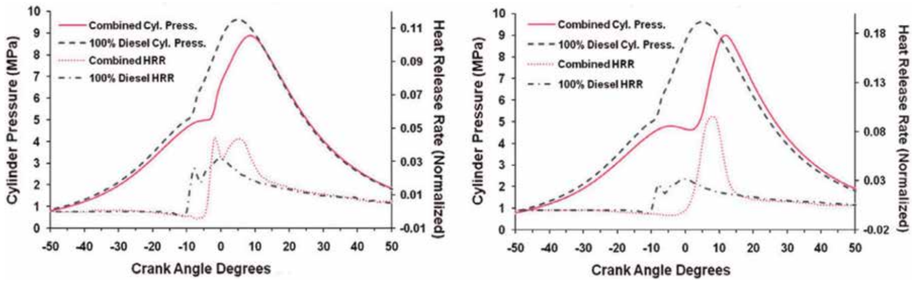

Figure 6.
In-cylinder pressure and heat release rate of dual-fuel engine fueled with (a) 60% diesel +40% ammonia and (b) 40% diesel +60% ammonia at constant power output (40 kW at 1000 rpm) conditions, reprinted from [35].

substituted with ammonia in the fuel blend, the combustion temperature was reduced, resulting in higher HC and CO emissions [35]. Fuel-rich zones inside engine cylinders were the principal sources of soot emission in diesel engines, and replacing diesel with ammonia significantly (>40%) reduced soot emission. The in-cylinder pressure and heat release rate for constant power output conditions of the engine fueled with 60% diesel +40% ammonia (the start of injection (SOI) was 37°CA before top dead center (BTDC)) and 40% diesel +60% ammonia (35°CA BTDC SOI) are shown in **Figure 6**, where the effects of fuel composition on combustion phasing and peak pressure can be seen in detail. Compared to pure diesel combustion, the addition of ammonia showed a significant increase in ignition delay time. In the case of 60% diesel +40% ammonia combustion, premixed and diffusion combustion phases in traditional diesel combustion were kept, as evident from the history of heat release rate. When the ammonia energy share increased to 60%, the longer ignition delay time resulted in complete mixing and just one peak in the heat release rate.

In the past few years, researchers have applied advanced diesel injection systems with pilot and postinjections to manage combustion temperature and harmful emissions [36]. In Ref. [37], numerical simulations were carried out to study the effectiveness of diesel, diesel-kerosene, and kerosene pilot injections in an ammonia-fumigated CI engine. For ammonia energy-sharing ratios exceeding 60%, CO and CO_2 emissions were significantly decreased, while NO_x emissions were significantly increased. Yousefi et al. evaluated the ammonia/diesel dual-fuel mode on a heavy-duty diesel engine both experimentally and numerically [38]. A significant amount of unburned ammonia was produced from the poor flame propagation of the premixed ammonia-air mixture. Due to excess NH_3 inside the combustion chamber being used to consume nitric oxide (NO) rather than produce NO, NO_x emissions may be reduced by 58.8% when the ammonia energy share ratio increases from 0 to 40%.

2.2.2 High-pressure injection dual-fuel mode

Despite some experimental and numerical studies on the ammonia/diesel LPDF engines, research on the ammonia/diesel HPDF mode has not been widely documented [32]. For analyzing the spray combustion processes and emissions of diesel engines, three-dimensional computational fluid dynamics simulation has gained acceptance as a trustworthy tool [39]. Researchers from the Technical University of Munich used numerical simulations to explore the application of ammonia in the

HPDF engines [40, 41]. After the top dead center (ATDC), the pilot diesel and liquid ammonia were introduced into the cylinder at −2.5 and 1°CA, respectively. The fuel-air mixing rate determines the heat release rate for the HPDF mode, and liquid ammonia has the capacity to supply more than 95% of the total injected energy. This paper gave no information on emissions or engine performance but focused on cylinder pressure and heat release rate.

Accurate spray modeling near the TDC is necessary for a good simulation of the HPDF engines. Li et al. [32] used a constant-volume combustion chamber to measure the spray characteristics of liquid ammonia. The numerical model for the ammonia-diesel HPDF engine was built after calibrating the spray submodels against experimental ammonia spray data. The ammonia/diesel HPDF engine model was performed with the pilot diesel, and liquid ammonia was injected into the cylinder at −8 and − 5°CA ATDC, respectively. The authors compared the LPDF and HPDF modes, as shown in **Figures 7** and **8**. In HPDF mode, the ammonia energy share can reach up to 97%. The results revealed that the HPDF mode had equivalent indicated thermal efficiency, cooling, and exhaust loss to the pure diesel mode, but it may significantly reduce greenhouse gas emissions (CO_2 and nitrous oxide (N_2O)) with minor increases in NH_3 emissions.

Zhang et al. [33] explored the direct injection of liquid ammonia using experimental measurements on a two-stroke, low-speed CI engine. The authors investigated the combustion and emission characteristics of the diesel/ammonia dual direct injection strategy under different ammonia injection amounts and injection timing of ammonia and diesel. Diesel was injected at −8°CA ATDC, and the liquid ammonia injection timing was adjusted to −16, −8, and 0°CA, corresponding to the three different combustion modes of ammonia, including premixed combustion, premix-diffusion co-combustion, and diffusion combustion. The results demonstrated that injection timing is critical in ammonia ignition to control the combustion phase and duration. The shortest combustion duration and maximum indicated thermal efficiency of 38.8% were found for ammonia injected at −8°CA ATDC, but NO_x levels were high. A certain amount of ammonia diffusion combustion is important for enhancing

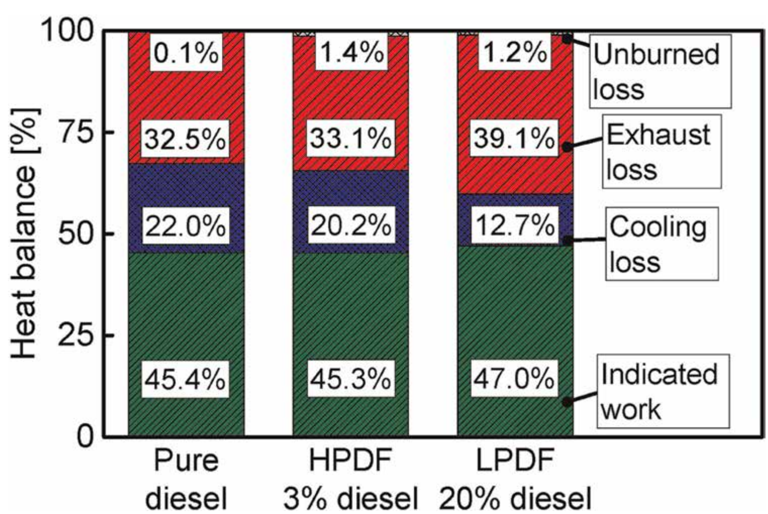

Figure 7.
Comparison of the energy balances among the pure diesel, HPDF and LPDF modes, reprinted from [32].

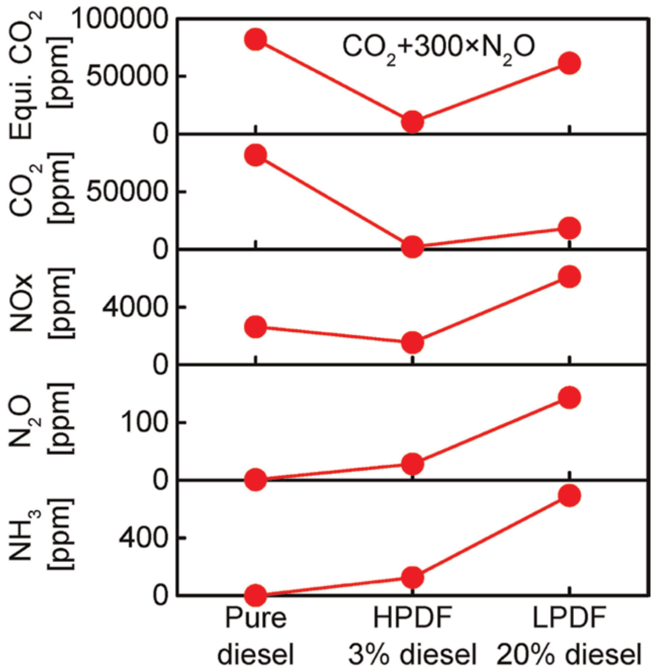

Figure 8.
Comparison of the emission characteristics among the pure diesel, HPDF, and LPDF modes, reprinted from [32].

ammonia combustion. Overall, soot and CO emissions were reduced, presumably because the liquid ammonia direct injection can improve the interaction of spray plumes inside the current combustion chamber, promoting atomization and evaporation of diesel. Injection timing of −8°CA ATDC was the best option for both diesel and liquid ammonia to balance the engine efficiency and emissions. The ammonia energy share in this work was only 50%, with a higher ratio hopefully to be achieved in the future.

2.3 Ammonia-DME dual-fuel operation

The researchers investigated the performance of CI engines using ammonia and DME because of the miscible nature of the two substances [42–44]. In comparison to ammonia, DME has a greater cetane number, a lower ignition temperature (350°C), a lower latent heat of vaporization (467 kJ/kg), and a higher lower heating value (LHV) (28.43 MJ/kg). It can be generated using renewable energy sources. Ammonia/DME combinations are commercially employed for refrigeration, making their distribution as an alternative fuel more practical [45]. On a single-cylinder, direct-injection diesel engine, Ryu et al. [42] tested three ammonia/DME mixtures (100% DME, 60% DME, and 40% DME). The injection pressure was kept at around 206 bar, and engine combustion and exhaust emissions were evaluated to compare the performance of various ratios of mixture compositions. The findings showed that the engine performance decreased when ammonia was added to the blend fuel mixture. There were noticeable cycle-to-cycle changes when 40% DME + 60% NH_3 was used. It is observed from **Figure 9** that the injection timing for successful engine operation needs to be advanced as the ammonia content in the fuel mixture increases. As shown in

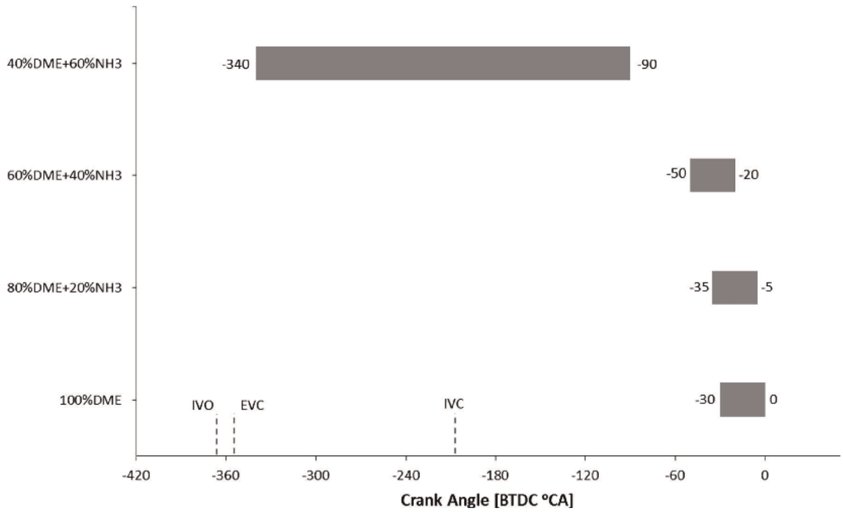

Figure 9.
Range of possible injection timing for successful combustion using different fuel mixtures, reprinted from [42].

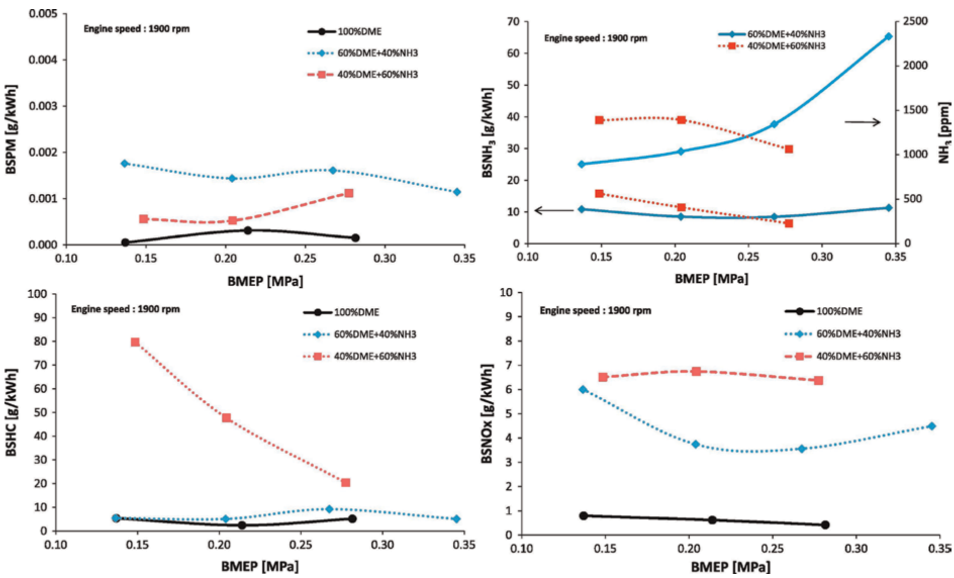

Figure 10.
Emissions for various fuel mixtures, reprinted from [42].

Figure 10, when ammonia was used in the blended fuel, various exhaust emissions increased. Although NO_x emissions were higher in the case of fuel mixtures containing ammonia compared to pure DME, the emissions remained well within Environmental Protection Agency regulations for small output engines (7.5 g/kWh), and soot emission levels were also quite low (less than 0.002 g/kWh) in all cases. The energy cost of ammonia-DME combinations was equivalent to diesel, and the possibility of producing them using renewable energy sources contributes to a reduction in carbon footprint [44].

2.4 Ammonia and other fuels

Gray et al. tested dimethyl hydrazine and amyl nitrate as alternative fuels for diesel in an ammonia dual-fuel CI engine [28]. The results showed that the high cetane number of the test fuel had a significant impact on the engine combustion characteristics. In Ref. [20], soy-based biodiesel was adopted as the ignition source by Reiter and Kong. The experimental results for the diesel-ammonia operation and the biodiesel operation were comparable. Lower NO_x emissions were observed when ammonia content was up to 70%, and using biodiesel also helps to sequester carbon.

3. Advanced combustion technologies in ammonia CI engines

3.1 Ammonia-hydrogen HCCI engines

Low-temperature combustion (LTC) is a series of advanced combustion technologies that promise savings in both fuel usage and pollutant emissions. HCCI is one of the earliest kinds of LTC and arguably the most extensively explored. A homogenous mixture of air and fuel was compressed until it autoignites in HCCI. HCCI has achieved extremely low NO_x and soot emissions while retaining or exceeding traditional diesel combustion efficiency [46]. Only a few studies have been conducted in recent years on the use of ammonia in HCCI engines. Unfortunately, the low power output of HCCI engines, along with ammonia's low lower heating value (LHV) and the high intake temperature required, reduces the power density of such an application. However, it may be highly appealing for stationary applications such as combined heat and power plants, where great efficiency is achievable.

In Ref. [47], pure ammonia was proven for HCCI engine operation but with a CR of 40:1. Due to the high autoignition resistance of ammonia, hydrogen is required to promote and stabilize HCCI combustion. Pochet et al. developed an HCCI engine operating with ammonia and hydrogen blends under a variable blending ratio [48]. With the addition of hydrogen, the required CR was reduced to 16:1. The results showed that the required intake temperature for pure hydrogen combustion was about 154°C, and there was little impact on autoignition resistance until the ammonia share reached 60%. The engine operated HCCI conditions with an ammonia content of up to 70% by setting the intake pressure to 1.5 bar and the intake temperature to 202°C. The authors were one of the earliest research groups to use exhaust gas recirculation to reduce NO_x emissions from an ammonia-fueled engine [48]. To reduce N_2O generation, measures to compensate for the associated decrease in combustion efficiency and deploying a selective catalytic reduction (SCR) system would be necessary. In the other engine with a CR of 22:1, they were able to burn an NH_3-H_2 blend, with ammonia content varying from 0 to 94% in the fuel blend [49].

3.2 Ammonia cracking and hydrogen fumigation

One advantage of ammonia as an energy carrier is that it may be utilized directly as fuel or cracked and supplied as a hydrogen source. Gill et al. [50] first investigated the effects of providing ammonia, dissociated ammonia (1–2% NH_3, 75% H_2, and 23–24% N_2), and hydrogen to a dual-fuel diesel engine in order to reduce the engine's carbon-based emissions. Three fuels were supplied directly into the intake manifold, respectively, replacing roughly 3% of the intake air. Diesel was injected directly into the cylinder to ignite the mixture. The results showed that the braking thermal efficiency of all three operations was lower when compared to the pure diesel operation. Among the three distinct ammonia use procedures studied, the application of pure hydrogen was the best for reducing emissions and improving engine performance. However, it is challenging to isolate hydrogen from the dissociated NH_3 mixture on a vehicle. Thus, the better strategy is to partially dissociate the NH_3 to enhance combustion and reduce engine emissions. Using dissociated NH_3 minimizes NH_3 slip and N_2O formation during combustion.

The possibility of ammonia exhaust gas reforming for hydrogen production used shown in transportation was investigated for the first time by Wang et al. [51]. The investigation began with an examination of ammonia autothermal reforming, which combined selective oxidation of ammonia (into nitrogen and water) and ammonia thermal decomposition over a ruthenium catalyst with air as the oxygen supply. Later, the air was replaced with diesel engine exhaust gas to supply the oxygen required for the exothermic reactions that raise the temperature and enhance NH_3 decomposition. The specific experimental setup is shown in **Figure 11**. The catalytic decomposition of NH_3 requires a temperature higher than 500°C to produce steady NH_3 conversion and substantial H_2 generation. Eq. (3) and Eq. (4) express the selective catalytic

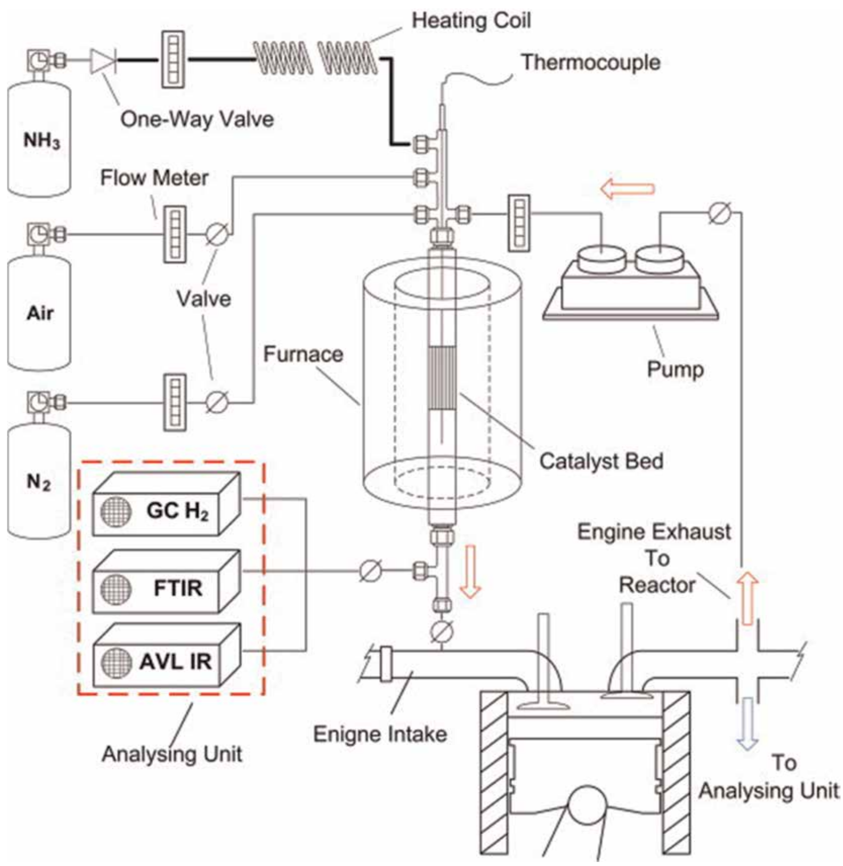

Figure 11.
CI engine with a modified ammonia autothermal reforming system, reprinted from [51].

oxidation of ammonia and NH_3 decomposition processes, respectively. Eq. (5) shows the desired combination.

$$4NH_3 + 3O_2 = 6H_2O + 2N_2; \Delta H_r = -1260kJ/mol \tag{3}$$

$$2NH_3 = 3H_2 + N_2; \Delta H_r = +46kJ/mol \tag{4}$$

$$NH_3 + xO_2 = 2xH_2O + (1.5 - 2x)H_2 + 0.5N_2; x < 0.75 \tag{5}$$

The hydrogen production efficiency and reforming process efficiency of the NH_3 exhaust gas reforming are shown in **Figure 12**. Although increasing O_2/NH_3 ratios resulted in higher H_2 generation, the reforming process efficiency declined due to increased NH_3 consumption in exothermic oxidation. The authors added reforming products (H_2 and unconverted NH_3) to the intake port and utilized them as additives to diesel fuel for combustion to explore how different components of reforming products impact engine performance and emissions. Because the NH_3 was not effectively combusted, the addition of the reformate reduces brake thermal efficiency. In terms of engine emissions, replacing diesel with a noncarbon-based reformate reduced carbon emissions but increased NO_x emissions.

In the above study, ammonia was used more as a hydrogen carrier to produce hydrogen, and the addition of hydrogen to a diesel-fueled engine can significantly reduce HC, CO, and CO_2 emissions. However, the addition of ammonia may have adverse effects on CI engines. The engine should be improved to take advantage of the potential of ammonia reforming into hydrogen systems.

4. Exhaust emissions in ammonia CI engines

As discussed above, adding ammonia to diesel engines can reduce carbon emissions, but it will also inevitably produce high levels of NO_x and unburned NH_3 emissions. Advanced combustion strategies are beneficial for reducing emissions, but after-treatment measures are still necessary. NO_x, such as NO and nitrogen dioxide

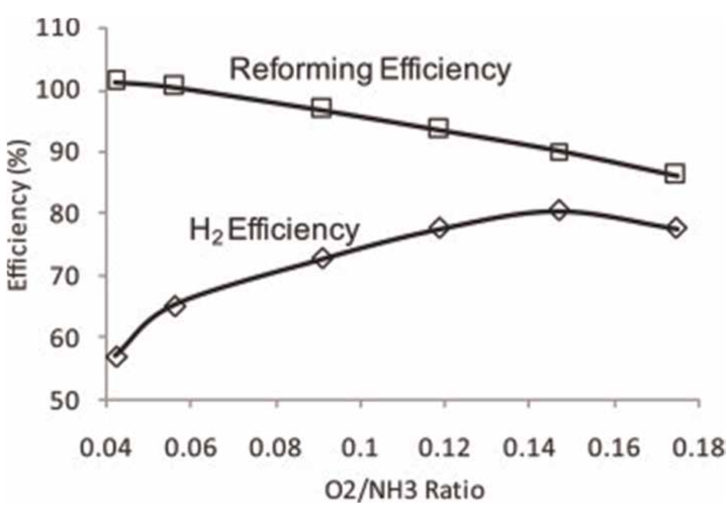

Figure 12.
H_2 efficiency and reforming efficiency at 16 g catalyst and a 3 L/min NH_3 flow rate, reprinted from [51].

(NO_2), contribute to the destruction of the ozone layer and lead to respiratory issues. Nitric acid causes acid rain when NO is combined with atmospheric air and NO_2, which causes smog in and around cities. Due to the fact that fuel and air are premixed in SI engines, the combustion chamber temperature is consistent with flame propagation, resulting in a NO_2/NO_x ratio of less than 2%. However, the combustion in a CI engine is regulated by mixing and has a wide distribution of cold areas and a larger NO_2/NO_x ratio. N_2O is a severe concern since it has a 300-fold greater potential to cause global warming than CO_2 over a 100-year time horizon. The ammonia itself is poisonous, and the quantity of unburned ammonia in the exhaust may cause issues for automobiles.

For the development of efficient abatement technologies, a deeper understanding of nitrogen chemistry during ammonia combustion is required. Miller and Bowman [52] researched the chemistry of nitrogen in combustion, focusing on the production and destruction of NO_x by examining the reaction rates and reaction paths of the primary routes of NH_x radicals. Their work developed the first detailed mechanism for ammonia combustion that was confirmed. After decades of study, researchers now have a thorough understanding of the chemical kinetics of ammonia. They focused not only on the combustion of pure ammonia but also on the co-combustion of ammonia and other fuels. Feng et al. [53] prepared an NH_3-diesel mechanism with complex diesel substitutes (n-cetane, iso-cetane, and 1-methylnaphthalene) and achieved good validation. **Figure 13** shows the reaction path of ammonia-diesel at low temperatures. However, there is still insufficient understanding of the cross-reaction between ammonia and diesel. In order to improve the accuracy of the mixing mechanism, it is necessary to conduct experiments and quantum calculations on the cross-reaction.

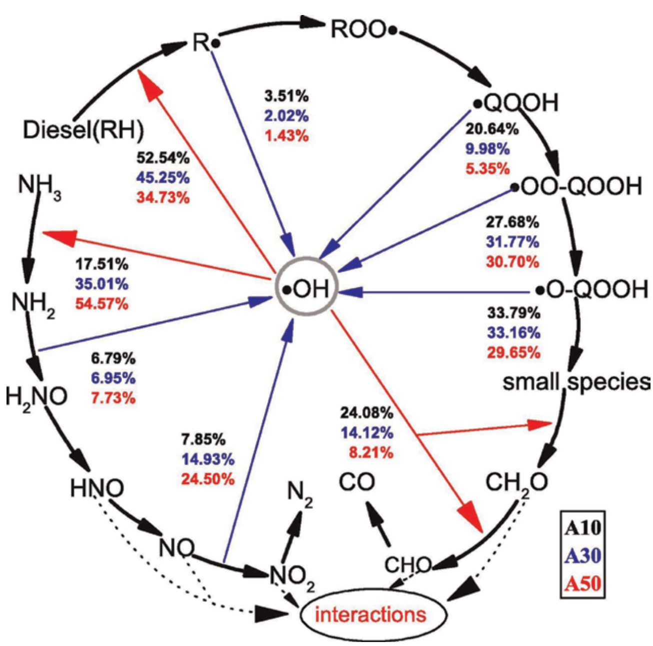

Figure 13.
Main reaction pathways of NH_3/diesel mixtures, with the initial condition of ϕ = 1.0, pc = 15 bar, and Tc = 690 K, reprinted from [53].

Ammonia burns slowly and has a long quenching distance, making it challenging to completely burn it in the engine. As a result, more unburned ammonia is frequently left in the crevice volume, which increases unburned ammonia emissions. The engine architecture (piston design, crevice, compression ratio, and squish zone for CI engines) plays an important role in the ammonia slit. When gaseous ammonia is used as a fuel, the formation of unburned ammonia is greater as compared to liquid ammonia [54]. Unburned ammonia in the exhaust stream may be beneficial for the operation of the SCR system, which reduces NO_x emissions to nitrogen in the presence of a catalyst, as shown in Eqs. (6) and (7):

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{6}$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \tag{7}$$

The Lean NO_x Trap (LNT) may be used to absorb NO and NO_2 regardless of the oxygen exhaust concentration. However, LNT only achieves partial N_2O adsorption-conversion and generates NH_3 as a bi-product during regeneration. Recent studies have provided practical evidence of the beneficial combination of LNT and SCR in series: the fuel penalty can be mitigated when compared to pure LNT, the ideal operating temperature of both systems is more flexible and in the 200–300°C range, and total conversion of NO_x–N_2O–NH_3 is achieved [55]. Three-way catalytic converters can also be used to convert NO_x emissions.

5. Conclusions

Green ammonia is one of the key strategies for diesel engines to attain carbon neutrality. The evolution of ammonia combustion technologies in diesel engines has been reviewed. Not only ammonia is a hydrogen carrier, but it is also readily available, easy to store and transport, and has an established network for transportation and distribution globally by pipeline and bulk carrier. Ammonia as a fuel in CI engines is hampered by its high autoignition temperature and long ignition delay time, resulting in low engine performance. References suggest that the combustion of ammonia in CI engines can be achieved by several strategies: (1) blending with other fuels; (2) higher CR, preheating, or supercharging; (3) high-pressure direct injection of liquid ammonia; (4) ammonia dissociation. It has been successfully demonstrated that highly reactive fuels, including diesel, biodiesel, hydrogen, and DME, may ignite ammonia in CI engines. Ammonia-diesel dual-fuel CI engine operation with ammonia rates up to 95% can be found in the literature. Blending ammonia with traditional fuels reduces the requirement for engine modifications (material compatibility), ensuring cost-effectiveness for the transition to a hydrogen economy.

Due to ammonia's lower energy density and calorific value, the increased ammonia content in blend fuels reduced carbon emissions but had a negative impact on engine performance. Additionally, ammonia dual-fuel combustion currently produces relatively high levels of unburned ammonia and NO_x emissions because of the fuel-bound nitrogen. Researchers have actively explored solutions to these problems. The use of advanced injection strategies for the secondary fuel can contribute to enhanced performance and overall emissions improvement. Compared to port injection, liquid ammonia direct injection may achieve greater combustion efficiency, and the energy share of ammonia is expected to rise to 97%. Partial dissociation of ammonia contributes to improved combustion performance. Ammonia-hydrogen combustion in HCCI engines is also a viable technical route. The use of various advanced strategies may reduce NO_x and unburned NH_3 emissions, but posttreatment measures such as SCR systems are still necessary. It will be more cost-effective and convenient to reduce emissions by using unburned ammonia emissions in the exhaust stream rather than a separate urea/ammonia injection. Ammonia as a compression ignition fuel is currently only considered a viable option for maritime, power-generating, and heavy-duty applications without serious space restrictions.

There is currently limited literature on ammonia combustion in CI engines, and more research is needed to grow the use of ammonia as a hydrogen energy carrier from an incipient stage to one that is well-established and commercially viable. Although numerical simulations are already a well-respected method for investigating ammonia combustion in engines, more research is still needed to provide reliable data and enhance the simulation tools' ability to forecast how future ammonia engines will be designed and optimized. The potential of ammonia in advanced CI engines should also be considered in the future, including homogeneous charge compression ignition, premixed charge compression ignition, and reactivity-controlled compression ignition.

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Chapter 3

Diesel Engine Fuel and Fuel Emulsion Influence on Diesel Engine Performance and Emission

Osama Ahmed Elsanusi, Mustafa Elayeb, Mustafa Aburwais and Mohamed Shetwan

Abstract

The diesel engine's superior energy conversion efficiency and cost-effective power source have made it a popular choice for a wide range of applications, including but not limited to agricultural machinery, transportation, and mining equipment. Diesel engines produce harmful emissions, including exhaust fumes that contain pollutants such as particulate matter and nitrogen oxides. These emissions are detrimental to the environment and public health, and as a result, strict standards are imposed to reduce them using modern technologies in diesel engine manufacturing, exhaust treatment systems improvement and fuel modifying technologies. This chapter reviewed the effect of wide verity of fuel in diesel engine performance and emission.

Keywords: diesel engine, fuel, fuel emulsion, performance, emission

1. Introduction

Diesel engine has high energy conversion and economic power source compared to other engines which make it used in many applications, such as agricultural machines, transportation, and mining equipment [1]. On the other hand, diesel engines emit pollutant that is harmful for the environment, since regulated emissions like HC, CO, NOx and particulate matter (PM) were put in place [2, 3]. Increased concerns over environmental and emissions regulations have heightened the motivation to control diesel engine emissions. Consequently, there are three main approaches to control diesel engine emission which are: engine design techniques, exhaust gas after treatment and fuel. Injection timing has great influence on diesel engine emission. Advanced injection timing contributes to high NOx emission and low fuel consumption while delaying injection timing reduces NOx emission and increases fuel consumption [3]. The selective catalytic reduction as an aftertreatment system has proved significant reduction in both NOx and PM compared to engine without this system [4–6]. Similarly, The exhaust gas recirculation (EGR) contribute to reduce NOx and PM emission [7–9]. Correspondingly, The diesel particulate filter has proven dramatic decrease on PM emission [5]. The diesel oxidation catalysts are equipped to diesel engines to decrease regulated emission such as CO and HC [10].

Based on the above discussion, the objective of this chapter is to investigate the effect of fuel on diesel engine emission. Diesel engines are increasingly being developed and adopted to work with wide verity of fuel and fuel additives. The fuel, fuel blends, fuel additives and fuel emulsion effect on diesel engine regulated emission will be reviewed in this chapter.

2. Diesel engine fuel

Diesel engines could work with a wide range verity of fuel in which fuel ignition take a place without a spark as a result of air compression and fuel injection. Correspondingly, any fuel shows significant compression ignition features and other properties such as, viscosity, flash point, heat value and cetane number (CN). Fuel viscosity is simply a measure of flow resistance. According to ASTM D6751 the accepted fuel viscosity for the diesel engine varies between 1.9 to 6.0 cSt at 40°C [11]. Fuel with higher viscosity than diesel decreases the injection rate and less atomization and vaporization hence incomplete combustion tends to increase smoke opacity, HC and CO [12]. CN is a measure for fuel ignition quality. The CN of fuel affects the ignition delay time and the premixed combustion phase, which decrease by raising the CN in the fuel. Therefore, fuels with a high CN cause a reduction of NOx emission, whereas it improves high CO, HC and smoke emissions [13]. Additionally, A higher CN of biodiesel contributes to quieter engine operation and easier engine start-up [14, 15]. The energy content of fuel is a key element in fuel economy, as well as in an engine's ability to produce power. Typically, fuel with higher heating value will provide better economic performance [16]. Overall, many fuels have been experimentally tested for running diesel engine such as biodiesel, diesel, kerosene, n-butanol and n-heptane [17–20].

3. Fuel blends

Diesel is usually blended and used in different concentration with other fuels to improve diesel engine performance and emissions. Nageswara Rao et al. [18], tested Common Rail Direct Injection 4-stroke 4-Cylinder engine fueled with ethanol, biodiesel and diesel blends. The blend percentages were 50 vol% biodiesel with different percentages of ethanol and diesel. They concluded that increasing ethanol percentages in the fuel blend results in reducing brake thermal efficiency (BTE) and increasing brake specific fuel consumption (BSFC). The CO and HC emissions decreased while the NO_x emission increased. They reasoned that the higher latent heat of vaporization, lower CN (longer ignition delay), and lower heat content of ethanol are the main reason for those results. Many other studies on fuel blends have investigated their effect on diesel engine emission and performance as listed in **Table 1**.

4. Fuel additives

Using additives is an effective method to modify the fuel properties. Some additives are used as CN improvers such as acetone and diethyl ether [16, 23]. Other additives are used to decrease fuel viscosity, density and cold flow properties. **Table 2** summarized many studies that have been conducted to control diesel engine performance and emissions.

Fuel blend	Emission	Performance	Reason	Ref.
Diesel 85% + heated grape seed oil 30% + propanol 5%	4.22% NOx reduction. 5.61% smoke opacity reduction. 6.17% HC increase 4.23% CO increase Compared to diesel.	3.26% BSFC increase. 5.50% BTE reduction Compared to Diesel.	Low thermal value, high viscosity and poor evaporation properties compared to diesel were thought to be influential on diesel engine emission and performance.	[21]
Polanga biodiesel + diesel (B0, B5, B10, B15, B20, B25, B100)	Increasing biodiesel amount on blend increases NOx emission. PM emission decreases with biodiesel amount increase on the blend.	There is a slight decrease in engine BTE. The BSFC was not tested in this experimental study.	Increase the amount of biodiesel increases the fuel viscosity leading to poor air-fuel mixture. NOx emission in biodiesel rises due to higher combustion temperatures, longer combustion durations, and higher oxygen.	[22]
Canola biodiesel + diesel blends	Diesel amounts decrease in the blend increases NOx emission. On the other hand, both HC and co emission decrease with biodiesel amount increase in the blend.	N/A	Oxygen content in biodiesel improves combustion temperature leads to more NOx emission.	[23]

Table 1.
Fuel blend effect on diesel engine performance and emission.

Ref.	Additives	Results
[24]	Methanol, ethanol, diethyl ether (DEE) were added to B40 blend	Methanol and ethanol reduced NOx emission and considerably increased CO and HC emission emissions, DEE was found to improve NOx and smoke compared to its base fuel.
[25]	Acetone	The best concentration of acetone in diesel fuel was found to be 3% due to enhancing the engine performance and reducing the emissions without affecting the engine stability. The engine emissions were reduced at all loads with low concentration of acetone.
[26]	Silicon dioxide (SiO2) nanoparticle additives to methanol	The addition of SiO2 nanoparticle in methanol could enhance the combustion and performance characteristics, and suppress the emissions of diesel engines.
[27]	Nano additive in water (5% WiDE); 25 ppm cylindrical carbon nanotube (CNT) and 25 ppm spherical Al2O3 nano-additives	Therefore, 5%WiDE based Al2O3-CNT hybrid nano fuel has a high potential to be an alternate conventional fuel for diesel engines without any design modification.
[28]	Four-carbon alcohol (n-butanol) and ester (ethyl ethanoate) were separately blended with pure diesel (D100) at three blending ratios.	At low loads, up to 20.9% rise in brake specific fuel consumption (BSFC) was recorded but EE15 (15% ethyl ethanoate, 85% diesel) achieved 15.35% lower BSFC at 60% load.

Ref.	Additives	Results
		NOx emissions reduced for all blends, with n-butanol blends achieving 30.6% less NOx emissions compared to D100. However, CO emissions increased by up to 37.6% for n-butanol and 32.9% for ethyl ethanoate.
[29]	Higher alcohols and graphene oxide nano-additives (GO) to Jatropha biodiesel	The NOx, CO, UHC, and smoke concentrations are dropped curiously by 20, 30, 30, and 40%, respectively, with introducing of higher alcohols with a conventional oil-jatropha blend. The CO, UHC, and smoke intensity are lowered noticeably by 15%, 60%, 70, and 80%, respectively, whereas NOx is expanded by 13% with implanting of GO.
[30]	ZnO nanoparticles	Reduction of smoke by 11.86%, CO by 5.7%, UHC by 28%, and NOx by 14.93%, along with the enhancement of BTE by 2.47%, were noticed at maximum load with 100 ppm particles.
[31]	The Tri ethylene glycol mono-methyl-ether (TGME)	CO, CO2, and NOx emissions decreased by 76.77, 40.9, 1.31%, respectively. Brake power, and brake thermal efficiency increased by 10.54 and 12.77%, the generated power cost amount decreased by 20.16%.
[32]	Diethyl Ether	BTE increases as the power is increased. BSFC is being seen to decrease with the increment in power. NOx emission increases whereas HC emission decreases with increment in power. Overall study concludes with B60BD30DEE10 showing the best feasible results out of all the blends and pure diesel. CO emission increases for blends as compared with pure diesel for lower values of power but as the power is increased, after some specific value of brake power CO emissions for blended fuels decreases and goes below than that for pure diesel fuel.
[33]	Alcohol and Nano additives	Higher alcohol-biodiesel-diesel blends were recommended for engines as an alternative substitute for conventional diesel. Metal base additives have improved combustion efficiency and reduced emissions by enhancing combustion efficiency. Further, metal base additives increased the NOx emission, but the remaining emissions are getting decreased under all operating conditions.
[34]	1-Hexanol, D70H30/H2	It was observed that the higher the proportion of 1-Hexanol, the lower the engine performance. for the blend D70H30/H2, around 8.24% rise in brake specific fuel consumption, slight rise in hydrocarbon, 2.80% reduction in brake thermal efficiency, and 16.70% reduction in nitrogen oxides (NOx) emission.

Ref.	Additives	Results
[35]	Various nanoparticles blended with PB20FTPO10 (20 palm biodiesel+10% filtered tire pyrolysis oil) MgO nano-fuel, graphene and Al2O3 nano-fuel models.	The tribological behavior of the nano fuels made of MgO, graphene and Al2O3 had been improved. In contrast to MgO and graphene nano fuel, the optimized Al2O3 nano fuel demonstrated the best tribological performance with the lowest concentration, price, load and speed.

Table 2.
Fuel additives effect on diesel engine performance and emission.

5. Emulsion fuel

Emulsion fuel is a mixture of water and fuel that is blended with emulsifiers. The emulsifiers is usually consist of two different surfactants that responsible for minimizing surface tension between immiscible liquids [16, 36, 37]. Polar liquid like water has different charges at the end of each molecule, those molecules could dissolve only in a polar solvent. Contrary, non-polar liquids like fuel have an equal charge at each end of their molecules and they could dissolve only in a non-polar agent [38]. Generally, surfactants are liquids that have an imbalanced concentration of polar (hydrophilic) and nonpolar (lipophilic) molecules. Each surfactant has a value called hydrophilic- lipophilic balance (HLB) varying between 0 to 20. HLB measures surfactant degree of hydrophilicity or lipophilicity, that determined by calculating molecular percentages weight of the hydrophilic and lipophilic portion of the surfactant molecule [39]. The emulsified diesel and biodiesel have significant effect on reducing NO_x and PM emissions while it improves CO emission [40–43]. The emulsified fuel generally reduces the combustion temperature, and improves the fuel atomization inside the combustion chamber hence lower NO_x and PM emissions but higher CO emission compared to the base fuel [16, 38].

5.1 Emulsion types

Generally, there are two approaches of emulsifying fuel, **Figure 1**, known as: 2-phase and 3-phase fuel emulsion. 2-phese emulsion could be water-in-oil (W/O), or Oil-in-water (O/W) [45]. The 3-phase emulsion and also known as multi-phase emulsion consists of water-in-oil-in-water (W/O/W) or oil-in-water-in-oil (O/W/O) [46]. The name of emulsion describes the liquid added to the other. For example, O/W emulsions the oil is the dispersed phase that is distributed into the continuous phase, water. Similarly, in a 3-phase emulsion the liquid is added to emulsion whether the liquid added oil or water. Compared 2-phase emulsion to 3-phase emulsion Lin et al. [47] found that 2-phase emulsion provides higher lower heating value and lower droplet size. In the other hand, 3-phase emulsion is more viscous, and it attributes lower CO and NO_x emission compared to 2-phase emulsion [42].

5.2 Emulsion production methods

Emulsion could be done in different approaches. The most common approach is the external force. In this method, the emulsion is made by using mechanical stirrer

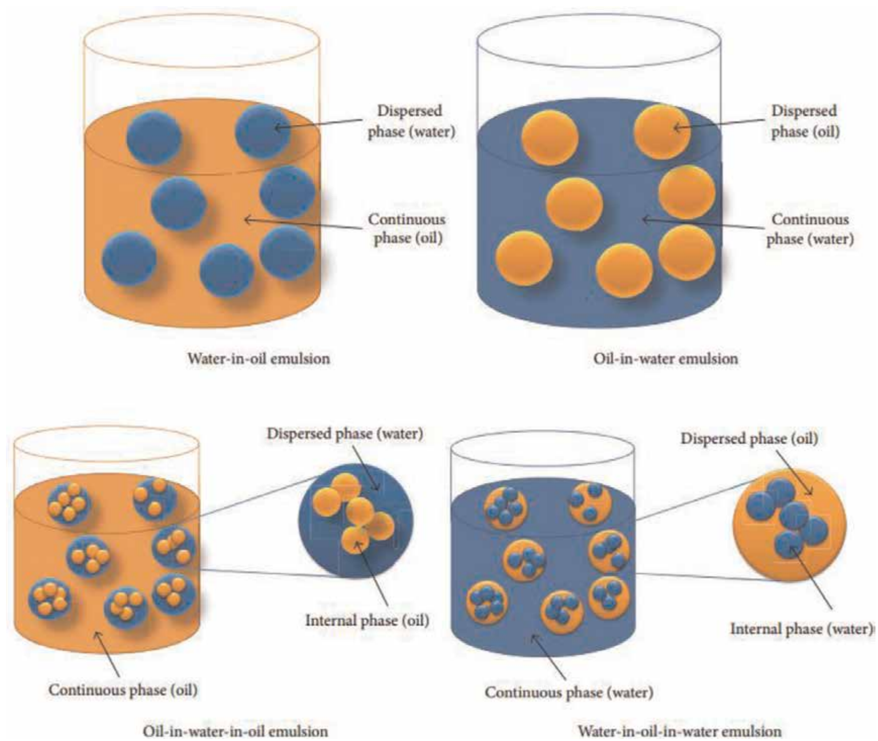

Figure 1.
Concept of two-phase water-in-oil and oil-in- water and three-phase oil-in-water-in-oil and water-in-oil-in-water emulsions [44].

machine, and it is used widely for emulsifying fuel industries [16]. This device converts the electric energy to mechanical energy (sound wave vibration), **Figure 2** illustrates schematic diagram of this device. The other method of making emulsion is ultrasonic vibrator. To achieve satisfied fuel emulsion, the ultrasonic vibrator is usually done by setting its frequency at range of 20 kHz – 40 kHz and the power at range from 150 W to 700 W [47, 49].

For making fuel emulsion, first mix two surfactants to gain suitable HLB value. The required HLB value is mainly obtained experimentally and different oil types require different HLB value that achieves significant emulsion [50]. Generally, the required HLB value for W/O emulsion is raging between 3 and 8 while to achieve suitable emulsion of O/W emulsion the HLB value required is ranging between 9 and 12 [51]. There is wide verity of surfactants used for emulsion But in fuel emulsion more common using *sorbitan monoleate* (span) and *polyoxyethylene sorbitan monoleate* (tween) surfactants [38]. Blending the two surfactants could be conducted to obtain suitable HLB value by using the following formula [16]:

$$Tween\ 80\% = \frac{100\left(x - HLB_{span80}\right)}{HLB_{Tween80} - HLB_{span80}} \tag{1}$$

$$span80\% = 100 - Tween80\% \tag{2}$$

Where,
X = required HLB value,
$HLB_{Tween\ 80}$ is 15 for Tween 80.

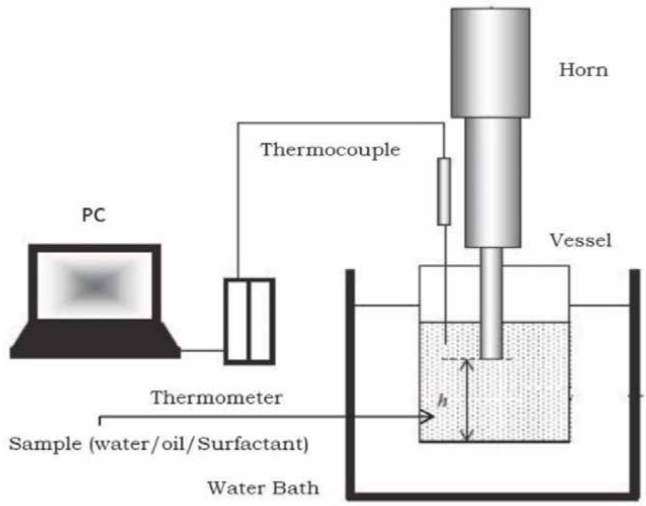

Figure 2.
Schematic diagram for preparation [48].

There are many other indications that need to be considered to achieve better results for emulsions. Higher water quantity in emulsion affects the emulsion results and it leads to less emulsion stability [16]. Accordingly, the flow rate of surfactant blend with suitable HLB value to the continues phase affects both emulsion stability and droplet size [38]. Finally, the amount of surfactants varies from 0.5 to 2% of the total volume [38, 48, 51].

5.3 Emulsion fuel stability

The emulsion is stabilized whenever no separation could be detected [48]. The water and surfactant amount on emulsion are the main two indicators that affect emulsion fuel stability. Elsanusi [16] has done different emulsion fuel types using external force method and measured their stability and the results are shown in **Figure 3**.

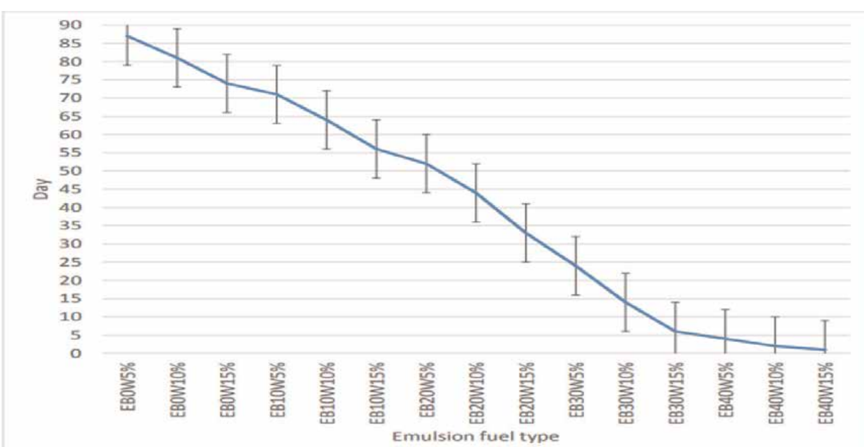

Figure 3.
Emulsion fuel stability [16].

Figure 3 illustrates that fuel EB0W5% (Emulsion Biodiesel 0%, Diesel 100%, water 5%) shows better emulsion stability compared to EB0W15% (Emulsion Biodiesel 0%, Diesel 100%, water 15%). Additionally, the biodiesel amount in the emulsion blend was found to affect emulsion stability at the same study. The droplet size of fuel emulsion affects the emulsion stability. A review study conducted on recent progress on mixing technology for water-emulsion fuel, showed that the mixing time effect the emulsion droplet size and smaller droplet size of emulsion leads to increase emulsion stability [52]. A similar result was obtained from another study, they measured the emulsion droplet size using *Malvern Mastersizer 2000* and emulsion diesel with 5% water showed smaller droplet size and higher emulsion stability see [38].

5.4 Emulsified fuel benefits

The utilization of emulsified fuel in diesel engines offers several benefits that could positively impact both the engine's regulated emissions and performance. Alahmer et al. [53], studied the engine performance fueled using emulsified diesel and they concluded that engine brake specific fuel consumption (BSFC) increases compared to diesel but when subtracting the amount of water from emulsion was found slightly less amount of diesel consumed for the same comparison. The lower heating value of fuel emulsion is the main reason for higher BSFC. The emulsified fuel was found to slightly increase brake thermal efficiency (BTE) in many studies [54–56]. The micro-explosion of emulsion that is enhanced by water content evaporation in the diesel engine combustion chamber making secondary atomization, promotes combustion efficiency, see **Figure 4**.

Fuel emulsion has dramatic influence on diesel engine regulated emissions. The water content in fuel emulsion reduces combustion temperature hence lower NO_x emission since higher combustion improves NO_x emission. The equivalent temperature effect on diesel engine NO_x is shown in **Figure 5** [58]. Similarly, smoke opacity of

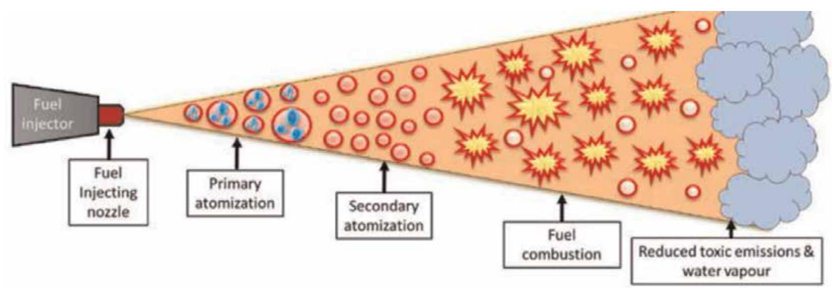

Figure 4.
Primary and secondary atomization in spray flame of emulsified fuel [57].

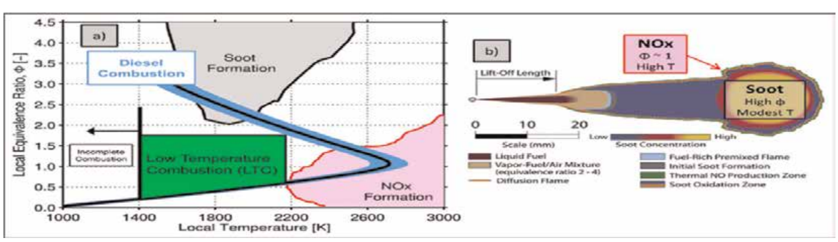

Figure 5.
Regions of NOx and soot formation in local equivalence ratio versus local temperature space [58].

diesel engine tends to be decreased. Osama et al. [38], explained that the micro-explosion, secondary atomization, and vaporization by the injectors are the main reasons for smoke opacity reduction.

The CO and HC emissions are caused by incomplete combustion. Emulsified diesel reduces the in-cylinder temperature hence lower combustion efficiency "higher percentage of heat losses" hence high CO emission compared to base fuel [16, 38, 57, 59–62]. Interestingly, the emulsion fuel does not have a major effect on HC emission compared to base fuel and that is obtained from micro-explosion resulting from better atomization of emulsified fuel [16, 38].

5.5 Fuel emulsion downside

Emulsified diesel increases CO emission due to reducing combustion temperature [38, 42]. Fuel emulsion were complained that lead to potential issues such as: corrosion of tank storage and fuel pumping system in diesel engine [63], low cold flow properties of emulsified fuel since the fuel temperature affects the emulsion stability [16].

6. Conclusion

This investigated the effect of fuel on diesel engine emission and performance. Diesel engines are increasingly being developed and adopted to work with wide verity of fuel and fuel additives. The fuel, fuel blends, fuel additives and fuel emulsion effect on diesel engine regulated emission and performance were reviewed. The main finding of this conducted study as following:

- Diesel engines could run with wide verity of fuel, and each fuel provides different results in terms of engine performance and emissions. Biodiesel emits slightly higher NO_x emission while lower HC and CO emission achieved compared to diesel. The BSFC of diesel engine for biodiesel were found to be higher compared to diesel whereas BTE were shown to be approximately like diesel results. Kerosene n-heptane were found to decrease HC, CO emissions and smoke opacity, while NO_x showed a slight increase. Additionally, kerosene as fuel decreases the BSFC and raises BTE.

- Fuel blends affect diesel engine emission and performance. Blending diesel with biodiesel improves engine BTE and BSFC, reduces engine HC, CO, and smoke opacity of diesel engine while it affects negatively the NO_x to diesel. On the other hand, blending diesel or biodiesel with methanol and ethanol was found to provide opposite results. Blending n-heptane with diesel or biodiesel has proven lower HC, CO and smoke opacity but increases NO_x emission compared to base fuel.

- Fuel additives play a major role in modifying fuel properties. Some additives are considered as CN improvers and increasing CN improves combustion quality. Other additives are used to reduce fuel viscosity which improves fuel atomization through injection process hence better combustion and lower PPM, HC, CO and BSFC and higher BTE.

- All types of fuel emulsion have shown dramatic decrease on NO_x and smoke emissions and improves the combustion quality by providing better atomization and decreasing the combustion temperature. Additionally, emulsion fuel has shown a slight increase in BSFC but less fuel consumption if water amount in emulsion subtracted. However, emulsion fuel improves HC, and CO emission and the BTE was found to be slightly lower compared to base fuel. Emulsion fuel droplet size and stability are the two factors affecting diesel engine performance and emission. Smaller droplet size better combustion and lower emissions. Emulsion fuel has some downsides like corrosion and low cold flow properties.

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Chapter 4

Hydrogen Onboard Storage Technologies for Vehicles

Marek Flekiewicz and Grzegorz Kubica

Abstract

Over the past few years, significant progress has been made in hydrogen-powered vehicles. Most of the development work focused on the powertrain and its integration into the vehicle. Currently, one of the key technologies that determines the development of the automotive industry are on-board hydrogen storage systems. Without efficient storage systems, the using of hydrogen to drive motor vehicles will be difficult to achieve. The physical storage density limits of compressed and liquid hydrogen have been more or less reached, whilst there is still potential in the development of various hydrogen storage materials. This chapter presents methods and problems related to hydrogen storage. Some of discussed technologies are immature, however this does not rule out for them future use therefore, their opportunities and foreseen potential were also presented.

Keywords: hydrogen, storage, compression, liquefaction, hydrogen mobility

1. Introduction

Hydrogen has the potential to become the sustainable fuel of the future, reduce global dependence on fossil resources and reduce pollutant emissions from transport. The spread of hydrogen as a fuel for vehicle propulsion poses several challenges regarding the way we use the energy contained in hydrogen, storing hydrogen on the vehicle and ensuring its availability. Currently, there are two ways to feed a motor vehicle using hydrogen. These are hydrogen internal combustion engines (Hydrogen ICE) and hydrogen fuel cells (FC). The first uses hydrogen to power an internal combustion engine. The second uses a fuel cell in combination with electric motors and a battery. Hydrogen-based internal combustion engines have recently attracted a lot of interest, but several practical barriers have prevented the rapid development of this technology. Therefore, the use of hydrogen as an additive to hydrocarbon fuels has been considered at this stage in order to achieve higher performance than purely hydrogen internal combustion engines. The use of a dual-fuel strategy increases combustion stability and thermal efficiency whilst reducing CO_2 and unburnt hydrocarbon emissions and fuel consumption. The use of hydrogen in internal combustion engines achieves only 20–26% efficiency and low power output compared to internal combustion engines powered by fossil fuels [1]. However, its alternative use in fuel cells allows to achieve an efficiency of up to 60% [2]. Both ways of converting hydrogen energy require storing hydrogen in an amount that ensures a satisfactory vehicle mileage.

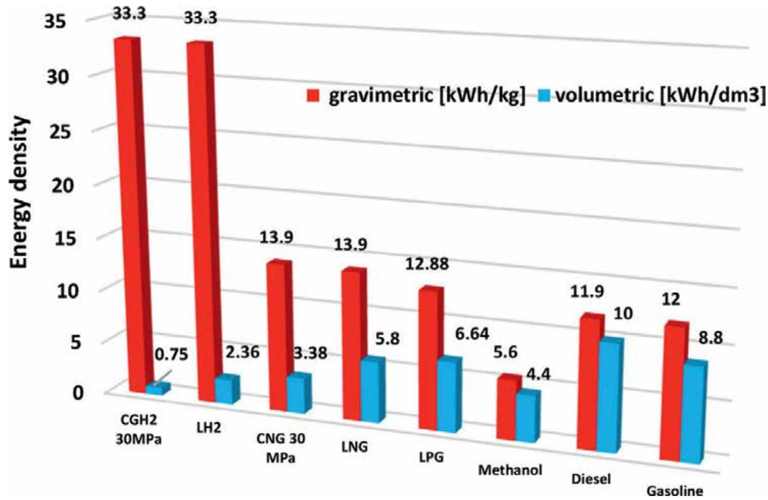

Figure 1.
Gravimetric and volumetric energy density of selected motor fuels [3].

Hydrogen has the highest calorific value per mass of all chemical fuels. In addition, hydrogen is regenerative and environmentally friendly. Unfortunately, this element occurs in nature in the form of water and hydrocarbons. These means that its acquisition and storage require a significant amount of energy, its volumetric density is of crucial importance, which determines the weight and volume of the storage system. This problem is explained in **Figure 1**, which compares the values of hydrogen's volumetric and gravimetric density with the values characteristic of conventional fuels and selected alternative fuels. The low energy density per unit volume of hydrogen makes storing and transporting gas a significant research and technical challenge. Consequently, storing hydrogen on a motor vehicle is a key technology enabling the development of hydrogen and fuel cell technologies [3, 4].

Amongst the most important hydrogen storage methods that have been tried and tested over a long period of time is the physical method of storage based on compression or cooling, or a combination of both. Currently, many other new hydrogen storage technologies are being sought or investigated. These technologies can be grouped together under the name material-based storage technologies. These can include solids, liquids, or surfaces.

The hydrogen storage methods listed above should be characterised by technological simplicity and low price and should ensure operational safety. The current state of hydrogen storage technology in motor vehicles and the likely directions of their development are shown in **Figure 2**.

The weight and volume of a storage system based on each of the technologies listed above will depend on the expected mileage of the vehicle. To ensure a mileage of 400 km, the mass of hydrogen stored should be:

- for a passenger car powered by an internal combustion engine, 8 kg of hydrogen, and 4 kg when a fuel cell is used,
- for a truck, 32 kg, and respectively 16 kg,
- and for the bus, respectively 41 kg and 20 kg [6].

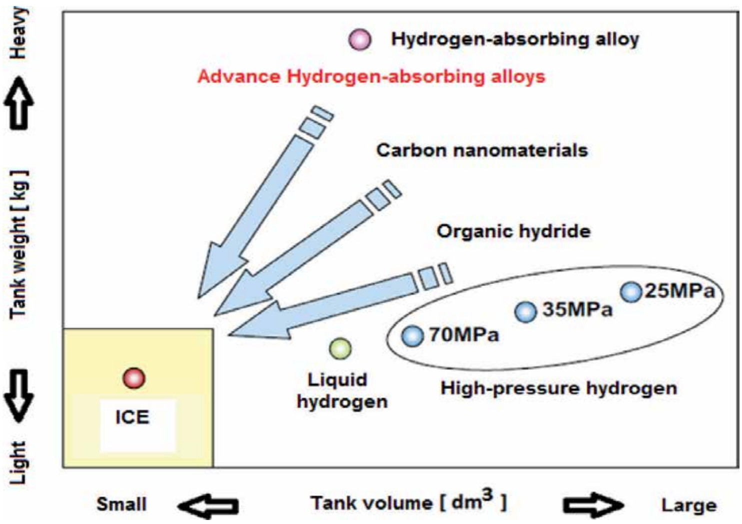

Figure 2.
Hydrogen storage technologies and directions of their development [5].

2. Physical hydrogen storage

Physical hydrogen storage methods are based primarily on the compression and cooling/liquification of hydrogen. The difference between these methods is explained in **Figure 3**.

This figure shows areas characteristic of liquified hydrogen (LH2), liquified hydrogen at high-pressure (Cryo-Compressed Hydrogen) and compressed hydrogen (CGH2).

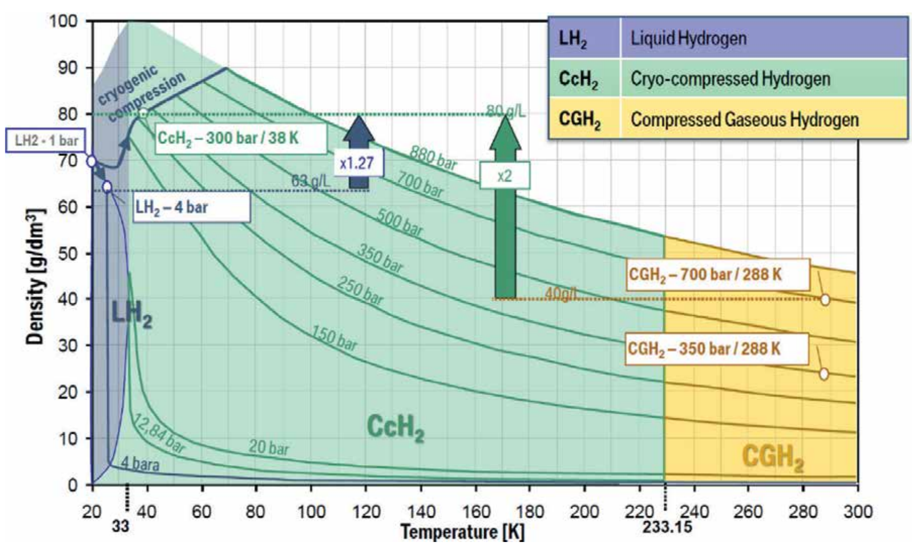

Figure 3.
Hydrogen density dependence on pressure and temperature [7].

2.1 Compressed hydrogen storage

By storing compressed hydrogen-CGH2 (Compress Gaseous Hydrogen), we compress it to pressures ranging from 25 to 90 MPa and store it in pressure tanks. It is the conceptually simplest method of hydrogen storage, which allows the use of modern high pressure tanks type 3 and 4, based on lightweight composite materials (in which the material transferring the loads caused by huge pressures is a composite of carbon and glass fibres and the synthetic resins, secured from the inside with a metal or polymer liner). These designs allow hydrogen to be stored under a pressure exceeding 100 MPa. Today, the tanks are filled with hydrogen to a pressure of 35 or 70 MPa (Toyota Mirai and Hyundai Ix35 and Honda Clarity) [8, 9]. In practise, the compression of hydrogen to a pressure of 70 MPa requires energy approximately equal to 18 MJ/kg, which is about 15.5% of the energy obtained from hydrogen combustion. In addition to the significant advantages of this form of storage, such as a relatively simple construction of the tank, high rate of hydrogen release and refuelling, one of the most important disadvantages of these tanks is the low density of stored energy (**Figure 4**).

Storing compressed hydrogen-CGH2 (Compress Gaseous Hydrogen) is the conceptually most straightforward method of hydrogen storage, which allows the use of modern high pressure tanks type 3 and 4, based on lightweight composite materials (in which material transferring the loads caused by the high pressures is a composite of carbon fibre and synthetic resins, secured from the inside with a metal or polymer liner) [10, 11]. Today, the tanks are filled with hydrogen to a pressure of 35 or 70 MPa (Toyota Mirai, Hyundai Ix35, and Honda Clarity). In practise, hydrogen compression to a pressure of 70 MPa requires energy of approximately 18 MJ/kg, about 15.5% of the energy obtained from hydrogen combustion. In addition to the significant advantages of this form of storage, such as a relatively simple construction of the tank's high rate of hydrogen release and refuelling, one of the most important disadvantages of these tanks is the low density of stored energy.

Vehicle manufacturers impose several requirements on tanks intended for hydrogen storage, not only regarding strength parameters defined in standards and regulations but also expect the tanks to be characterised by favourable performance parameters, i.e., satisfactory gravimetric and volumetric energy density of the energy storage system.

The mass of hydrogen per unit volume (kgH_2/m^3) at 25°C can be calculated using the simple relation 0.0807*p. This relationship originates in the ideal gas equations, and p is the hydrogen storage pressure in bars. For example, for a pressure of

Figure 4.
Hydrogen storage tank under 70 MPa pressure for the Toyota Mirai car and a hydrogen storage system in the Honda FCX Clarity car [10, 11].

p = 35 MPa, the mass of stored hydrogen equals 28 kgH_2/m^3 [12]. Considering that 5 kg of hydrogen is necessary to ensure the light vehicle's mileage in the 400–600 km range, the tank should have a capacity of 0.18 m^3 [12]. The efficiency of energy storage in compressed hydrogen is about 94% and can be compared with the efficiency of energy storage in batteries, which is 75% [13].

It should be noted that increasing the hydrogen pressure increases the volumetric storage density (kgH_2/m^3) but reduces the overall energy efficiency. Moreover, doubling the pressure only increases the stored energy by 40–50%.

Type 1 steel tanks have been commonly used to store compressed hydrogen for many years, but steel is not desirable. The penetration and accumulation of hydrogen atoms inside the metal contribute to the so-called "Hydrogen embrittlement", a group of corrosive phenomena that negatively affect the operation process. Considering that steel tanks are too heavy, tanks of types 3 and 4 are mainly used to store compressed hydrogen in modern motor vehicles.

The main parameters considered when considering hydrogen storage in automotive pressure tanks are type of vehicle, tank capacity, pressure of the stored hydrogen, and tank price.

Compressed hydrogen is stored in a closed system (**Figure 5**), which means that hydrogen can be stored without loss for a long time, provided that the materials used prevent hydrogen diffusion. The cylindrical shape given to the currently used pressure tanks results primarily from the favourable distribution of stress and the recommended and proven in-operation starting materials for their production. Designers strive to develop tanks whose form will be adapted to the spatial possibilities created by the structure of the chassis or body of the vehicle.

New materials and technologies create the possibility of producing nanocomposite layers, which are characterised by very low permeability of hydrogen

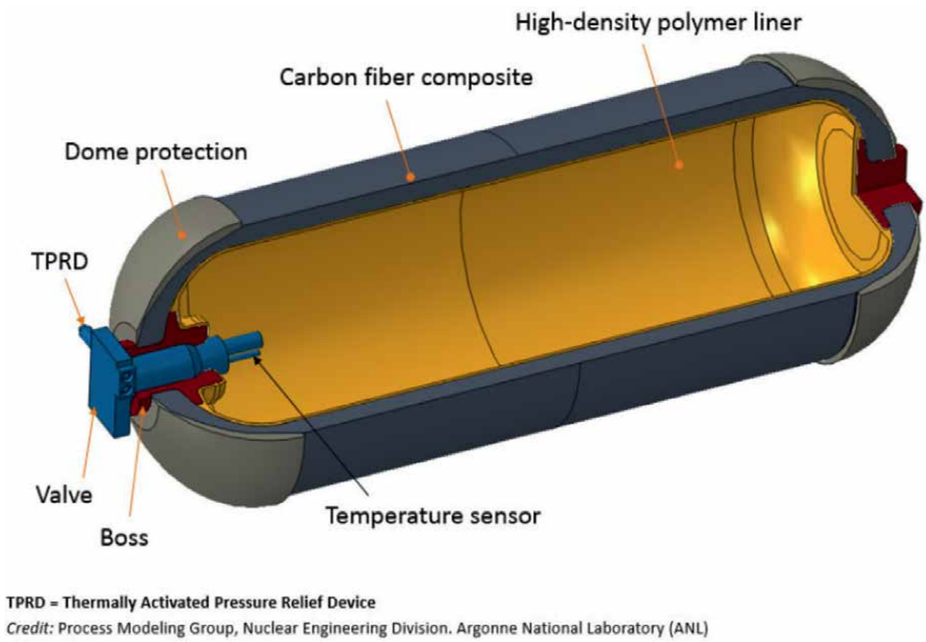

Figure 5.
Components of a pressurised hydrogen storage tank.

($0.6 cm^3 \mu m/m^2 day atm$). These ultra-high-performance nanocomposite barrier layers are achieved, amongst other things, by spray coating liquid crystal nano silicates mixed with polyvinyl alcohol (PVA) on a PET substrate film. The technology of improving the surface of the liner by spray coating allows for the creation of a barrier limiting the permeability of hydrogen in irregularly shaped tanks [14].

2.2 Equipment of the hydrogen storage tank

The equipment of the compressed hydrogen storage tank should consist of at least the following: manual and automatic shut-off valves, pressure relief devices and non-return valves on the gas supply and discharge lines. A diagram explaining the flow of hydrogen through the channels of the multi-function valve is shown in **Figure 6**. Selected solutions of these valves and their technical parameters are shown in **Figure 7**.

Following the requirements of the Regulations of the European Economic Commission as well as the relevant technical standards, the tank equipment is selected by the tank manufacturer. Considering the needs of motor vehicle manufacturers, the tanks are mounted in containers in the so-called gaseous fuel storage systems. These systems, in addition to the previously mentioned elements, also contain additional devices, such as, for example, a preliminary hydrogen pressure regulator, a ventilation system, etc. (**Figure 8A** and **B**). An example of a hydrogen storage system for an electric bus with a fuel cell is shown in **Figure 9**.

Following the requirements of the Regulations of the European Economic Commission as well as the relevant technical standards, the tank equipment is selected by the tank manufacturer. Considering the needs of motor vehicle manufacturers, the tanks are mounted in containers in the so-called hydrogen storage systems (HSS).

These systems, in addition to the previously mentioned elements, also contain additional devices, such as, for example, a preliminary hydrogen pressure regulator, a ventilation system, etc. (**Figure 8A** and **B**). An example of a hydrogen storage system for an electric bus with a fuel cell is shown in **Figure 9**.

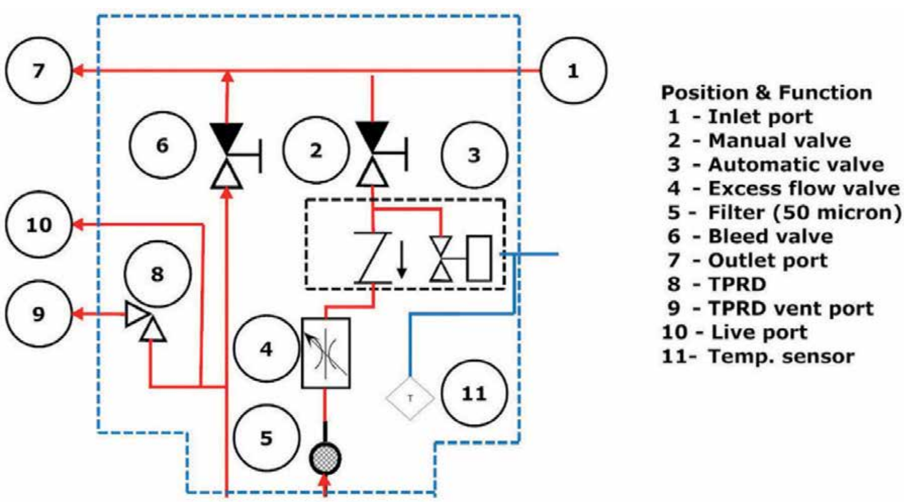

Figure 6.
A diagram explaining the hydrogen flow through the operational valve [15].

Working pressure	35 MPa @ 15 °C
Maximum working pressure	47.5 MPa
Maximum allowable working pressure	48.3 MPa
Minimum working pressure	0.7 MPa
Operating temperature range	from -40°C to +85°C
TPRD activation temperature	110°C ±5°C
Temperature sensor	NTC type - thermistor
Flow rate	3g/s
Filter size	from 10 to 50 mm
Approval	Conforms to the requirements of EC79/2009

Figure 7.
Sketch of the HTV 350 OMB Saleri operation valve for composite valve and its primary technical data.

A

Service pressure - 35 MPa
Min. burst pressure (design pressure) - 115 MPa
Water capacity - 78 litres,
Mass of stored hydrogen - 1.9 kg,
The energy density per unit mass of the system - 0.86 kWh/kg,
Gravimetric Density - 2.3%
The energy density per unit volume of the system - 0.31 kWh/L,
Weight of the hydrogen storage system - max. 73.3 kg

B

Service pressure - 70 MPa
Water capacity - 82 litres
Gravimetric energy density - 1.79 kWh/kg
Volumetric energy density - 1.34 kWh/litre
Hydrogen permeability ⍰ 6 Ncm3/litre
Production cost - 15 Euro/kWh
Energy efficiency - 0.93

Figure 8.
Examples of compressed hydrogen storage systems, A-35 MPa and B-70 MPa.

In the lower part of **Figure 10**, there are pipes constituting the gas main serving all storage tanks. The upper line, with a diameter of 10 mm, supplies gas to the tanks during their filling, whilst the lower pipe, with a diameter of 8 mm, allows the collection of the stored gas.

Figure 9.
Compressed hydrogen storage system for a bus.

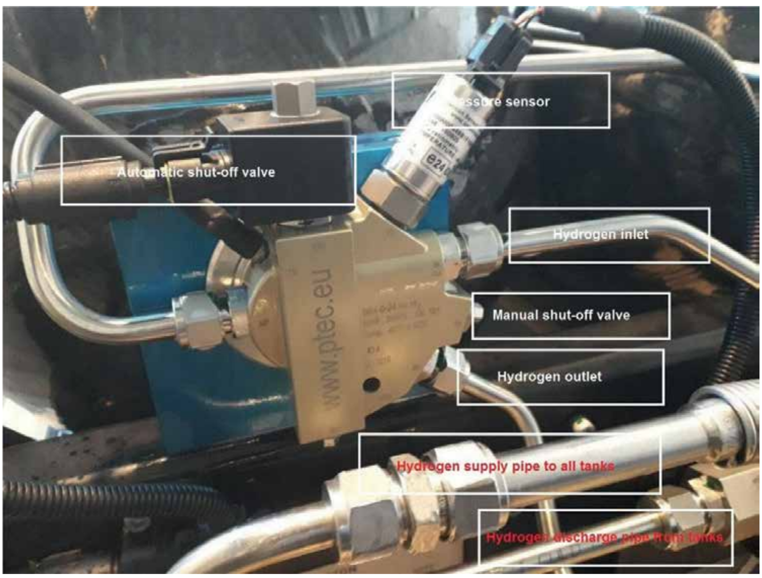

Figure 10.
Operation valve of one of the tanks, its essential devices, and its connection to the other tanks.

Figure 11 shows the other two devices protecting the tank, i.e., in its central part and the end plug located at the other end of the tank. Each of these devices is connected by pipes to the inside of the tank, i.e., when opened it ensures the emptying of the tank.

Hydrogen storage tanks delivered to vehicle manufacturers must meet several requirements, including the assurance of the purity so-called "hydrogen purity", essential for protecting the fuel cell from damage. The required purity of hydrogen and the level of its impurities for ensuring the homogeneity of hydrogen intended for use in

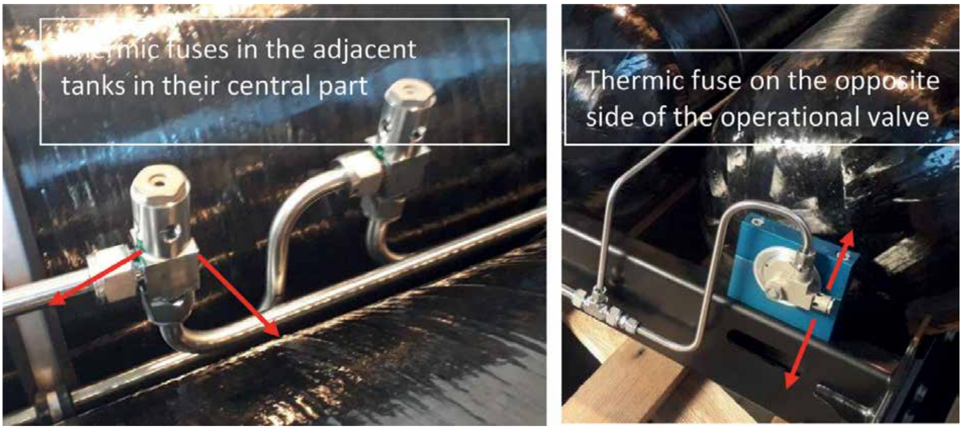

Figure 11.
Thermic fusible (TPRD) mounted in the middle of the tanks and on the opposite side of the operational valve (red arrows indicate the direction of the gas outlet after opening the fuse).

road vehicle systems with proton cells (PEM) are specified in the EC 79/2009 and ISO/TS 14687-2 standards. These requirements mean that after the process of manufacture, the container is subjected to leak tests. Then the tank is subjected to rinsing, first with nitrogen, to obtain an atmosphere below the hydrogen explosion level, and is flushed with hydrogen to achieve a minimum concentration of 99.97% in the entire volume. For this purpose, pure hydrogen, 99.99% is used. Completing achieving the required purity, a certain amount of gas is left in the storage tanks, with pressure not lower than 0.2 MPa, which protects the storage tank against air entering its interior.

2.3 Storage of liquefied hydrogen

Liquid hydrogen (LH2) is a very light liquid (density 70 g/dm^3 at −253° C). LH2 evaporates quickly at standard temperature, producing approximately 845 litres of hydrogen gas from 1 litre of LH2. Immediately after evaporation, gaseous hydrogen is still very cold and has a weight comparable to that of air, which makes it spread practically horizontally. It does not heat up quickly; its density gradually decreases and rises to the top.

Hydrogen can be stored in liquid form in tanks specially adapted for this purpose [16]. Changing the state of hydrogen from gaseous to liquid (liquefaction) allows us to increase the energy density of hydrogen significantly. However, hydrogen liquefaction is a process that requires much more energy than its compression. The energy needed to liquefy hydrogen is estimated to be 30–40% higher than that required to compress hydrogen. Thus, the energy efficiency of this process is relatively low. However, storing liquid hydrogen allows us to obtain a much higher density by mass and volume than other hydrogen storage methods. In addition, the storage of liquefied hydrogen in cryogenic tanks ensures much lower losses due to gas "escape" than in pressurised tanks for compressed hydrogen. These losses are even 25 times lower.

In order to keep hydrogen in a liquid state, it is necessary to use very low temperatures (of the order of 20 K, i.e. −253.15°C), for this reason, the tanks must be constantly cooled and thermally insulated from the environment.

The liquefied hydrogen storage tank developed by MAGNA STEYR Fahrzeugtechnik AG & Co KG is shown in **Figure 12**. This tank, consisting of an inner

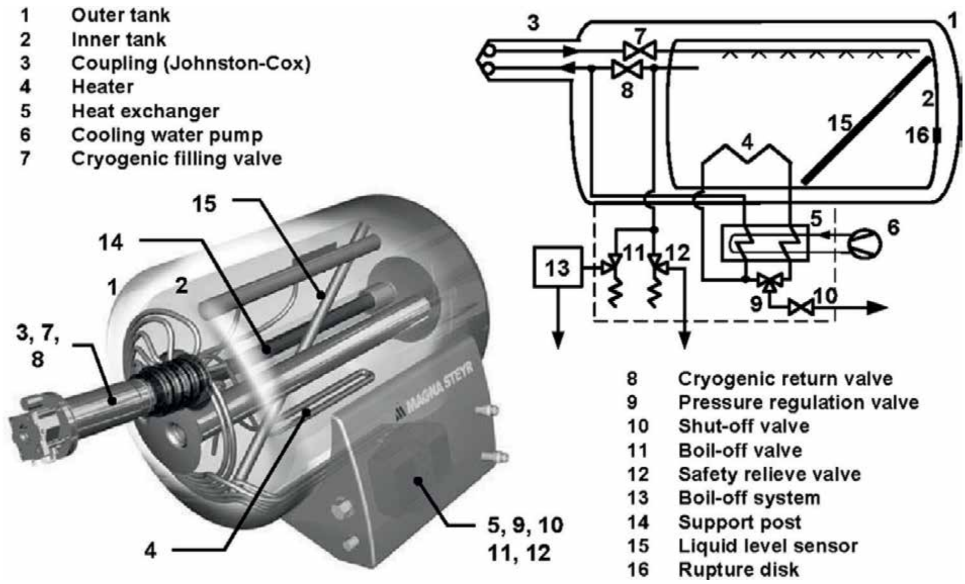

Figure 12.
Liquefied hydrogen storage tank [17].

and an outer tank, stores approximately 10 kg of hydrogen. The materials used to make this tank are stainless steel or aluminium alloy. Both materials are very resistant to hydrogen embrittlement and exhibit negligible hydrogen permeation. In addition, their low specific weight, high strength, and high coefficient of thermal expansion, combined with excellent thermal conductivity properties, make the total weight of the tank with accessories around 150 kg.

The space between the inner and outer tanks is filled with a highly insulating material and a vacuum, i.e., about 40 layers of foil limited the heat transfer through thermal radiation with a weight of 1.5–3.0 kg/m^2, composed of polished aluminium or aluminized and polymer foils, which are separated from each other by fibreglass spacers. The vacuum pressure at 20 K is about 10^{-3} Pa, reducing thermal convection to a minimum. This insulation ensures that, when the vehicle is not used for more than 3 days, the heat input contributes to the evaporation of liquefied gas in an amount not exceeding 1–3% per day.

The cryogenic filling valve (7) and cryogenic check valve (8) are open during filling. Liquid hydrogen flows from the filling station through the Johnston-Cox connector (3) and the cryogenic filling valve into the inner vessel (1). The evaporated hydrogen leaves the internal tank through a cryogenic non-return valve and flows back to the filling station to maintain low pressure. When filling is complete, both cryogenic valves close. The evaporated hydrogen flows from the internal tank to the cooling water heat exchanger (5). The hydrogen heats to ambient temperature and flows further to the pressure control valve (9). If the inlet pressure is higher than the set regulation pressure, the flow will be closed, and hydrogen will not be able to flow through the tank heater (4). The pressure will drop because no heat will be delivered to the internal tank heater. In standby mode, both cryogenic valves are closed. When the vehicle is parked for a long time, the hydrogen pressure in the inner tank increases to the valve opening pressure (11). Overpressure in the inner tank cannot open the cryogenic valves. If the valve (11) is damaged, the pressure in the internal tank increases until the safety valve (12) opens. The last device that prevents the tank from exploding is the plate valve (PRV) (16).

Liquid hydrogen storage reaches the highest gravimetric and volumetric storage densities and, about adequate energy availability, is the most suitable fuel storage solution for future hydrogen vehicles. Despite the use of highly high-performance super-insulation designs, it has not yet been possible to find a solution for the problem of the boil-off losses occurring in liquid hydrogen storage tanks induced by heat input during relatively long periods of idleness or in unfavourable driving cycles. In particular, the limited down-scalability of liquid hydrogen storage tanks defines the optimum field of application in the segments of large passenger cars, buses, and trucks.

2.4 Cryo-compressed hydrogen storage tanks

The storage of hydrogen in cryo-compressed tanks offers many more advantages, opportunities and potential as compared with pressurised hydrogen and liquid hydrogen storage technology [18]:

- lower requirements for expensive carbon fibres due to designing for a maximum tank pressure of 350 bar compared with 700 bar for state-of-the-art CGH2 storage tanks could lead to lower material and even production costs for CcH2 compared with CGH2 tanks,

- long hydrogen loss-free dormancy time minimise the risk of hydrogen boil-off losses during long parking periods or low vehicle use compared to LH2 tanks.

- energy and heat management requirements are compatible with internal combustion engines and fuel cell systems. In particular, low-temperature PEM fuel cells might benefit from the cooling power of cryogenic hydrogen that is warmed up by waste heat from the fuel cell.

As a possible solution for the problem of boil-off losses and the high requirements regarding insulation quality, BMW has developed the concept of supercritical cryo-compressed hydrogen storage (CcH2 Cryo-compressed Hydrogen), which promises more straightforward and more cost-efficient insulation whilst enabling loss-free operation of the storage tank in under all typical vehicle operating conditions [19]. This innovative concept reduced the weight of the finished tank to one-third of the importance of a conventional cylindrical steel tank (**Figure 13**). Freedom in shaping its form ensures a high degree of flexibility and allows for significant energy savings in the manufacturing process. As all auxiliary systems have been integrated into the tank housing, it takes up less car space and is much easier to handle. The internal tank is designed modularly, simplifying the production process compared to existing hydrogen tanks. This tank, filled with 10 kg of hydrogen, could allow a range of over 500 kilometres.

A prototype solution for a tank storing cryo-compressed hydrogen at a pressure of 30 MPa is shown in **Figure 14**. It is a tank also developed by BMW, where it is possible to store both liquefied and compressed gas. The essential technical parameters of this tank are listed in **Table 1**.

Figure 13.
A tank developed by the BMW group for a hydrogen-powered car [20].

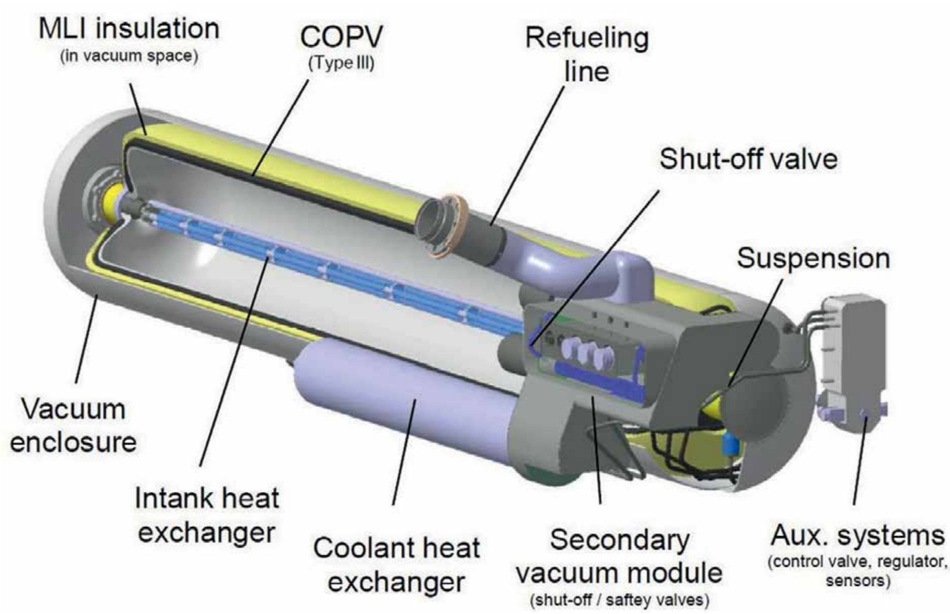

Figure 14.
Prototype solution of a tank for storing compressed and liquefied hydrogen [7].

Considering the advantages and disadvantages of the above methods, compressed hydrogen (CGH2) is the best system and is a state-of-art technology [21]. Hydrogen storage systems with 70 MPa tanks are sufficient to ensure desired mileage of vehicle. Tanks can be refuelled with hydrogen in 3–5minutes. The storage of liquefied hydrogen is also a relatively mature technology, but it is associated with a very significant problem of hydrogen losses whilst shutting down the vehicle from traffic. These losses and the related losses during refuelling are very substantial. Cryo-compress hydrogen storage helps to improve volumetric hydrogen density and safety over compressed hydrogen or cryogenic LH2 alone. However, the availability and cost of infrastructure are still the main obstacles to developing this storage method.

Maximum usable capacity	CcH_2–7,8 kg (260 kWh) CGH_2–2,5 kg (83 kWh)
Working pressure	≤ 35 MPa
Emergency opening pressure	≥ 35 MPa
Filling pressure	CcH_2–30 MPa CGH_2–32 MPa
Filling time	< 5 minutes
Storage system capacity	~235 dm^3
Mass of the storage system plus mass of hydrogen	~145 kg
Hydrogen losses	<< 3 g/day 3 ÷ 7 g/day (CcH_2) < 1% per year
Additional features	• Active pressure control inside the tank • Integration with the car body • Using the waste heat of an internal combustion engine or fuel cell

Table 1.
Characteristics of the CGH2, and CcH2 storage system.

3. Material-based hydrogen storage technologies

The hydrogen storage technologies discussed above in gaseous and liquefied form are characterised by the structure's maturity and many years of operational experience. However, searching for a technology that could increase the energy density of stored hydrogen has created an option that today engages the efforts of many research centres worldwide. This possibility is based on metal hydrides, carbon sorbents, and chemical hydrides (**Figure 15**).

The main requirements for these modern materials are high gravimetric density (over 6.0% by weight), easy hydrogen absorption/desorption at moderate temperatures and pressures, low price of materials and their ecological safety [22].

Metal hydrides are solid materials that enable safe hydrogen storage at moderate temperatures and pressures. Many metal hydrides reach volumetric energy densities that approximate those of liquefied hydrogen. Metal hydrides consist of metal ions that form a lattice structure. Hydrogen adsorbs at a metal centre, dissociates to form atomic hydrogen, and is finally inserted into the metal lattice. The total process is exothermic [22]. Thus, when the carrier is loaded, heat must be removed.

In recent years, research into new hydrogen storage materials has focused on light metals such as Li, Be, Na, Mg, B and Al. These metals are of particular interest because they can contain a high percentage by weight of hydrogen. The US Department of Energy (DOE) has outlined several requirements for an onboard hydrogen storage system. For large-scale storage, the sensitivity of metal hydrides is problematic. Moreover, their solid nature, combined with the considerable enthalpy of dehydrogenation, creates challenges concerning heat transfer for fast hydrogen release. Whereas heat transfer onto liquids and gases is comparatively simple, uniform heat distribution into a large solid mass is possible only when complex and expensive devices are used. However, hydrogen storage in metal hydrides is undoubtedly more appropriate for small- and very-small-scale applications. Although metal hydride

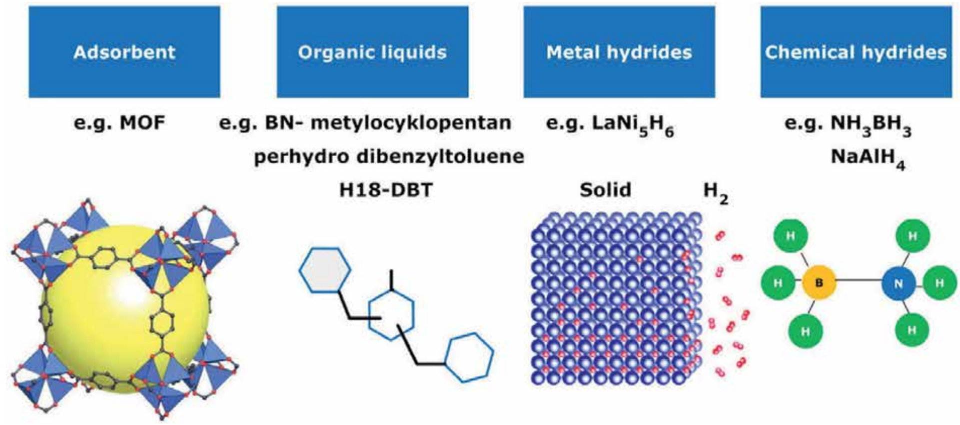

Figure 15.
Simplified division of hydrides and an exemplary structure of selected compounds.

storage has a very high volumetric storage density (> 100 H_2 kg/m^3), the gravimetric storage density is very low due to the heavy metals or alloys. The gravimetric storage density of hydrides is between about 0.02–0.07 H_2kg/kg. At ambient temperature and pressure gravimetric storage density is of about 0.03 H_2 kg/kg [22].

In summary, the features that determine the suitability of hydrides as hydrogen storage include:

- the ability to reversibly store hydrogen,
- large capacity of stored hydrogen,
- low pressure and temperature (up to ~90°C) of hydride dissociation,
- high rate of absorption and desorption,
- a small amount of energy required to release hydrogen,
- low sensitivity to gaseous pollutants,
- a large number of possible charging and discharging cycles,
- safety (low pressure, non-flammability),
- low price.

The prospective hydrogen storage may be highly porous carbon materials with a large specific surface area. The storage of molecular and atomic hydrogen in carbon materials takes place through electrochemical reactions and physical sorption (adsorption) on the surface of solids, primarily due to the interaction of Van der Waals forces. Desorption of hydrogen from carbonaceous materials occurs due to the supply of the appropriate amount of thermal energy to the system. The most considered carbon materials storing hydrogen include activated carbon, graphite, fullerenes and carbon nanotubes. Activated carbon is an interesting material for hydrogen storage because it has a very large specific surface resulting from its structure, with numerous pores and microcracks. Micropores have the greatest adsorption capacity because their sizes are comparable to potential particles that can be stored on activated carbon. Mesopores play a minor role in the adsorption process, whilst macropores are used mainly to transport substances. The hydrogen sorption capacity achieved at a temperature of 77 K by activated carbon, whose specific surface area is 1315 m^2/g, is equal to 2% m/m (where m/m—the mass of hydrogen to the mass of the storage material). Modifying activated carbon with potassium hydroxide (KOH) allows for further development of such material's porous structure, increasing the amount of stored hydrogen by 3.7 times.

Graphite, one of the allotropes of carbon, is also considered a potential hydrogen storage material. It has a multi-layer structure composed of single graphene layers. The individual layers of graphite are connected to each other by weak Van der Waals interactions, which makes it possible to manipulate them appropriately. The storage of hydrogen between graphite layers can be configured by adjusting the distance between adjacent layers. On the other hand, hydrogen desorption can occur when the storage system is heated to a temperature of about 450°C. In the case of a graphite layer with a specific surface area of 1315 m^2/g, the sorption capacity of such a system is 3.3 m/m.

Fullerenes, like graphite, are one of the allotropes of carbon. Fullerene molecules are built of pentagonal or hexagonal rings forming a hollow, closed block, which is built of 28 ÷ 1500 carbon atoms. The most popular fullerene is C60 fullerene, built of 60 carbon atoms. Due to its susceptibility to hydrogen addition, it finds the most comprehensive application as hydrogen storage amongst other types of fullerenes (**Figures 16** and **17**).

Carbon nanotubes, due to their unique structure, are interesting material for storing hydrogen due to their unique structure. Nanotube structures are made of cylindrically wound graphene layers in the form of hollow cylinders. Nanotubes differ in length, diameter, and angle of rotation. Due to the number of graphene walls that build carbon nanotubes, the following division is used:

- Single-Walled Carbon Nanotubes-SWCNT,
- Double-Walled Carbon Nanotubes-DWCNT,
- Multi-Walled Carbon Nanotubes-MWCNT.

Carbon materials are characterised by high hydrogen capacity, low desorption and allow hydrogen storage depending on the form of carbon in the following weight percentages: activated carbon-5.5%, graphite-4.48%, carbon fibres-6.5%. Single-walled carbon nanotubes-4.5%, multi-walled carbon nanotubes-6.3%.

In addition to a group of materials listed above, which includes coal and materials with a large surface area should be mentioned a technology for storing hydrogen in glass capillary arrays and glass microspheres [25]. Glass capillary arrays are placed in pressure-resistant vessels. Capillaries are closed by melting one end and closing the other with an alloy. Filling the vessel with hydrogen continues until the storage pressure is reached. Glass capillary arrays are used for the safe filling, storage, and controlled release of hydrogen in mobile applications [26, 27]. Flexible glass capillaries using the cryo-compression method of hydrogen storage can provide the expected gravimetric and volume density. However, this technology is accompanied

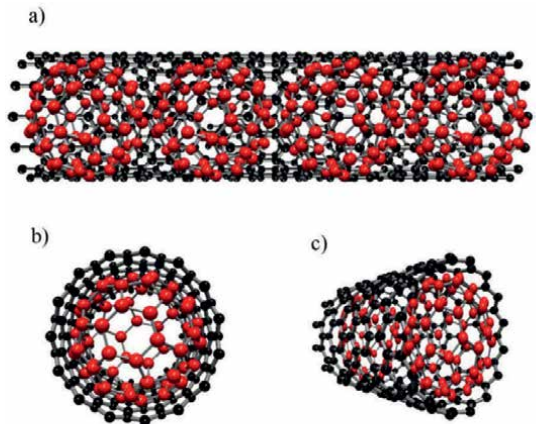

Figure 16.
Schematic image of C60 peapods @ SWCNTs: (a) side view; (b) front view; (c) tilted view (Carbon Peapod is a hybrid nanomaterial and consists of spherical fullerenes enclosed in carbon nanotubes) [23].

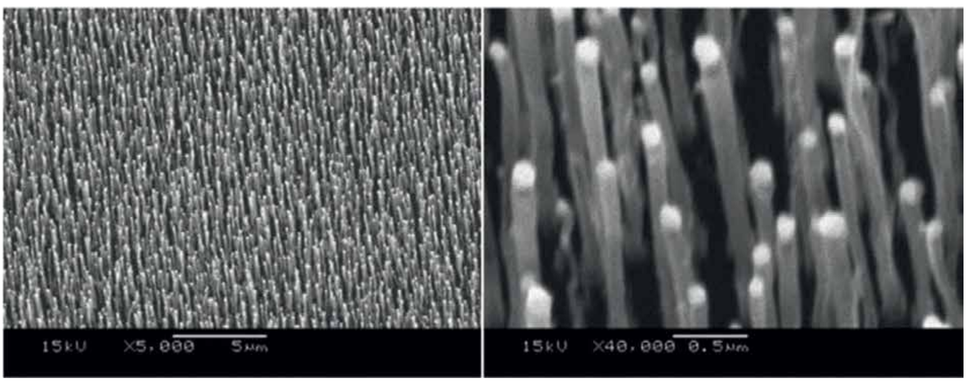

Figure 17.
Scanning photo of carbon nanotubes [24].

by disadvantages that limit the durability of the storage system. These defects occur in glass structures and are caused by bubbles, cracks or grooves (**Figure 18**).

An innovative storage device for compressed hydrogen is based on glass capillary arrays with a honeycomb-like structure and a diameter of approximately 100 μm. This structure is mechanically stable and can manage pressures over 1000 bar, even with thin capillary walls [29]. The experimental work reports that the volumetric and gravimetric capacities of the investigated structures can exceed the DOE target, at least in the investigated microscale device, which has a volume of 8.5 cm^3.

Another method is to use glass microspheres that are first filled with hydrogen at high pressure of around 350–700 bar at 300°C, followed by rapid cooling at room temperature. The spheres are then transferred to the low pressured vehicle tank and are reheated again at 200–300°C for controlled release of hydrogen. The materials possess low volumetric density and require high pressure for filling [30].

Also, of interest are those technologies that would allow the use of the existing infrastructure and conventional fuel tanks. The method is described by researchers at the University of Oregon, who have developed a liquid-phase hydrogen storage material-based on boron and nitrogen that works safely at room temperature; it is resistant to both air and moisture; releases H_2 in a controlled and clean manner below or on the proton membrane (PEM) at 80°C; moreover, it uses cheap and readily available catalysts for H2 desorption and has a relatively good gravimetric and volumetric energy density [31, 32] (**Figure 19**).

Figure 20 explains the impact of using liquid hydrides in propulsion systems on the construction of a motor vehicle. Liquid fuel and low pressure during its storage allow using a tank of any shape. However, the tank design must allow for the

Figure 18.
Examples of hydrogen storage system solutions used by C.En the hydrogen storage solution [28].

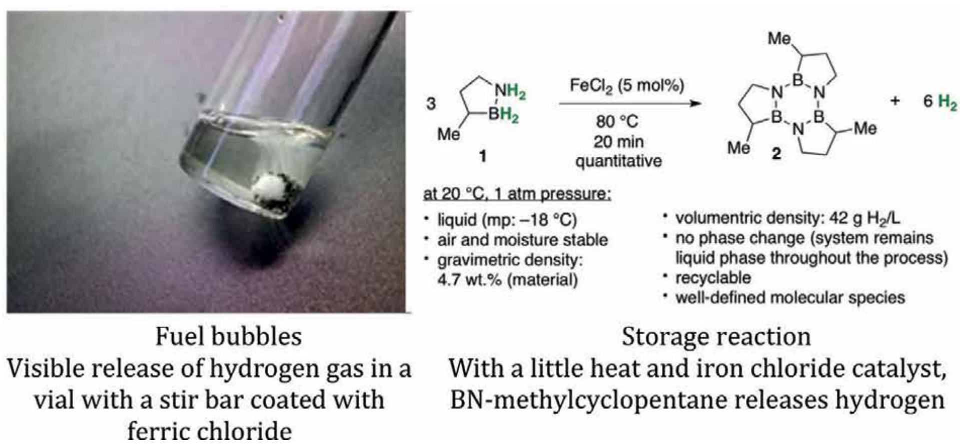

Figure 19.
An example of hydrogen adsorption and desorption using BN-methylcyclopentane and a catalyst [31].

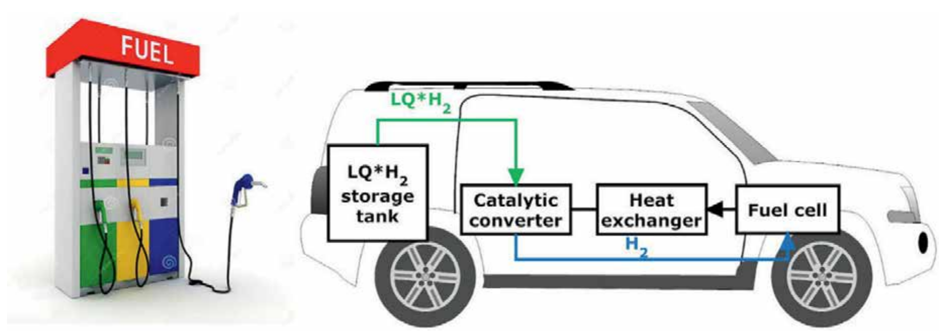

Figure 20.
A simplified diagram of a vehicle powered by hydrogen stored in liquid hydrides.

collection of products generated during hydrogen desorption, and the fuel infrastructure should be adapted to receive these products during the next refuelling. This waste threatens the environment, and the condition for disseminating this storage method is to solve the problem of their disposal.

In summary, the features that determine the suitability of hydrides as hydrogen storage include:

- the ability to reversibly store hydrogen,
- large capacity of stored hydrogen,
- low pressure and temperature (up to ~90°C) of hydride dissociation,
- high rate of absorption and desorption,
- a small amount of energy required to release hydrogen,
- low sensitivity to gaseous pollutants,
- a large number of possible charging and discharging cycles,
- safety (low pressure, non-flammability),
- and low price.

4. Conclusions

Hydrogen storage is a key technology enabling the development of hydrogen-powered vehicles. However, storing enough hydrogen on board to achieve a range of 500 km is a significant challenge. Due to hydrogen's gravimetric and volumetric density, hydrogen storage systems today face challenges in cost, durability, operational safety, and infrastructure costs. Consequently, the widespread commercialization of hydrogen-powered vehicles may be limited if new innovative technologies are not implemented.

Methods and technologies of hydrogen storage are currently the subject of intensive research, and their objective assessment is challenging because each of the technologies presented above has advantages and disadvantages. However, specific criteria can be adopted that compromise determining which technology is recommended for today's automotive industry.

To address all challenges of hydrogen storage systems, performance targets for light-duty vehicles were developed by the U.S. Department of Energy (DOE) assuming an estimated mileage of circa 500 km. The goals set by the DOE, which are presented in **Table 2**, determine the research directions of most research centres [33].

It is found that the pressure vessel technology is favourable because it is easy to implement with high storage energy efficiency and at low cost. The main drawback is low volumetric storage density. The influence of this disadvantage can be lessened if the technology develops for safe operation at higher storage pressures. Hydrogen liquefaction is more suitable for space applications than automotive because of its high volumetric and gravimetric efficiency. The disadvantages are the high cost and

Storage Parameter	Units	2020	2025	Ultimate
System gravimetric capacity: **Usable, specific energy from H2 (net useful energy/max system mass)**	kWh/kg (kg H2/kg system)	1.5 (0.055)	1.5 (0.055)	2.2 (0.065)
System volumetric capacity: **Usable energy density from H2 (net useful energy/max system volume)**	kWh/L (kg H2/L system)	1.0 (0.030)	1.3 (0.040)	1.7 (0.050)
Storage system cost:	\$/kWh net (\$/kg H2)	10 333	9 300	8 266
Fuel cost	\$/gge at pump	4	4	4
Durability/Operability: **Min delivery pressure from storage system**	bar (abs)		5	5
Charging/Discharging rates: **System fill time**	min	3–5	3–5	3–5

Useful constants: 0.2778 kWh/MJ; Lower heating value for H_2 is 33.3 kWh/kg H2; 1 kg H2 ≈ 1 gal gasoline equivalent (gge) on energy basis.

Table 2.
Technical system targets: Onboard hydrogen storage for light-duty fuel cell vehicles [1].

low energy efficiency. Metal hydride and carbon nanotube adsorption are promising hydrogen storage technologies as the volumetric efficiency is very high, and the gravimetric efficiency is comparable with the high pressure gas compression method. Therefore, metal hydride and carbon nanotube adsorption should receive more research efforts to realise a sustainable hydrogen economy.

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Chapter 5

Low-Temperature Combustion in Diesel Engines

Tsegaye Getachew and Mesay Dejene

Abstract

The growing energy demand for transportation has led to a shift towards eco-friendly combustion or improved diesel engines with increased efficiency, reduced emissions, and sustainability. Low-temperature combustion (LTC) aims to achieve controlled combustion, balancing optimal performance with lower NOx and SO_2 emissions. This chapter summarizes the recent trends in LTC strategies under further exploration such as fuel injection techniques, optimized air-fuel mixing, and accurate combustion phasing management, to discern existing literatures in extensive efforts to reduce flame stability and emissions. Subsequently, LTC faces challenges like stable ignition, precise control, and economical fuel choice. Liquefied biogas, methanol, biofuels, and thermo-physically enhanced biofuels are among the LTC diesel alternative fuels under investigation. Higher-octane fuels like biodiesels exhibited promising performance at low to medium loads, while natural gases and dual-fuel mode techniques seen promising choices for high-duty applications. Studies revealed that stakeholder collaboration could make cleaner fuel choices, meeting rigorous emissions rules while operating optimal LTC engines. Therefore, Future LTC research should focus on emission reduction, fuel flexibility, optimum performance at various working conditions, combustion stability, and accurate modeling and simulation.

Keywords: emissions reduction, engine performance, combustion characteristics, RCCI, SCCI, fuel injection, SoI, BSFC, combustion control, PPC, alternative fuels, EGR, fuel stratification

1. Introduction

The world's fastest-growing economies account for the majority of growth due to stronger infrastructure and commercial transportation; as a result, global transportation energy consumption, including developed economies, is predicted to ascend. There is an urgent need to increase transportation efficiency, reduce emissions, and promote sustainability on a global scale. Because transportation is an essential component of economic growth, the cost of commercial transportation solutions must be inexpensive while meeting customer expectations for total cost of possession, efficiency, dependability, resilience, and sustainability. Clean mixed controlled combustion engines are necessary for the transportation industry, as global transportation energy demand is expected to climb by 25% over the next two decades. The quest for sustainable transportation with the best environmental performance has led to rise in innovative combustion strategies for internal combustion (IC) engines. Diesel engines have well-established technology for their efficiency and durability currently facing challenges in meeting stringent emission regulations. Nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs) are critical pollutants that must be controlled and managed because they have a negative impact on local and global air quality.

Low-temperature combustion (LTC) as its name indicates is a strategy to maintain a low-temperature combustion by reducing peak cylinder temperatures and pressures that involves a highly dilute premixed air-fuel charge before the start of combustion, particularly in internal combustion engines, with the purpose of a simultaneous reduction of NO_x and soot emissions. Low-temperature combustion (LTC) strategy attracted plethora of new research significance as a promising alternative to conventional combustion for its benefits beyond reduced emissions such as lower peak pressures and temperatures, which enable reduced noise and vibration levels that enhance an overall driving experience, improved fuel consumption, improved thermal efficiency, and improved engine performance. By reducing formation of NO_x and particulate matter (PM) pollutants emissions, LTC enables mitigation of adverse environmental impacts of diesel engines. One of LTC approaches is utilizing a highly dilute charge of premixed air-fuel mixture before the starting of actual combustion process aiming at more controlled and more homogeneous combustion process that results in enhanced emission characteristics and improved thermal efficiency. The conventional combustion relies on high pressures and temperatures that lead to formation of pollutants.

However, the LTC implementation in diesel engines presents its own challenges such as achieving stable ignition and precise control to optimize combustion phasing in highly dilute charge conditions that demand advanced engine management systems. Furthermore, efforts to characterize combustion behavior and reactivity in order to address issues of flame stability and further reduction of pollutant emissions have given rise to the development of advanced combustion technologies and diagnosis technologies. Advanced combustion technologies include partially premixed and homogeneous compression combustion, catalytic combustion, and carbon-free fuel combustion. The diagnosis methods include flow velocity, species, and temperature.

Additionally, the fuel choice plays a vital role to ensure a desired LTC combustion performance. This chapter consists of reviews of LTC in diesel engines from various published literature and presented in various subtopics as types and strategies of LTC, principles and challenges, combustion characteristics, experimental techniques, advanced technologies, consideration of transport sectors application, and future research directions.

2. Basic components of LTC, LTC strategy types, and their significance

Low-temperature combustion (LTC) strategies include:

1. Reactivity controlled compression ignition (RCCI),
2. Homogeneous charge compression ignition (HCCI),
3. Partially premixed combustion (PPC),
4. Dual-fuel combustion (DFC), and
5. Stratified charge compression ignition (SCCI).

Figure 1 shows a simplified schematic diagram with stratified and multiple fuel injection LTC engine. Generally, LTC combines homogeneous charge compression ignition (HCCI) and partially premixed combustion (PPC), which reduces NOx production by lowering combustion temperatures and starting the fuel spray earlier in the engine cycle.

The key components of LTC to achieve an optimum LTC performance (efficient and clean combustion) comprise:

1. Modified shape and size combustion chamber to promote the desired combustion characteristics

2. Stratified fuel preinjector is used to charge small fuel amount in to prechamber in which a lean-air-fuel mixture is formed.

3. Multiple fuel-injection systems:

    a. Preinjectors: The introduction of multiple stratified fuel injectors charge small amount of fuel to aid homogeneous lean mixing of air-fuel

    b. Main injection: delivers bulk of fuel into main combustion chamber to ensure complete combustion.

    c. Post-injection: incorporating not more than a post-injection facility resulted in further NOx emission reductions.

4. Fuel pump and injection control unit: work in tandem to ensure precise regulation of fuel flow and injection timing based on various engine parameters.

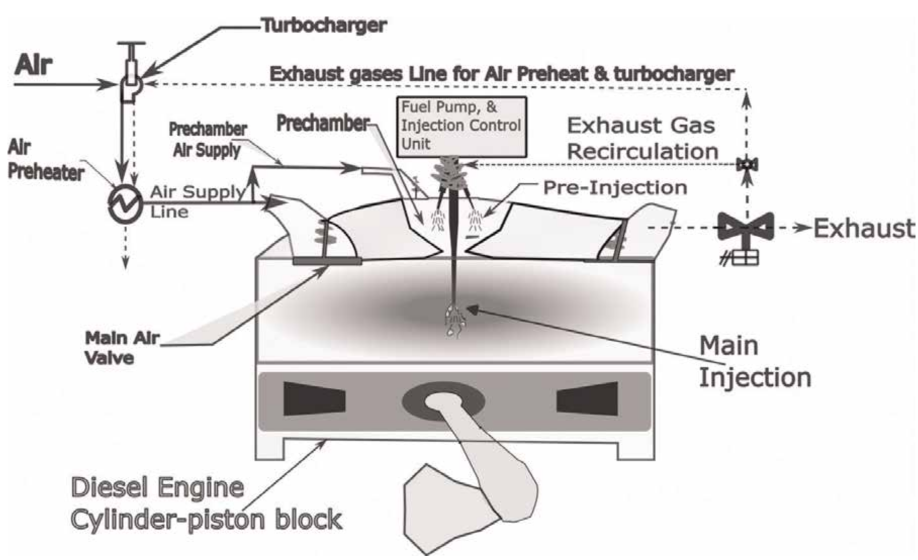

Figure 1.
Simplified schematic diagram of a hypothetical LTC diesel engine setup (stratified and multiple fuel injection).

5. Exhaust gas recirculation (EGR): Since the fuel gas analyses of LTC show that the exhaust gas has more unburned fuel content compared to the conventional diesel combustion (CDC), the EGR ensures taking back a portion of it back into the intake manifold.

6. Turbocharger: driven by exhaust gases compresses the intake air contributing to an overall engine efficiency enhancement.

7. Preheater: since exhaust gases temperature measurements show that LTC fuel gases have higher temperature than that of CDC, a preheater elevates the intake air temperature as well as reduce heat loss to enhance the combustion processes (mixing, complete combustion, and combustion stability) and improve combustion efficiency.

These facilities collectively contribute to ensuring LTC achieves improved fuel efficiency and reduced pollutants emissions. The main aim of LTC is to achieve low emissions while maintaining or improving thermal efficiency. Each strategy has its own advantages and disadvantages depending on the specific application and operating conditions.

These LTC strategies (summarized in the **Table 1**) can either be employed in the modern combustion systems in the diesel engines individually to exploit their corresponding benefits or combined to further enhance the system performance as shown in the hypothetical scheme **Figure 1**. HCCI, for example, is often possible by the integration of multiple fuel injectors and a pre-chamber, whereas SCCI increased system performance even further by achieving a leaner mixture with multiple ideal phased pre-injection time.

2.1 Objectives and scope

An energy surge due to spiking associated world population explosion and technology boom elevated concerns such as greenhouse gas emissions (GHG) and air pollution, climate change and health risks, and depletion of reservoirs over conventional burning of petroleum products to fuel power-essentials like engines. As a result, advanced combustion subjects such as fuel and combustion, alternative fuels, and diesel engine pollutants garnered an immense significance and unwavering attention from policy-makers, researchers, fossil fuel traders, engine manufacturers, and a plethora of other stakeholders. Low-temperature combustion (LTC) is considered as an engendered potential solution due to enhanced fuel efficiency, reduced emissions, and improved combustion characteristics. Yet, the underlying mechanisms, operational limits, optimization parameters, and effective advanced technologies of the LTC remain to be fully understood so that to unlock its practical potential across various industries operating under stringent emission regulations that make it particularly relevant for the diesel engine due to the LTC's verified profile of minimizing the NO_x, PM, and beyond.

This chapter document aimed at summarizing the recent trends, challenges, and future prospectives in LTC diesel engines from various published and unpublished research and review literature and technical documents for the past 5 years. It starts with general principles of each LTC method, specific fuel characteristics requirement of the LTC along with comparisons frameworks. The second section describes challenges of implementing the LTC followed by experimental techniques used in

LTC Methos	Principle	Combustion controlled	Advantage	Disadvantage
Homogeneous charge compression ignition (HCCI)	The oldest premixed LTC strategy uses compression of a homogeneous air-fuel mixture until self-ignition. High exhaust gas recirculation (EGR) rates along with an early injection timing used.	adjusting the intake temperature (for ignition timing and combustion rate), EGR, and fuel injection timing. Other parameters include: Fuel properties (volatility and cetane number for reactivity), and air-fuel ratio (to ensure leaner mixture)	Low NO_x and soot emissions	Risk of knock at high compression ratios, limited range, and difficult to control due to an indirect control.
Reactivity controlled compression ignition (RCCI)	Uses two different fuels: a low-reactivity fuel (LRF) that injected into the intake port using a port fuel injector (PFI) and a high-reactivity fuel (HRF) that is injected directly into the cylinder using a direct injector (DI). The fuel injection timing is adjusted for controlling the timing of the low and high-temperature heat releases (LTHR)/(HTHR) phases	Adjusting intake temperature, quantity, and LRF-HRF ratio for both fuels (for reactivity and advance combustion phasing, ignition timing, and combustion rate), fuel injection timing, EGR (to reduce NO_x emission, peak temperatures, and pressures in the cylinder), and engine load (to regulate fuel injection rate and amount, ignition timing, and combustion rate)	better thermal efficiency and NOx-soot trade-off than CDC under a wide range of operating conditions	optimization of RCCI for different engine types and operating conditions not yet understood.
Partially Premixed Combustion (PPC)	An early injection timing for a partially premixed mixture of fuel-air in the cylinder before ignition. Involves delayed injection timing than HCCI resulting in stratified (less-homogeneous) air-fuel mixture that offers more control on injection timing, and more sequential auto-ignition.	Injection timing (delayed to enable more control). Other key combustion parameters are: air-fuel ratio, stratification level, and combustion phasing.	More operation range, less combustion noise, and reduced excessive maximum excessive pressure rise rates (PRR)	The high reactivity of diesel limits its range. Optimum operation under various conditions and fuel types is not yet fully understood.
Dual-fuel combustion	Like RCCI, dual-fuel combustion uses two different fuels,	The combined adjustments of injection timing of	Low emissions while improving thermal efficiency compared	Performance optimization for various operating

LTC Methos	Principle	Combustion controlled	Advantage	Disadvantage
	the primary fuel and another fuel, are used as secondary fuels to enhance combustion efficiency and reduce emissions. The dual-mode dual-fuel (DMDF) type where diesel and gasoline/natural gas are the primary and secondary fuels, respectively.	both fuels (for the optimal combustion phasing and ignition timing), injection pressure (for fuel atomization & mixing quality), & intake air temperature (for reactivity).	to conventional diesel engines.	conditions and fuel types is yet to be fully understood.
Stratified Charge Compression Ignition (SCCI)	Combines SI and HCCI, injecting small fuel near spark-plug that creates leaner mixture and while the rest of fuel is into intake port offering richer mix in the rest of combustion chamber.	Adjusting injection strategy and spark timing. Other parameters: air-fuel ratio, engine load, and intake temperature.	Stable and efficient combustion under certain conditions.	Complex process to optimize due to multiple parameters adjustment needs.
Conventional diesel combustion	Conventional diesel combustion involves injecting fuel directly into the combustion chamber at high pressure and temperature.	Adjusting fuel injection timing, injection pressure, EGR rate, and intake boost pressure.	Simplicity and reliability.	High NO_x and soot emissions.

Table 1.
Comparison of various LTC strategies.

monitoring and evaluation of the LTC diesel engines in the third section. The fourth section tries to address the LTC strategies along with advanced engine technologies from various renowned Scopus research and review databases followed by its various light to heavy-duty engines application in transport sectors in section five. The chapter concluded with the descriptions of the future research directions and perspectives of the LTC. Overall, by doing these, this chapter tries to answer the following academic questions about the LTC diesel engines:

1. What are the recent trends for LTC rail diesel engines to improve emissions, fuel efficiency, and durability?

2. What viable LTC implementation options and issues do the passenger car and commercial truck diesel engine manufacturers have?

3. What are the most promising hardware design modification and experimental validation for an LTC diesel engine?

4. What advanced engine control techniques optimize LTC diesel engine performance, emissions, and fuel economy?

5. LTC is a potential emission reduction technology, but how can it be implemented in diesel engines and locomotives given specific challenges and constraints of optimizing LTC for manufacturers?

3. Principles of operation and challenges in implementing the low-temperature combustion in diesel engines

Low-temperature combustion (LTC) refers to a series of combustion modes that can reduce soot and NO_x emissions. It entails a lean air-fuel charge/preinjection before start of ignition (SOC), adjusting engine parameters such as start of injection (SoI) timing, air-fuel ratio, and injection pressure to reduce NO_x and soot emissions, optimizing LTC performance by adjusting engine parameters such as SoI timing, air-fuel ratio, and injection pressure, and balancing combustion efficiency and heat transfer losses for optimal LTC performance. LTC optimization imposes a number of difficulties.

According to Olmeda et al. [1], the general combustion characteristics of LTC [2] are:

- A diluted air-fuel charge/preinjection before start of ignition (SOC).

- Setting the timing of the end of the main (EoI) of the direct fuel injection independent SOC to reduce NOx and soot emissions.

- Optimizing LTC performance is achieved by adjusting engine parameters such as start of injection (SoI) timing, air-fuel ratio, and injection pressure.

- SoI timings should balance combustion efficiency and heat transfer losses for optimal LTC performance. The optimal LTC performance with SoI timings saw a trade-off between combustion efficiency and heat transfer losses.

- The delayed start of injection (SoI) in diesel results in diffusive combustion with higher heat release profile with two peaks the first in the premixed phase and diffusive phase enhancing heat transfer.

3.1 Challenging and complex optimization process in LTC

The LTC is a diffusive combustion that maintains higher temperatures during the premixed phase, enhancing heat transfer when compared to conventional combustion. As stated in the last paragraph of Section 1.1.1, LTC can involve either a single strategy among the list in the table 0 or a combination of many, which involves a complex approach to optimize the system. Low-temperature combustion (LTC) modes, according to Dan et al. [2], are a series of combustion methods that can avoid the creation of soot and NOx emissions. Partially premixed combustion (PPC), partial fuel stratification (PFS), gasoline compression ignition (GCI), and reactivity controlled compression ignition (RCCI) are examples of LTC modes. According to the PDF, these tactics can avoid locally rich and high-temperature zones, which can result in soot and NOx emissions [1].

LTC optimization thus entails multiple and complex procedures, each of which presents its own set of obstacles, such as:

1. Multiple combustion dystem design parameters: chamber design modification, injection techniques, and air-fuel mixing.

2. Challenging fuel injection strategies: determination of the ideal timing, duration, and quantity of fuel injection to ensure balance between higher efficiency and reduced emissions.

3. Exhaustive combustion control: Controlling combustion parameters such as combustion timing and heat release rates impose difficulties in achieving consistent and steady combustion over various operating conditions and loads.

4. Complex emission control: Compromise between low NO_x and particulate matter (PM) emissions and high combustion efficiency.

5. Meticulous combustion stability: regulation of air-fuel ratios and ignition timing to ensure stable combustion under a variety of operating circumstances, including idle, low load, and high load.

6. Incorporating sophisticated technologies like exhaust gas recirculation (EGR), turbocharging, and after-treatment systems into LTC brings new challenge of optimizing system interaction.

7. Difficulty of accurate modeling and simulation: realistic computational models and simulations to understand and optimize LTC processes is difficult to achieve

The most common conventional and renewable fuels being researched discussed in the next section along with their possible benefits and drawbacks considering their viable use in LTC diesel engines. Furthermore, extraction techniques from their ubiquitous fuel sources are also summarized in **Table 2**.

3.2 Fuel choice-extraction economy quandary and complex combustion characteristics

Various fuels tested in the LTC diesel engines with multifaceted outcomes due to fuel selection and imposed economy dichotomy, complex combustion process, and sophisticated combustion control and management requirements along with underexplored optimization methodologies.

Garcia & Boronat et al. [3] conducted research and review on the impact of low-temperature combustion-achieving techniques on diesel engine emissions for diesel and also employed in the experiment sustainable fuels such as biodiesel and renewable diesel. The result revealed that the use of alternative fuels can have both good and negative effects on the low-temperature combustion performance of diesel engines.

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Fuel / Property	Diesel $C_{12}H_{24}$	n-Butanol C_4H_9OH	Gasoline C_8H_{18}	Biodiesel $C_3H_5(OCOCH_3)_3$	Ethanol C_2H_5OH	Natural gas CH_4	Hydrogen H_2	Dimethyl ether C_2H_6O
Extraction	Petroleum extraction or fractional distillation	Fermentation of organic matter	Crude-oil refining or fractional distillation	Feedstock-oil extraction *via* pressing or chemical/ solvent, then transesterification	Fermentation followed by distillation/ purification	Deep-well-to-surface pumping of gas, followed by adsorption/purification of contaminants such as sulfur, CO_2, N_2 etc	1. Steam methane reforming 2. Electrolysis 3. Partial oxidation 4. Biomass Gasification	gasification /syngas production preceding methanol synthesis and dehydration
Physical properties								
flash point	65–88 ^oC	35 ^oC	40–45^oC	130–160^oC	16.6^oC	NA	41^oC	-42^oC
Density kg/m^3 stp	835–845	810–810.9	715–775	880–900	789	0.716	0.0899	2.02
Viscosity mm^2/s stp	2–4.5	2.5	0.4–0.8	3.5–5.5	1.2	0.0172	8.76×10^{-6}	0.22
Boiling range	180–360 ^oC	117–119 ^oC	30–215^oC	300–400^oC	78.3–78.5^oC	-82.6^oC @ 46 bar	0^oC	-24.8^oC
Boiling point at stp	190–280 ^oC	108.1^oC	30–220^oC	200–350^oC	78.3^oC	−161.6	-252.9^oC	-24.9^oC
Sulfur cont. Ppm	< 15	—	< 10	< 10	—	< 1	—	—
chemical properties								
cetane number	40–55	6–17	NA	50–60	8–15	NA	NA	NA
octane no.	NA	94	85–95	NA	100–105	85–110	130–140	55–60
Heat of combustion MJ/kg	42–46	27–29	44–48	39–43	26–30	50–55	120–142	28–32

Fuel / Property	Diesel $C_{12}H_{24}$	n-Butanol C_4H_9OH	Gasoline C_8H_{18}	Biodiesel $C_3H_5(OCOCH_3)_3$	Ethanol C_2H_5OH	Natural gas CH_4	Hydrogen H_2	Dimethyl ether C_2H_6O
Fuel sensitivity	—	—	3–12 RON	—	5–20	5–15	10–20	8–15
Ignition delay ms	2–5	2–8	—	2–6	—	—	—	1–2
LTCs: HCCI, RCCI, PPC, SCCI	High	Low	Low	Low	Low	NA	NA	NA
LTCs: DI benefits	High energy density and cetane no., good lubricity, robust systems	Low PM used as diesel blend, renewable, sustainable	Used for dual fuel as blend for low carbon alternative	Renewable, sustainable, low PM, and sulfur improved lubricity	Nearly similar to gasoline used as diesel blend	Low emission, abundant	Zero emission, high energy density	High cetane no., good cold start, renewable, and low emission
LTCs: DI Drawbacks	high emission, non-renewable	Low energy density, low η_{thermal}	Low cetane number, low energy density	High viscosity, low energy density	Low energy density, lower heating value	Low energy density, storage, and refueling infrastructure cost	Safety concerns and infrastructure cost refueling and storage	Low energy density, handling safety concerns

Table 2.
Comparison of fuel types for LTC: Extraction, physical and chemical properties, benefits, and drawbacks.

Biodiesel, for example, can lower particulate matter emissions while increasing nitrogen oxide emissions, and renewable diesel can enhance combustion efficiency while increasing carbon monoxide emissions [3].

In the other studies, the authors proposed combining various alternative fuels, such as biofuels, methanol, and liquefied natural gas (LNG), to minimize emissions and satisfy environmental targets [4]. Using response surface methodology (RSM), regression model that involves identifying the optimal input factors in complex combustion process that results in desired engine performance. Elkelawy et al. [5] determined the optimal inputs of variables such as biodiesel percentage, alcohol percentage, retarded injection timing, injection pressure, piston geometry, and EGR percentage that will result in maximum brake thermal efficiency (BTE), minimum brake-specific fuel consumption (BSFC), and reduced emissions. Using response surface methods, it optimizes the input variables and output responses for a diesel engine running on diesel and low-grade coal-based generated gas. The equivalency ratio, compression ratio, and engine load were the input variables. The optimum input variables were 0.12 for equivalency ratio, 17.01 for compression ratio, and 12 Kg for engine load. Total of 3.54 kW for braking power (BP), 28.23% for brake thermal efficiency (BTE), and 0.38 Kg/kWh for brake-specific fuel consumption (BSFC). Despite this, emissions remained at 0.023% vol for CO, 4.2539 ppm for unburned hydrocarbon UHC, 0.9569 vol% for CO_2, and 9.6958 ppm for NOx emissions [5].

The specific important diesel fuel property requirement for optimal LTC operation include: viscosity, surface tension, and ignition tendency/cetane number. The four major challenges of LTC implementation with biodiesel despite its popular production and utilization that Wei et al. (2020) addressed in the book "Diesel and Gasoline" [6] can be summarized as:

1. Dilemma selection of an economic feedstock,

2. Complex specific fuel properties are prerequisites for LTC to ensure optimal performance, combustion control, and emission reduction in advanced engines systems,

3. Imposed significant temperature and pressure requirement and intensive methanol-demanding nature of the transesterification to reduce its viscosity, and

4. limited options of verified nonedible feedstock from which biodiesel can be derived and used without requirement of substantial alterations to conventional diesel engine.

It must be noted from the above table that the specific values vary depending on the fuel composition, blend or impurities, and extraction processes specifically for synthetic ones. The boiling range refers to the range of temperatures at which the highest to the lowest volatile constituents of the specific fuel evaporate where as boiling point refers to the specific temperature at which the fuel evaporates at the given standard pressure. The fuel with shorter boiling range and lower boiling is preferred because those enable better air-fuel mixing and volatility to ensure LTC. The other relevant fuel characteristics for LTC comprise cetane number-a measure of the ignition quality of diesel fuel, octane number-a measure of knock resistance of gasoline engine, heat of combustion, fuel sensitivity-the performance, difference between research cetane number (RCN) and motor octane number (MON) for gasoline fuels, and ignition delay. Generally speaking, fuels with higher values of heat release/ heat of combustion, and cetane number with faster combustion or shorter delay, are considered to perform better in LTC. The final four rows illustrate the recent research modification and testing trend in LTC optimization attempts for various fuels. The three gaseous fuels in the three last columns with not applicable (NA) LTC application in the third row from the bottom are listed with benefits/drawbacks considering their properties along with potential LTC compression ignition application.

The experimental research by Jun et al. [7] on the combustion characteristics of ammonia, present it as a carbon-free fuel, describes its advantages as an alternative fuel with exceptional performance, durability, reliability, optimize combustion properties, and lower pollutant emissions. It did not go without challenges such as a lack of understanding of the NH_3 combustion characteristics, methods of combustion enhancement, and optimization of NOx formation in combustion, and problems such as low burning velocity in a combustion zone [7].

4. Combustion characteristics

The soot emission and delayed ignition are other major challenges in LTC diesel engine where unburned hydrocarbon leaves the exhaust and contribute to pollution. The relationship between the premixed mass and delayed ignition (DI) mass in a combustion zone is given in Eq. (1).

$$\begin{aligned} PREi &= \frac{m_{\text{premixed}}}{m_{\text{premixed}} + MDI, i} \\ MDI, i &= m_{\text{premixed}}(1 - PREi) \end{aligned} \tag{1}$$

where PREi is the PRE mass fraction of fuel in a combustion zone, mpremixed is the premixed mass, and MDI, i is the DI mass [7]. The experiment in ref. [7] revealed that

1. RCCI heat transfer has higher bulk temperature than diesel combustion.

2. RCCI combustion reduces heat transfer (an in-cylinder heat transfer loss) by 13% due to its shorter duration. The reduction is also associated to decrease in localized effect or uniformity of global (average temperature of entire combustion chamber) and local (temperature at the specific location within combustion chamber) temperatures.

3. The heat transfer losses for both low reactivity fuels (LRF): gasoline and 85:15 ethanol-gasoline (E85) blend exhibited similar trends with insignificant absolute differences, despite the exhaust gas temperature for the later being seen as higher due to the combustion process over longer period.

4. The E85 is seen potential LRF fuel for RCCI combustion to be cleaner and more efficient than diesel. However, engine settings optimizations such as SoI and EGR recommended to address the E85 drawbacks such as low heating value

compared to gasoline, longer combustion duration, and high exhaust temperature.

5. Increase in gasoline fraction (GF) from 60 to 80% resulted in shorter period of combustion.

Ignition delay, therefore, is another undesired combustion characteristic in LTC diesel engines. It is related to the other important characteristics of combustion, equivalence ratio, the ratio of actual combustion air-fuel ratio to that of stoichiometric ratio. Considering multiple stages of chains of reaction, Eq. (2) is used to predict the delay time τ [2]:

$$\begin{aligned} S &= \frac{1}{\Delta\tau}, \quad \tau = f(T,\phi) \quad \text{for} \quad T = T(x) \quad \& \quad \phi = \phi(x) \\ \Delta\tau &= \frac{\partial\tau}{\partial x}\frac{d\phi}{dx} + \frac{\partial\tau}{\partial T}\frac{dT}{dx} \end{aligned} \tag{2}$$

For the given zero initial concentration, the subsequent combustion, ϕ_{ox} CFD estimator used showed that increase in temperature T gradient with x-displacement of the stroke [8].

According to Antonio et al. [3], premixed low-temperature combustion strategies are used to investigate a way to reduce NO_x and particulate pollutants directly during the combustion process, implying that it may have advantages over after-treatment systems such as selective catalytic reduction (SCR), though additional research may be required to fully evaluate the potential benefits and drawbacks of the technologies for diesel engines. Emissions testing under various engine loads and operating situations, as well as fuel efficiency tests, could be measurable and achievable approaches to evaluate the performance of low-temperature combustion systems [3, 9].

The equivalence ratio is used to predict predicting ignition and subsequent combustion, ϕ_{ox} CFD estimator used

$$\phi_{ox} = \frac{2\sum_i (N_i\eta_{C,i}) + 0.5\sum_i (N_i\eta_{H,i})}{\sum_i (N_i\eta_{O,i})} \tag{3}$$

for the N number of moles of $C, H, and\ O$ in species i. According to Elkelawy et al. [5] with similar approach, adding nanofluid additives to blended diesel-biodiesel can reduce BSFC, reduce overall emissions, and boost BTE [5].

The spatial and temporal distribution of combustion within the engine cylinder during the combustion process are portrayed by combustion zone mapping shown in the **Figure 2**. The simulation data for typical fuel (n-Heptane) was obtained from Aneesh et al. [10] and presented here for conventional diesel combustion (CDC) and LTC side-by-side to enable comparison [10]. The greater fuel penetration with leaner mixture is seen for the CDC than LTC at entry/start of injection because combustion takes place at higher equivalence ratio. The combustion temperature at the fuel injection area was also observed to be higher but lower at the near exhaust (from left to right) for the CDC when compared to LTC. This implies faster combustion. The LTC, on the other hand, is seen to have fewer combustion-emissions intersection areas (reduced emissions). Relatively wider central combustion area (more uniform/homogeneous mixing) toward center and lower peak temperature for LTC account for reduced emissions.

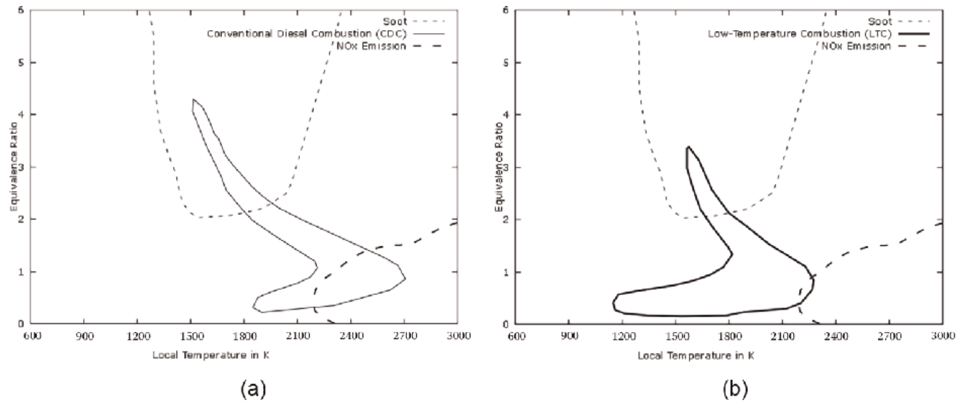

Figure 2.
Combustion zone map comparison of CDC and LTC for n-heptane fuel in diesel engine.

Brake mean effective pressure and heat release rate are essential for combustion stability, extended combustion duration, and ignition delays. Eq. (4) is used in typical engine configuration to calculate mean effective pressure and heat release rate [11].

$$\begin{aligned}\overline{P} &= \frac{\int_{180^{o}C}^{180^{o}C} PdV}{V_d} \\ \eta_I &= \frac{\int_{180^{o}C}^{180^{o}C} PdV}{m_f LHV_f} \\ HRR &= \left.\frac{dQ}{d\alpha}\right|_{\text{chemical}} - \left.\frac{dQ}{d\alpha}\right|_{\text{wall loss}} = \frac{1}{\gamma-1} V\frac{dP}{d\alpha} + \frac{\gamma}{\gamma-1} P\frac{dV}{d\alpha}\end{aligned} \tag{4}$$

Eq. (5) gives the relative heat release [12].

$$\begin{aligned}&dQ_{HR} = g_c \times W_u \times dHR \quad \text{(a.) until this time} \quad Q = g_c \times W_u \quad \text{(b.) Total} \\ &dHR = dHR_i + dHR_{str} \quad \text{(c.) Net HR until present} \quad HR_i = HR - HR_{str} \quad \text{(d.) net HR} \\ &HR = \frac{Q(\alpha)}{g_c \times W_u} \quad \text{(e.) HR until present } g_c, \quad HR_i = \frac{U_i - U_{ps} + \int_{V_{aps}}^{V_t} pdV}{g_c \times W_u} \text{(f.) Indicated HR} \\ &HRR = \frac{HR_i - HR_{i-1}}{\alpha_i - \alpha_{i-1}} \quad \text{(g.) Relative HR}\end{aligned} \tag{5}$$

where $Q(\alpha)$ = the amount of heat released until the present, g_c = the dose of fuel supplied in one engine work cycle, and W_u = the calorific value of fuel in burnout fuel dose. HR = heat release, U = internal energy, the subscript str = thermodynamic process cylinder stroke, i = current injection process point, ps = the beginning before the start of combustion, and α = crankshaft rotation.

Teyler et al. [13] used the brake-specific efficiencies: volumetric efficiency, combustion efficiency, and fuel efficiency from the energy conservation using the first law of thermodynamics on crank angle basis [14].

$$
\begin{aligned}
\eta_v &= \frac{\dot{m}_{\text{air}}\overline{R}T_{\text{intake}}}{NM_{\text{air}}P_{\text{intake}}V_d} \\
\eta_c &= 1 - \frac{P_b}{\dot{m}_f uel}\Big((bsQ_{LHV})_{CO} + (bsQ_{LHV})_{THC} + (bsQ_{LHV})_{H_2}\Big) \\
\eta_f &= \frac{P_b}{m_{\text{fuel}}Q_{LHV}} \\
\eta_{th} &= \frac{\eta_f}{\eta_c} \\
IMEP_n &= \frac{W_{in}}{V_d} \\
W_{in} &= \int_{ivc}^{ivo} PdV + \int_{ivo}^{ivc} PdV = \frac{P_1 + P_N}{2} + \sum_{i=2}^{i=N}\left(\frac{P_i + P_{i-1}}{2}\right)(V_i + P_{i-1}) \\
\frac{dQ_{hr}}{d\alpha} &= \frac{dU_{cv}}{d\alpha} + \frac{dW_{cv}}{d\alpha} + \frac{dQ_{ht}}{d\alpha} + \sum h\frac{dm_{cv}}{d\alpha}
\end{aligned}
\tag{6}
$$

Where P_b, Q_{LHV}, and IMEP are break power, lower heating value, and indicated mean-effective pressure, respectively. W and V_d are thermodynamic work and stroke volume, respectively. The indices ivc and ivo are inlet valve opening and closing, respectively. As shown in the **Figure 3** (data obtained from ref [15]), LTC has higher mechanical efficiency despite having less thermal efficiency at TDC of the power stroke (beginning at 90^o cam angle) and lower mean effective pressure implying potential of achieving advanced combustion phasing. The higher mechanical efficiency also implies reduced specific base fuel consumption. Despite having lower combustion peak pressure and temperature see **Figure 3**, LTC tends to have higher heat release at the later combustion stages and therefore the exhaust leaves at relatively higher temperature. Regardless of having lower combustion efficiency of LTC as seen in **Figure 4**, the larger proportion of it being converted to useful work leads

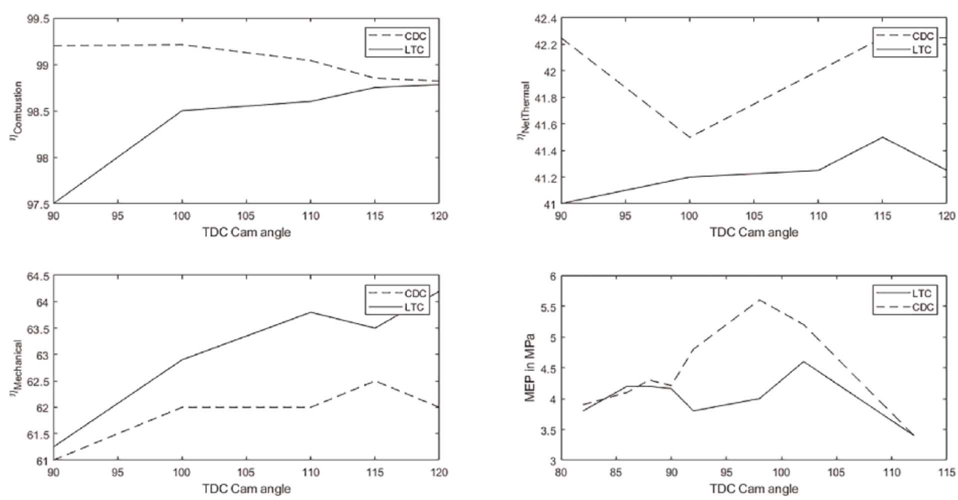

Figure 3.
Comparison of combustion efficiencies and mean effective pressure (MEP) for CDC and LTC.

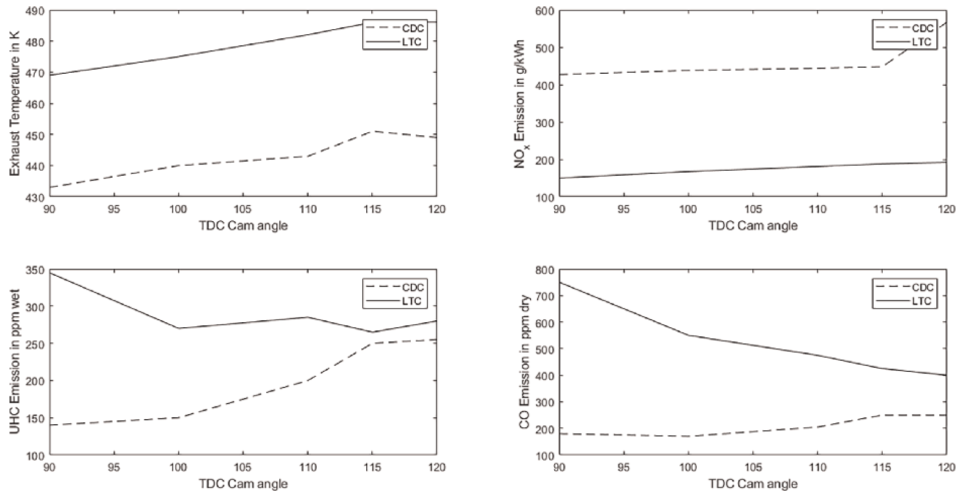

Figure 4.
Exhaust temperatures and emissions comparison of CDC and LTC.

the LTC process to better performance. Overall, the low-temperature oxidation process results in an ultimate reduced emissions particularly, NO_x emission.

The realistic consideration of alternative fuels for LTC gives their respective benefits and drawbacks, based on corresponding extraction methods from their feedstock or natural resource, physical and chemical qualities. The physical and chemical properties of such as flash point, density, viscosity, boiling range, sulfur content, cetane number, octane number, and heat of combustion are the most essential details in this text. Due to fuel selection, economy dichotomy, complex combustion process, and underexplored optimization approaches, the fuels' corresponding testing in LTC diesel engines, produced diverse results. The optimum input factors for LTC are biodiesel %, alcohol percentage, retarded injection timing, injection pressure, piston shape, and EGR percentage, resulting in reduced pollutant emissions, maximum brake thermal efficiency (BTE), minimum brake specific fuel consumption, and maximum brake specific fuel consumption.

5. Experimental techniques for LTC analysis

The experimental techniques in LTC so far comprise:

1. Combustion diagnosis: to capture detailed information and combustion process such as high-speed imaging, laser induced-florescence (LIF), and particle image velocimetry (PIV).

2. In-cylinder pressure measurement: to analyze combustion process

3. Emission sampling and analysis

4. Optical access engines where transparent set-up allows for access through various optical diagnosis

5. Advanced fuel injection systems
6. Combustion chamber design
7. Engine calibration and control
8. Combustion kinetics and chemical analysis

According to BB, the investigated variables in single-cylinder diesel engines fuelled with diesel biodiesel and alcohols utilizing response surface methodology (RSM) are NOx, smoke emissions, and BSFC. The biodiesel percentage, alcohol percentage, retarded injection time, injection pressure, piston geometry, and EGR percentage are the data for input factors. The influencing factor for the variables was determined using ANOVA. Taguchi design was utilized to screen the elements and response surface method (RSM) was used to optimize the design [1].

Liu et al. [16] improved Method: Emission measurement methods for multicollinearity that relate speed/quality used to be based on three-stage OLSM of the estimated model of I/M test-based data to the vehicle emission with those measurement indicators are classified as:

1. Data emission measurement model based on driving condition,
2. Emission measurement model based on running state and emission measurement model based on road measurement.

More accurate regression model (stable: no collinearity: equal variance and residual normal distribution) or more fitting statistical model with profound relevant factors such as the driving mileage of the secondary trunk road, the service life of the vehicle, the load quality and the oil products, to estimate the vehicle emissions developed for the market-oriented road passenger emissions [17].

The technical report on experimental and analytical evaluation of combustion process parameters on FIAT 1.3 multijet SDE 90 HP engine equipped with Common Rail fuel supply system and electronically controlled solenoid injectors used rapeseed biodiesel or fatty acid methyl ester (FAME) and diesel oil Kierce University of Technology led by Dariusz et al. [12] to investigate the maximum combustion phenomena and reported that FAME exhibited slight P_{max} than diesel oil at lower and medium loads despite the superior values at the first two subsequent stages of the maximum combustion [18].

The heavy-duty (HD) dual-fuel engine experiment by Zuev et al. [19] used single pilot injection with α varying 30 to 5^o crank angles at BTDC increased emission despite improving performance. A four-stroke heavy-duty V6 diesel engine YAMZ6566 with displacement 12 L, bore/stroke 130/140 mm, compression ratio 17.5, rated power 197 kW at 1900 rpm, maximum torque 1124 Nm in range from 1100 rpm to 1500 rpm used with fuel injection pressure of $P_{max} = 1600$ bar, with $P_{\text{max,boost}} = 1.5$ bar, at $20 \pm 4^o C$ before pumping with the load instrumentation section made according to the standards of UN49-06 standard. In this standard, an in-cylinder pressure measurement of 25 and 100% loading at heavy-duty rpm of 1450 is recommended for HD dual-fuel engine. The double-shell piezoelectric pressure transducer with highest gauge of 250 bar is used for high pressure in the combustion chamber while intake and exhaust pressure are measured by another piezoelectric transducer up to 10 bar [19].

According to review information by Siti et al. [20], incorporating various sensor monitoring systems using advanced engine control strategies to corresponding engine parameters and adjusting fuel injection timing, quantity, and duration aided to capture enhanced fuel efficiency, reduced emission, and increased power output [20].

The Hunicz et al. [18] experiment used 99 percent hydrogenated vegetable oil from nonedible sources, with the remaining fraction of lubricant evaluated in the Neste's commercial renewable diesel engine and compared to EN 590 diesel fuel, both of which were free of FAME. The heat release rate and mass fraction burnt results show that neither EGR nor MAP (manifold absolute pressure) had a significant impact on the combustion, with similar fast oxidation propagation beginning at TDC and incorporating both premixed and diffusion-controlled combustion with stratification/spraying. The heat release rate curve depicts a clear transition point with distinct fuel-type and mixing condition-dependent position toward the end of premixed combustion [18].

Based on experimental findings by Dempsey et al. [11], high-octane fuels methanol and di-tert-butyl peroxide (DTBP) were employed in the GM1.9 L engine, and robust mixing was guaranteed, resulting in the mean indicated pressure and gross indicated efficiency stated in Eq. (4) [11].

According to review by Dan et al. [2], employing fuel stratification analysis (FSA) methodology to establish combustion parameters, with its assumptions and validation using both reacting and nonreacting 3-D CFD simulations, is recommended. Premixed mass fraction and primary reference fuel (PRF) number formulae, assumptions of equal pressure in the cylinder, and validation results of probability density function (pdf) and fsa with reacting cfd pressure, temperature, and mass fraction are all used to calculate the (PDF) of various variables of interest [1]. The heat transfer characteristics experiment conducted by Olmeda et al. [1] on a premixed compression ignition (PCI) reactivity controlled compression ignition (RCCI) engine using light-duty 1.9 liters a single-cylinder diesel engine (SCE) with a geometric compression ratio of 17.1:1 and fixed swirl ratio (the ratio of tangential to axial velocities) of 1.4, equipped with a distributed thirteen 25-K type thermocouples [2].

6. Advanced technologies and strategies for low-temperature combustion

The popular recent technologies such as hydrogen fuel and electric battery vehicles require substantial electrical grid infrastructure along with large storage/transport/filling-station investment and their lifecycle emission is still high. The high octane number fuels (volatile renewable alcohol fuels and resistant to auto-ignition fuels) are expected to compete with those alternatives by undergoing performance enhancement and emission reduction efforts. Dempsey et al. [11] maintained rate of injection from diesel data while modifying the profile for density that the computational fluid dynamics (CFD) overpredicted the spike, which suggests the injection is during ignition delay period [11].

Advanced combustion refers to the study of combustion characteristics and flame stability aimed at reducing resultant pollutant emission to reverse the effect of global warming associated with the conventional combustion. It incorporates low-temperature combustion: refers to combustion maintained at lean-fuel conditions *via* premixing and preheating to enhance efficiency and reduce emissions, catalytic combustion: combustion at accelerated rate through addition of catalysts to enable LTC and reduce emission, carbon-free combustion: use of no or reduced CO_2 fuels or technologies that capture CO_2, and use of an accurate modeling and instrumentation: such as hot-wire anemometry and laser Doppler velocity meter for flow measurement, gas chromatography, and Fourier transform infrared spectroscopy for fuel gas species analysis, and resistance and bi-metallic strip thermocouples along with infrared thermography for temperature measurements [7].

A significant increase in research interest in advanced compression ignition (ACI) engines operating in the low-temperature combustion regime is seen due to their diesel-like thermal efficiency and low emissions. Thorough mixing and preinjection were used with a high octane fuels such as methanol, ethanol, and di-tert-butyl peroxide (DTBP) in reference to n-heptane and iso-octane. Low-temperature regime manifested by the changes in fuel ignition delay iso-contour and engine thermodynamic trajectory measured by parameters such as motor octane numbers (RON and MON) and octane sensitivity (OS), and effects of engine operating condition, e.g., intake conditions, global equivalence ratio and level of exhaust gas recirculation (EGR). Mingyuan et al. [21] found that the ignition occurs t = 1.49 ms, second-stage that thermal-chemical conditions do not deviate much from the initial values before the first stage ignition occurs employing the classical Zeldovich reactivity gradient theory to model advanced compression ignition engine in the low-temperature combustion regime in 1-D to explain the auto-ignition with thermal and concentration stratification using reacting CFD flow model and n-alkane fuel (n-heptune) [8].

A review by Dan et al. [2] on fuel stratification analysis (FSA) methodology, its assumptions, and its validation using both reacting and nonreacting 3-D CFD simulations employing methods of calculating the probability density function (PDF) of various variables of interest, such as premixed mass fraction and primary reference fuel (PRF) number (typically used to determine ignition delay of blend against reference), assuming uniform pressure in the cylinder, and validation results of pdf and fsa with reacting cfd pressure, temperature, and mass fraction [1].

The experimental research by Jun et al. [7] on combustion characteristics of ammonia as a carbon-free fuel, its advantages as alternative fuels capabilities with outstanding performance, durability and reliability, optimize combustion properties, and lower pollutant emissions, and challenges such as the lack of understanding of the NH3 combustion characteristics, methods of combustion enhancement, and optimization of NOx formation in combustion (page 2), and problems such as low burning velocities and high NOx emissions and methods for optimizing its combustion properties, because page 11 suggest the only existing numerical simulations using mechanisms usually overpredict or underpredict when compared with those obtained during actual combustion processing, which not yet done.

The experiment conducted on heavy-duty (HD) dual-fuel engine by Zuev et al. [19] investigated the fuel injection parameters such as spilt injection, pressure rise rate and heat release rate (HRR), and reduction in the emissions to improve the efficiency of start of injection while maintaining its gain of enhanced compression work and NO_x emission reduction. An optimized injection strategy using ECFM-3Z models comprising: the breakup, evaporation, and spray-wall interaction models of 25.4% fuel preinjection with equally divided two crank angles (the second at 70 and the first at 10 $^o\alpha$) retarded with 5 $^o\alpha$ at bottom dead center (BTDC) pilots, 67.3% fuel a main injection along with a 7.3% post-injection that led to decrease in pressure rise rate and NO_x emission by 20 and 10% with increase in PM by 5% developed compared to the default two stage injection with similar settings utilizing diesel fuel and biofuel (rape methyl ester). This was achieved by only monitoring one injection while maintaining the others on the CFD and verified by the experiment without automation [19].

Fuel stratification, according to Dan et al. [2], has sparked a lot of attention because of its potential for great thermodynamic efficiency and low fuel use. As a result of lower heat transfer losses and lean air-fuel mixes, the possibility for great thermal efficiency with minimal pollutant emissions exists. The novel fuel stratification analysis (FSA) method, which uses the first law of thermodynamics and assumes a homogeneous mixture in each cell of the computational domain, and t fuel is injected at a constant rate throughout the injection event, can determine the required distribution of fuel required to achieve an optimal heat release profile without extensive and costly experimental or modeling effort. The reacting CFD pressure, temperature, and mass fraction burned profiles were used as input conditions in the FSA analysis to predict ignition locations and the representative fuel distribution versus the nonreacting 3-D CFD simulation (used to generate PDFs of fuel distributions for various injection timings and initial conditions/to model fluid flow and heat transfer without considering a reaction) [1].

In the Polish standard (PN-EN 14214), the FAME ester is produced *via* transesterification of rapeseed oil triglycerides with methanol. This report also summarized how FAME's high viscosity and density affect the injection and mixing processes, with the more oxygen content having the potential to contribute more spontaneous intensive ignition and complete combustion as fuel blends with 10, 20, and 50% volumetric content having delayed ignition with maximum heat release rates. The injection is electronically controlled by the crank load and speed and the air intake system is used with variable geometry turbocharger to improve the cylinder filling over the whole range of crankshaft speed. The change of fuel blend content is enabled by four valves attached to each cylinder controlled by two camshafts. Smart measurement systems are used to measure fast-changing values, with smart data acquisition system piezoelectric pressure transducer inside the cylinder and tensometric pressure sensor in the injection lines. The test was conducted in various configurations of load $10 - 60Nm$ and fuel composition of 5, 10, and 50% fuel dose with crankshaft rotation of 5, 10, 50, and 90% [12].

Shortened ignition time registered for with FAME blend obtained between 10 and 60 Nm with 5, 10, and 50% FAME composition. A significantly higher HRRs with p_max wave recorded between only in the range 10-40 Nm and otherwise the same trend for crank rotation [12].

The ultra-low sulfur diesel (ULSD) experiment conducted using hotter premixed combustion was preceded by regulated pilot injection of at $25^o \leq 20\%$. The use of ultra-low sulfur diesel (ULSD) in hot premixed combustion reduced the combustion noise while all pilot injections appeared beneficial with significant variations for medium 9 Nm load, and significant increase in particulate matter with increased combustion diffusion noticed without NO_x reduction. For cleaner combustion, the larger load necessitated less premixing. For cleaner combustion, the larger load necessitated less premixing. The base-fuel consumption improved due to slower isobaric premixed diffusion (due to density and viscosity) with load for biodiesel at less than 9 Nm load, but with increased main combustion temperature and increased soot emission (PM/HC), ULSD demonstrated no dramatic peak temperature rise with fuel with load with improvements or no change in base specific fuel consumption (BSFC) in all multiple phase injections.

While a single injection trial demonstrated no benefit for biodiesel over ULSD. The higher the load, the higher the BSFC for the biodiesel, which was reported to be improved with delayed main injection. Regulating mean effective pressure discovered a relevant way to improve BSFC [14].

6.1 Advanced engine design and control

As the discussion so far mainly focuses on LTC, the recent automotive industries witnessed significant advancements in diesel engine technologies driven by improved fuel efficiency and reduced emissions. The LTC approach gained significant attention because the combustion process that occurs at low pressure and temperature enabled significant reduction in NO_x and particulate matter emissions when compared to conventional diesel combustion.

The review by Siti et al. [20] revealed that some of the modifications such as using **multiple injections** (splitting the fuel into several smaller injections during the combustion process to reduce emission and improve fuel efficiency), **high-pressure common rail injection systems** (−delivers fuel to multiple injectors aiding precise control over the timing and amount of fuel injected into the engine to increase efficiency and reduce emission), and **swirl chambers** (to help fuel atomization and mixing with air to attain complete combustion) reported to have enhanced engine performance and reduced emission as well as enhanced fuel properties and overall combustion [20].

Norouzi et al. [22] developed a three-step multi-objective system model predictive control to accurately optimize complex thermo-kinetic reaction and non-linear turbulent flow inside the compression ignition internal combustion engine, incorporating various linear and semi-infinite non-linear models as well as real-time optimization, and achieved 40% compression ignition engine performance enhancement with 10–15% emission reduction, which was experimentally validated [22].

M. Elkelawy et al. [23] summarized the effect of nano-fluid additives on diesel/biofuel (B20-D80) blend and revealed that high heat release, high combustion, high thermal conductivity, and high oxygen content that percentage content increase with oxide of nano-graphene at 30, 60, and 90 ppm as well as reported on-going research in $Al_2O_3, TiO_2,$ and CeO_2 nanoparticle lead to a reduction in brake specific fuel consumption (BSFC), a reduction in all emissions, and an increase in brake thermal efficiency [5].

According to experimental studies by Antonio et al. [3], some of the most promising modifications to diesel engine fuel injection systems and combustion chambers to improve low-temperature combustion performance include *reactivity-controlled compression ignition (RCCI), homogeneous charge compression ignition (HCCI), and dual-fuel combustion*. These modifications have been validated through experiments and simulations. For example, it compared RCCI, HCCI, and CDC operation from low to full load in a diesel engine, while reviewing the impact of low-temperature combustion attaining strategies on diesel engine emissions for diesel and biodiesels [3].

Low-temperature combustion, therefore, relies on achieving controlled and homogeneous air-fuel mixing involving advanced fuel injection strategies, optimized air-fuel mixing, and precise combustion phasing control with key considerations such as fuel injection systems and air management.

7. LTC transport sectors applications in diesel engines

The model test for light-duty diesel transport (LDDT) and heavy-duty diesel transport (HDDT) by Mahesh et al. [24] revealed higher gaseous emission than standard and less for medium duty (MDDT) [17]. In an attempt to minimize the impact on greenhouse gases (GHGs) in short to medium term, the life cycle analysis (LCA) results revealed that natural gas claimed to be more reliable, affordable, and economical for HDDT and MDDT than diesel, while natural gas and LPG accessibility to fuelling station were still limited yet they offer cleaner combustion for vehicle applications, whereas more dense liquefied natural (LNG) offers more mileage over compressed natural gas (CNG), but demands complicated cryogenic infrastructure. Yet further reduction in carbon footprint possibility offered by switching to renewable natural gas without significant impact [25, 26].

Fats and oils pyrolyzed lower pour point, flash point, viscosity, and comparable calorific value to diesel. The diesel engine has continued to be the prime mover of the commercial heavy-duty road transport and marine vehicles since last century due to its high energy density and lengthy intervention, with the twice viscous fatty acid methyl ester (FAME) being the major 32% contributor, biofuel currently share of only 4% of the world transport energy demand [18].

Hansson et al. [27] conducted multi-criteria decision analysis for alternative marine diesel fuels and found that liquefied biogas, methanol, and bio-fuels as the most sustainable fuels. The MCDA, analytic hierarchy process (AHP) tool for managing complex decision problems and is used to find the optimal and most consensual solution by assessing interests and preferences alongside qualitative and quantitative information, approach involved identifying and weighting various criteria related to economic, technical, environmental, and social aspects of the different fuels. The authors also considered the influence of stakeholder preferences on the assessment. To gather data on stakeholder preferences, the authors conducted a survey of Swedish stakeholders involved in the maritime sector, including shipowners, fuel suppliers, regulators, and researchers. The survey responses were used to develop a set of scenarios reflecting different stakeholder perspectives. The authors suggest that a combination of different alternative fuels, such as biofuels, methanol, and liquefied natural gas (LNG), could be used to reduce emissions and meet environmental targets [4].

Ammonia has a far greater absolute minimum ignition energy than gasoline, making it safer to handle and carry, according to Jun et al. [7]. Furthermore, ammonia has the potential to be utilized as a fuel with performance comparable to traditional fuels such as gasoline and LPG. The driving range of an internal combustion engine using ammonia directly can reach 592 km, which is somewhat less than that of gasoline. Furthermore, because ammonia is a carbon-free fuel, it has the potential to minimize greenhouse gas emissions and reliance on fossil fuels [7].

Regardless of their recent growing concerns about fuel consumption, which necessitates extensive research into strategies such as delayed main injection, premixing, and further particulate-matter reduction, biofuels are expected to be major sources of transportation energy primarily for aviation, shipping, and heavy-duty road transport (trucks) rather than in light-duty vehicles [28, 29], where recent investments have encouraged pollution reduction, cleaner air, and optimum LTC combustion. According to Hunicz, hydrogenated vegetable oil derived from nonedible feedstock can fully utilize existing fuel infrastructure and is currently available as a stand-alone, drop-in fuel for diesel at over 500 filling stations in Europe and North America, with a 90% reduction in well-to-wheel carbon dioxide (CO_2) emissions when compared to diesel oil [18].

8. Future perspectives and research directions

While the LTC concept has been around for some time, the research continues to explore new dimensions and research perspectives with goal of further emission reduction, fuel flexibility, engine efficiency, combustion stability and control, and modeling and simulation. According to Antonio et al. [3, 30], more research is needed to thoroughly assess the possible benefits and drawbacks of various emission reduction methods for diesel engines, including low-temperature combustion. In addition, the report offered experimental data and analysis of various injection strategies for low-temperature combustion, which might be used as a starting point for future research [3, 9].

According to Hansson et al. [27], there is a rising interest in decreasing greenhouse gas emissions from the shipping industry, which has resulted in greater research and development of alternative fuels and propulsion technologies. It is suggested that the development and deployment of more flexible dual-fuel engines on ships is boosting fuel compatibility and, to some extent, lowering the risk of technology lock-in. Hansson et al. [27]. A dual-fuel engine, in general, can run on two or more distinct types of fuel, such as diesel and natural gas [3]. To accept the different fuels, the engine's fuel injection system, ignition system, and other components may need to be modified. The particular adjustments required may vary depending on the type of engine and fuels used [4].

Due to scattered information in multiple-zone chemical kinetics-based chains of models for low-temperature combustion (LTC) engines, the reactivity controlled compression ignition recommended for accurate model and simulation of LTC and examined to fulfill the following requirements of LTC:

1. Premixed air fuel, and

2. In-cylinder lean charge

A HCCI proved to have less NO_x emission than stoichiometric oxidation with localized low-temperature combustion that gave rise to multi-zone models. The ignition timing and HC/CO emission model of HCCI contains 291 species and 875 reactions but takes 3X as long as PRF20 model. A complete and accurate modeling requires coupling a set of submodels with multi-zone simulation that involves

1. Zero-dimensional gas exchange model: that captures the effect of variable valve actuation

2. Wall temperature model: enhancing the prediction of thermal stratification,

3. Simple rate-driven injection and fuel evaporation routines

4. Blow-by models or knock prediction functions

8.1 Alternative fuels for low-temperature combustion

On the other hand, Hansson et al. [27] conducted multi-criteria decision analysis and model estimation for alternative marine diesel fuels and revealed that the flexible dual-fuel engines can operate on two or more different types of fuel. In the context of the study, these engines are important because they increase the compatibility of different fuels with marine engines and reduce the risk of technology lock-in. The analysis report explained that the development and introduction of more flexible dual-fuel engines on *ships* is increasing fuel compatibility and reducing the risk of technology lock-in to some extent. This means that as more flexible dual-fuel engines become available, it may be possible for ships to switch between different types of fuels depending on availability, cost, and environmental considerations [4].

Using a high octane fuel with a combined prechamber injection and direct high-pressure injection offer stable combustion, improve efficiency (thermal/engine), and reduce emission; prechamber enables controlled combustion through prolonged mixing due to late oxidation during compression at top dead center (TDC), whereas high-octane fuels enable higher compression ratio and more advanced combustion control timing [11].

Hansson et al. [27] advise policymakers and industry stakeholders to collaborate in developing a supportive regulatory framework and infrastructure for alternative fuels. Finally, while implementing alternative fuel options, the authors underline the significance of taking stakeholder preferences into account and engaging in transparent decision-making processes. When implementing alternative fuel options, the authors underline the significance of taking stakeholder preferences into account and engaging in transparent decision-making processes. It should be noted that upgrading existing engines with dual-fuel capabilities is costly and may not be viable for all ships. However, when more versatile dual-fuel engines become available on the market, shipowners may find it easier to switch between fuel types without requiring extensive engine modifications [4].

Elkeway [5] proposes several promising future research directions in the field of diesel engine combustion using response surface methodology, with the goal of developing more efficient and environmentally friendly diesel engines that can meet increasingly stringent emission regulations while maintaining high levels of performance [5]:

1. Investigating the effects of different *types and concentrations of nanoparticles* on engine performance and emissions. Investigation of the impact of advanced combustion concepts such as LTC on engine performance and emissions.

2. Studying the impact of various *injection strategies*, such as multiple injections, on engine performance and emissions.

3. Exploring the *use of alternative fuels*, such as biofuels and synthetic fuels, in diesel engines to reduce emissions and improve efficiency.

4. Developing *new models that can accurately predict engine performance and emissions* under a wide range of operating conditions.

5. Investigating the impact of advanced combustion concepts, such as low-temperature combustion and homogeneous charge compression ignition (HCCI), on engine performance and emissions.

Furthermore, advanced combustion concepts, described in **Table 1**, powertrain integrations such as EGR, sustainability, and renewability are parts of future research direction. Overall, the LTC research will revolve around emission reduction, fuel flexibility, efficiency improvement, stability and control, and modeling and simulation as seen in the above literature.

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Chapter 6

Performance, Combustion, and Emission Characteristics of a VCR Engine Powered by Corn Bio-Diesel

Senthil Kumar Kandasamy

Abstract

The step-down of petroleum fuels has forced researchers to identify alternative fuels in the industrial and transportation sectors to satisfy energy demands. The most frequently used fuel alternative in compression ignition engines is methyl esters derived from vegetable oils. The present work aims to examine the performance, combustion, and emission characteristics of corn oil blends in a variable-compression-ratio engine. The Corn bio-diesel blends B20, B40, B60, B80, and B100 were compared with diesel for compression ratios of 13:1 and 14:1. The same blends were used in the experiments. The results of various parameters, such as brake thermal efficiency, specific fuel consumption, and emissions, showed that B100 had better outcomes than diesel. The average cylinder pressure and heat release rate compared with those of different blends and diesel at a compression ratio of 14 were also used in this study.

Keywords: corn oil, VCR CI engine, combustion, emission, diesel engine

1. Introduction

Corn's abundance and relatively simple conversion to ethyl alcohol (ethanol) make it a preferred feedstock for ethanol production in the United States. Although ethanol has been produced from corn and other high-starch cereals for thousands of years, the usage of these grains as fuel has increased significantly in the last century. Grinding, heating with enzymes, fermenting with yeast, and distilling to extract the water are all steps in the conversion process.

Two more processes are involved in fuel ethanol production: denaturing the ethanol to render it unfit for human consumption and utilizing a molecular sieve to extract the remaining water. After trans-esterification, corn oil can be utilized as biodiesel in compression ignition (CI) engines. Impact of residual gas trapping on the emissions and part-load efficiency of a wet ethanol-fueled spark-ignition direct-injection engine [1]. Experimental research and simulation were conducted on the impacts of blending diesel with waste-cooked oil methyl ester. Mohamed et al. [2] have published on the performance and emission characteristics of diesel engines. Researchers examined the efficiency and burning properties of diesel engines running on mixtures of waste-cooked biodiesel and grape seed [3], and the effects of changing the WCO/LDO blending ratio on exhaust emissions, combustion efficiency, and flame characteristics were studied. The range of the blending ratio was 0 to 100%. The equivalency ratio for each blend ranged from 0.6 to 1.05. The studies were carried out inside a cylindrical combustor that was cooled by water and equipped with a waste-oil burner that was positioned coaxially [4]. It has been documented that the combustion and emission properties of various generations of biodiesel can affect the performance of a compression ignition engine [5]. Using an electronic fuel fumigation approach, researchers have experimentally studied the performance and emission characteristics of compression ignition engines [6]. A single-cylinder compression-ignition (CI) engine was used for experimental research on pure diesel fuel and fuel oil-diesel fuel combinations. The engine's performance, combustion, and exhaust emission characteristics were all studied [7]. Various diesel-biodiesel mixes and their glycerin emulsions have been examined for performance and emissions [8]. With a unit capacity of close to or above 200,000 tons/year, the most economical method of producing green diesel in a petroleum refinery looks to be catalytic hydroprocessing. Under supercritical circumstances, the profitability of conventional ester biodiesel and noncatalytic ester biodiesel processes is lower at a given capacity. Ten years into the project lifetime, the unit capacities of the examined processes—less than 100,000 metric tons annually—are probably going to produce negative net present values [9]. It has been shown that using renewable diesel fuels can assist address issues with urban air quality while also reducing particulate matter and climate-warming emissions from transportation [10]. Using Taguchi techniques and varying operating conditions, the performance of a tiny Kirloskar diesel in an internal combustion engine was investigated. The test engine's NOx emissions were monitored with an AVL gas analyzer. Ramesh Babu et al. [11] examined how a thermal barrier-coated piston affected the operation and emissions of a diesel engine running on diesel fuel. Vidyasagar Reddya et al. [12] investigated the novel and distinctive acacia biodiesel's engine performance and emission properties [13].

Examined how a biodiesel derived from palm oil and an antioxidant ingredient performed in engines and what kind of emissions it produced [14]. Measured and compared with plain diesel emissions were the emissions of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NOx), hydrocarbons (HC), acetaldehyde, and formaldehyde from various mixtures. According to the test results, B20S2 has the lowest cloud point (34.8°C) of all the gasoline blends. Additionally, it was discovered that synergy could alter the biodiesel-diesel blend B20's crystal structure and size [15]. This study examined the production, efficiency, combustion, and emission properties of diesel and corn oil combined in a VCR engine at various load levels.

2. Experimental setup and methodology

2.1 Corn biodiesel production and characterization

A nearby merchant in Hyderabad provided the corn oil. The free fatty acid (FFA) content of the maize oil was 4.75%, which was more than the permitted 2% level. A snapshot of the biodiesel production facility is displayed in **Figure 1**. Methanol and catalyst concentration (NaOH) were used in a transesterification process that lasted 60 minutes at 65°C. Bulk corn oil was made in accordance with these parameters.

Figure 1.
Experimental setup of a bio-diesel producing plant.

To reach the required FFA content, more stirring was done for 20 minutes. After the required amount of biodiesel from maize oil was obtained, the glycerol, which can be used for further purposes, was separated from the biodiesel by gravity for a duration of 12 hours. In addition, the obtained biodiesel contained contaminants like NaOH and methanol. The elimination of these contaminants by hot distilled water washing of the sample is demonstrated in **Figure 2**. Once more, heating was done for 25 minutes at 100°C. Finally, a translucent, pale-yellow liquid was created that was based on corn for biodiesel. The diesel was mixed with various amounts of oil to test its miscibility. After fifteen days of observation, there were no indications of separation.

The test samples (a total of 5) with a 1000 ml fuel each were named B20, B40, B60, B80, and B100 according to the reference diesel fuel (by volume) and their blending proportions of 20, 40, 60, 80, and 100%, as indicated in **Figure 3**. **Tables 1** and **2** list the attributes of the combined maize oil and diesel, as well as the compositions of the blended fuels.

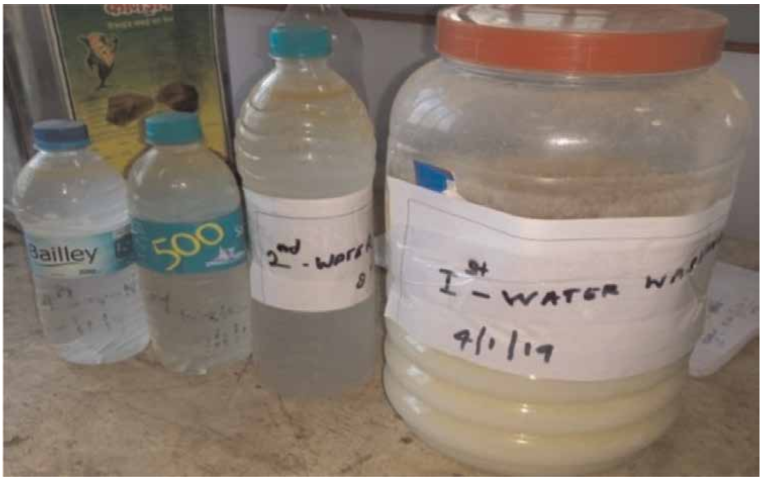

Figure 2.
The samples used to remove traces of methanol and NaOH.

Figure 3.
The blended fuels B20, B40, B60, B80, and B100 used.

Blended fuels	Compositions
B20	20% Corn Oil +80% Diesel
B40	40% Corn Oil +60% Diesel
B60	60% Corn Oil +40% Diesel
B80	80% Corn Oil +20% Diesel
B100	100% Corn Oil
Base Fuel	Diesel

Table 1.
Compositions of blended fuels.

Properties	Diesel	Blended corn oil					Test protocol
		B20	B40	B60	B80	B100	
Density (kg/m^3)	840	830	845	816	862	879	IS 1448 (P-16), 1990
Calorific Value (MJ/kg)	44.8	39.87	37.06	37.31	36.20	35.20	IS 1448 (P-6), 1984
Flash Point (°C)	50	56	58	60	61	60	IS 1448 (P-21), 1992
Fire Point (°C)	56	61	63	63	65	64	IS 1448 (P-20), 1998
Kinematic viscosity (mm^2/s)	2	4.68	5.28	6.10	6.24	7.26	IS 1448 (P-25), 1976
Pour Point (°C)	6	3	4	4	4	5	IS 1448 (P-10), 2012
Cetane Number	50	59	63	57	69	63	IS 1448 (P-19), 1989

Table 2.
Properties of fuel and test protocol.

2.2 Experimental setup and operating procedure

Figure 4 shows the experimental configuration employed in this investigation. An engine with a single cylinder and four strokes with a variable compression ratio was employed for the experiment. The cylinder's clearance capacity was changed by

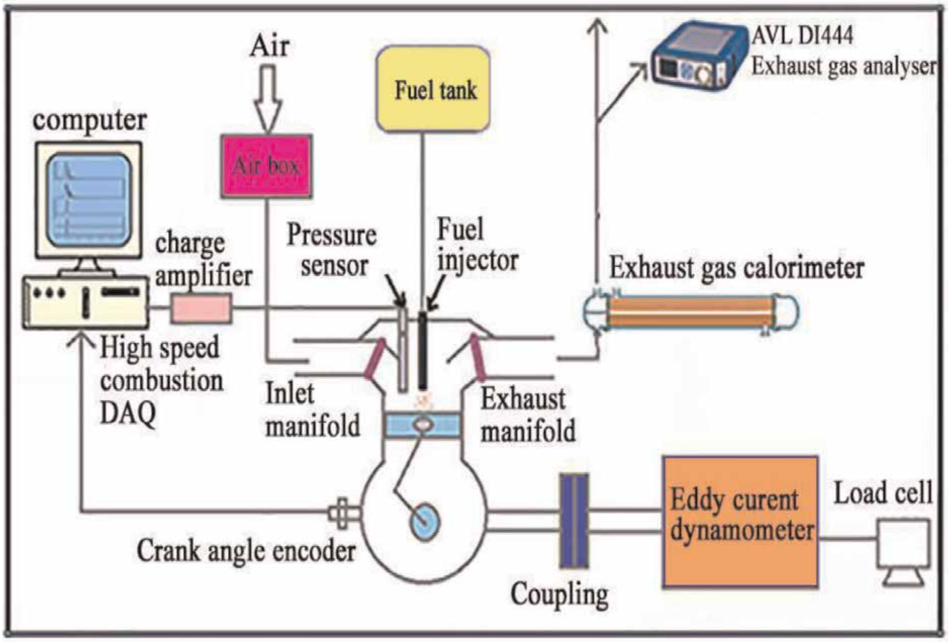

Figure 4.
Schematic of experimental setup [16].

pulling a lever, which alternated the compression ratio. A heat exchanger that served as a calorimeter was subjected to the exhaust gas. An exhaust gas analyzer called the AVL DI 444 was used to measure the emission parameters. An encoder fixed with a timing gear was used to monitor the crank angle, and a piezoelectric pressure sensor was installed on the cylinder head to measure the combustion pressure. Using a computer with a high-speed data gathering system, the parameters, including cylinder pressure, temperature, heat release rate, and so forth, were recorded at all the significant places. The experimental setup was preconditioned by running the VCR on diesel for fifteen minutes. Cooling water was supplied to the setup at a steady 100 LPH rate. As is customary, the engine was run for seven to ten minutes to stabilize it following any fuel blend changes. By mechanical injection, the fuel was injected at a temperature of 23° prior to the TDC and at a pressure of 200 psi. Brake power (BP), brake thermal efficiency (BTE), specific fuel consumption (SFC), and mass of fuel consumption were all calculated. Brake power (BP), brake thermal efficiency (BTE), specific fuel consumption (SFC), and mass of fuel consumption were all calculated. For every operating condition, measurements were made of the exhaust emission levels, combustion characteristics, and performance. **Table 3** provides a list of the engine, pressure sensor, and exhaust gas analyzer specifications employed in the experimental inquiry.

2.3 Error and uncertainty analysis

The experimental uncertainty, instrumental error, environmental conditions, and parallax error were considered during the analysis. Various parameters, such as specific fuel consumption, brake thermal efficiency, and carbon monoxide, were

Description	Specification
Variable compression ratio engine	Model: Kirloskar TV1, VCR, Single cylinder, 4-Stroke, water-cooled, stroke 110 mm, bore 87.5 mm
Power	3.5 kW
Speed	1500 rpm
Injection Point variation	0 to 25° BTDC
Maximum load	10 kg
Injection pressure	200 bar
Compression ratio range	12:1 to 18:1
Exhaust gas calorimeter	Shell and Tube, K-type thermocouple, water cooling
Exhaust gas analyzer	AVL DIGAS 444 N
Pressure sensor	Piezoelectric

Table 3.
Specifications of the engine parameters.

calculated using the percentage uncertainty of the respective instruments. The total uncertainty of the experiment is calculated using the following equation:

Total percentage of the uncertainty = $[(BP)^2 + (BTE)^2 + (CO)^2 + (HC)^2 + (O2)^2 + (NOx)^2 + (\text{crank angle encoder})^2 + (\text{Load})^2 + (\text{pressure sensor})^2 + (\text{Speed})^2 + (SFC)^2]^{1/2}$. The obtained value of total uncertainty lies in the acceptable range of $\pm 1.4\%$.

3. Results and discussion

3.1 Experimental results

Blends of corn biodiesel were tested. Diesel was contrasted with the outcomes for each of the five blends' parameters. Blends B20, B40, B60, B80, and B100 have generally better emissions, specific fuel consumption, and brake thermal efficiency than diesel. The ensuing sections provide more details on the performance, combustion, and emission features.

3.2 Brake thermal efficiency

Brake thermal efficiency can be used to assess how well the fuel's ignition quality is performing. **Figure 5** displays the BTEs of the fuels that were evaluated at various loads and compression ratios. The graphic illustrates how the BTE is greatly increased by the decrease in heat loss and the rise in brake power. The break thermal efficiency for diesel at full load at a compression ratio of 14 was roughly 22.98%, which was little less than that of the B20, B40, B60, B80, and B100. When using blends of biodiesel instead of diesel, a notable rise in BTE was noted. Diesel evaporated quickly and was easily mixed with the blends to create a homogenous mixture, which contributed to the blends' greater BTE. Diesel evaporated quickly and was easily mixed with the blends to create a homogenous mixture, which contributed to the blends' greater BTE. The blends' combustion characteristics are enhanced by the presence of oxygen.

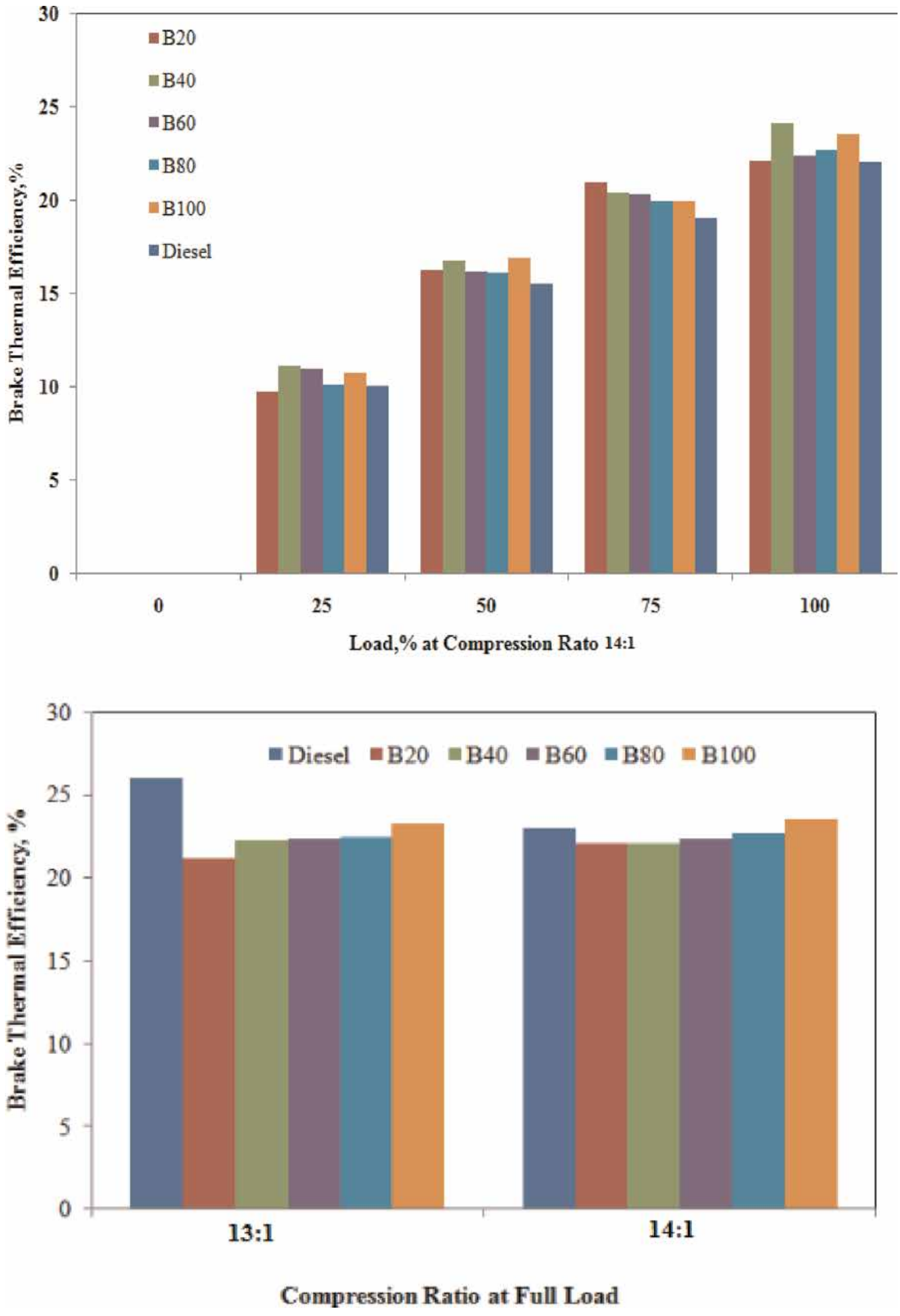

Figure 5.
Variations of brake thermal efficiency with load and compression ratio.

Diesel has a lower brake thermal efficiency (22.10%) than other mixes because of its low volatility, high viscosity, and low calorific value. All of these cause the fuel to burn poorly. The picture illustrates how the BTE of various blends of diesel grew when the CR (13 and 14) increased. One explanation for this could be that the tested fuels burn more efficiently at higher CRs due to greater compressed air temperatures.

3.3 Specific fuel consumption

Fuel economy is determined by specific fuel consumption. **Figure 6** displays the precise fuel consumptions of the tested fuels at various loads and compression ratios. For all fuels, as the braking power increased, the brake SFC dropped with increasing load. Relative to diesel, a smaller percentage of biodiesel blends (B20, B40, and B60)

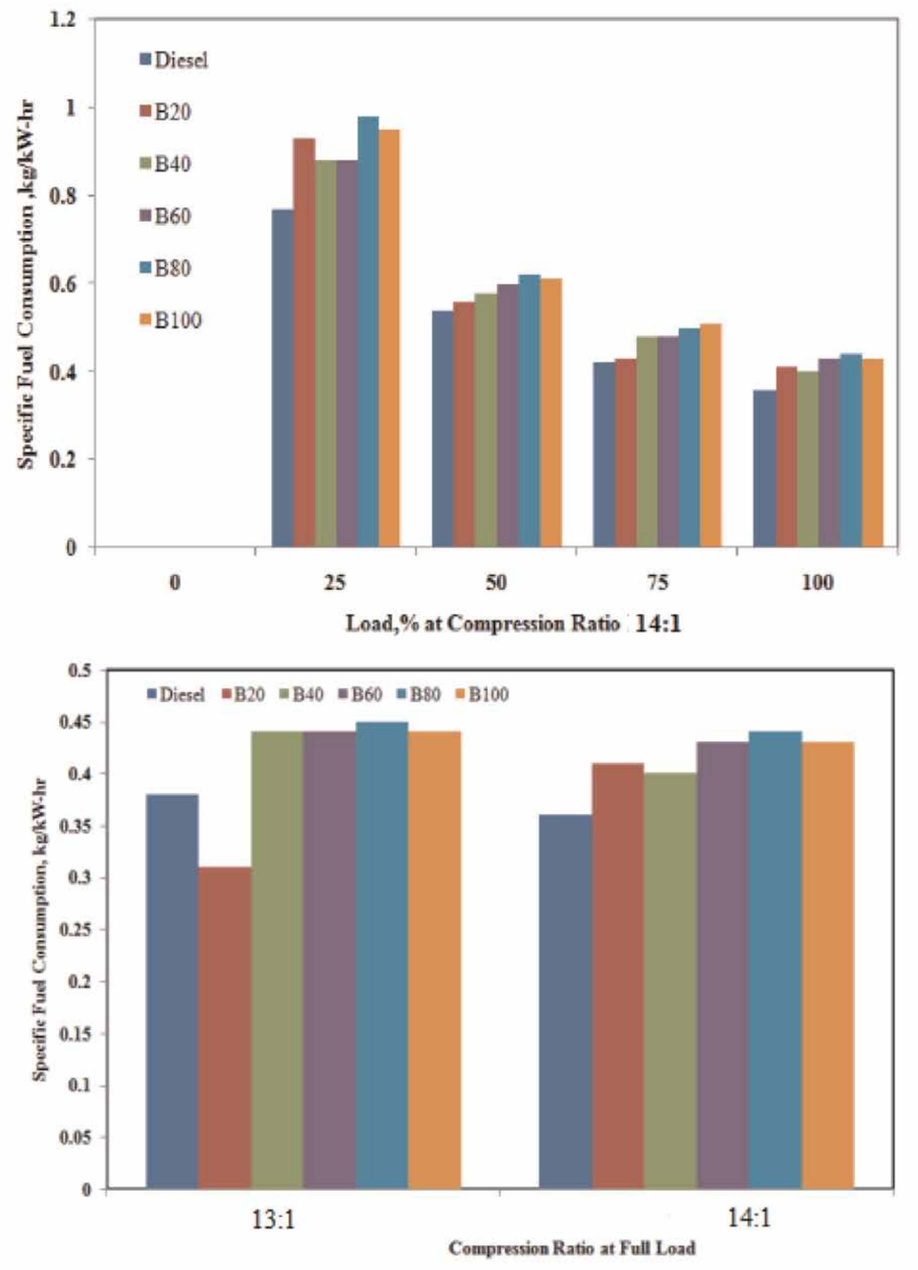

Figure 6.
Variations of brake SFC with load and compression ratio.

Fuel	Brake thermal efficiency %		Specific fuel consumption kg/kW-hr	
	CR13	CR14	CR13	CR14
B20	21.12	22.1	0.31	0.41
B40	22.14	24.05	0.44	0.40
B60	22.17	22.38	0.44	0.43
B80	21.85	22.69	0.45	0.44
B100	21.95	22.54	0.44	0.41
Diesel	22.23	22.98	0.38	0.34

Table 4.
Comparison of BTE and SFC at full load with variable compression ratio.

had no effect on the break of SFC. Diesel produced lower SFC than B80 and B100. By adding more oxygen and hydrocarbons to the blends, the rate of combustion was accelerated.

In comparison to other studied fuels, diesel's high density and poor volatility led to lower SFC. The air-fuel combination becomes lean beyond the stoichiometric area, which leads to a progressive fall in SFC as CR increases. In a compression ignition engine, the mass of fuel used will decrease up to a 75% load.

Table 4 shows the comparison of brake thermal efficiency values and specific fuel consumption values of the fuels being tested. The brake thermal efficiency of the fuels is in descending order and vice versa for SFC.

3.4 Carbon monoxide

Carbon monoxide is released when combustion is not completed. The tested fuels emit less CO at lighter loads and more CO at heavier loads as a result of the air-fuel ration decreasing with increasing load. The changes in CO emissions of the diesel and various blends operating at varied loads and compression ratios are displayed in **Figure 7**.

According to the figure, the engine produced greater CO emissions for B100 than for diesel and less for diesel. When compared to diesel (0.00% vol.) at full load, the CO emissions of B20 (0.01% vol.), B40 (0.00% vol.), B60 (0.00% vol.), B80 (0.00% vol.), and B100 (0.02% vol.) were shown to be significantly lower. Because to the poor atomization, increased viscosity, and low volatility in B100, the CO emission is higher (0.02% vol.). Because of increased pressure and compressed air temperature, a higher compression ratio results in a homogenous mixing of fuels, which lowers CO emissions.

3.5 Unburned hydrocarbons

The release of unburned hydrocarbons from an engine can be used to determine its performance. Low combustion temperatures, a weak flame, and fuel escaping from the flame zone are the main causes of HC emissions. The changes in HC emission with load and compression ratios are displayed in **Figure 8**.

In comparison to diesel fuel, it is seen that the HC emissions for blends (B20, B40, B60, B80, and B100) exhibit higher and lower values, respectively, at all loads. Increased density, atomization, and longer ignition delays cause fuel to build up in the

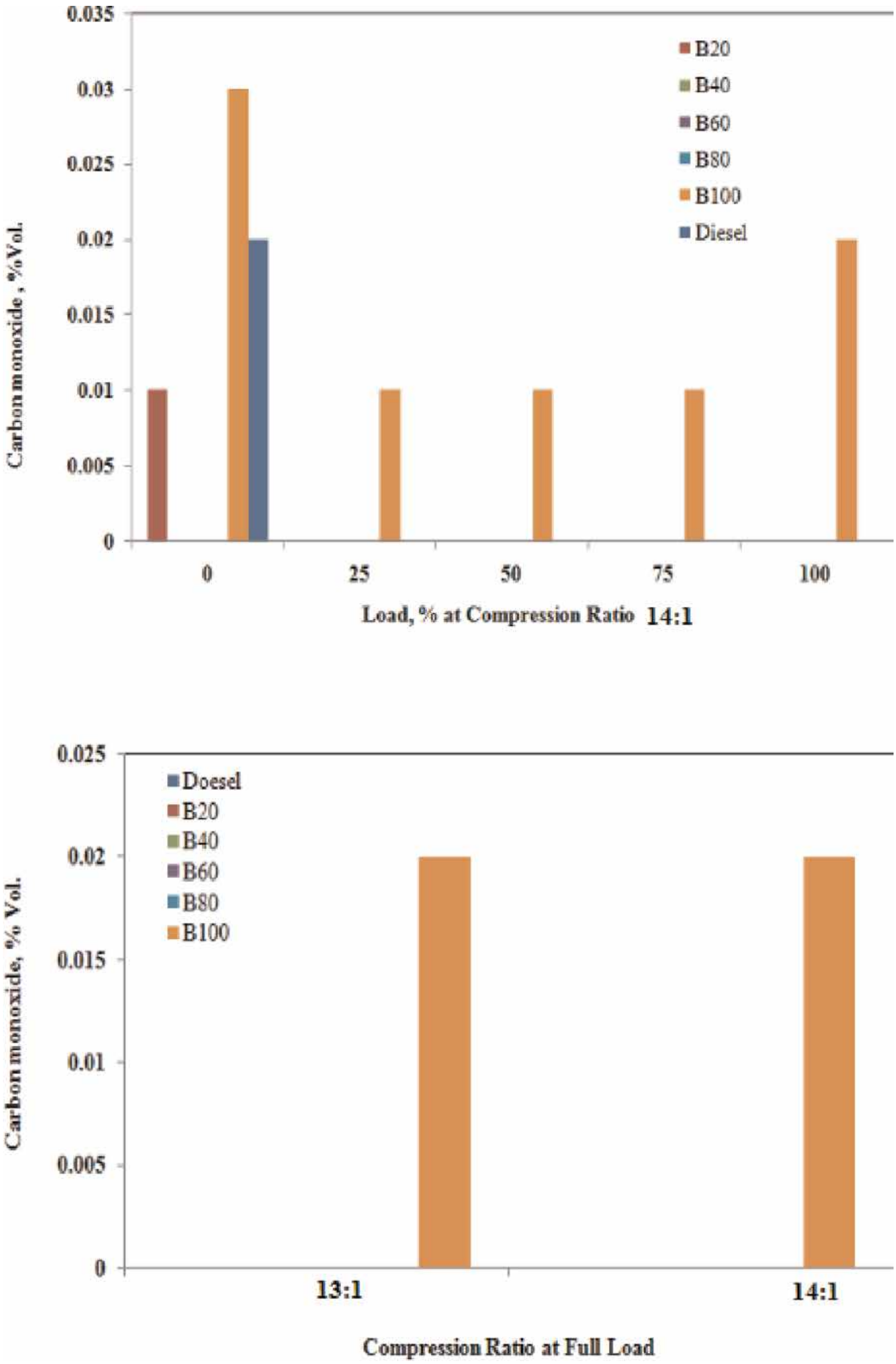

Figure 7.
Variations of carbon monoxide with load and compression ratio.

combustion chamber, which could be the cause of higher-than-average HC emissions. The mixes B20, B40, B60, B80, and B100 increase combustion rates and enrich oxygen to lower greenhouse gas emissions. Because the HC emission for the tested

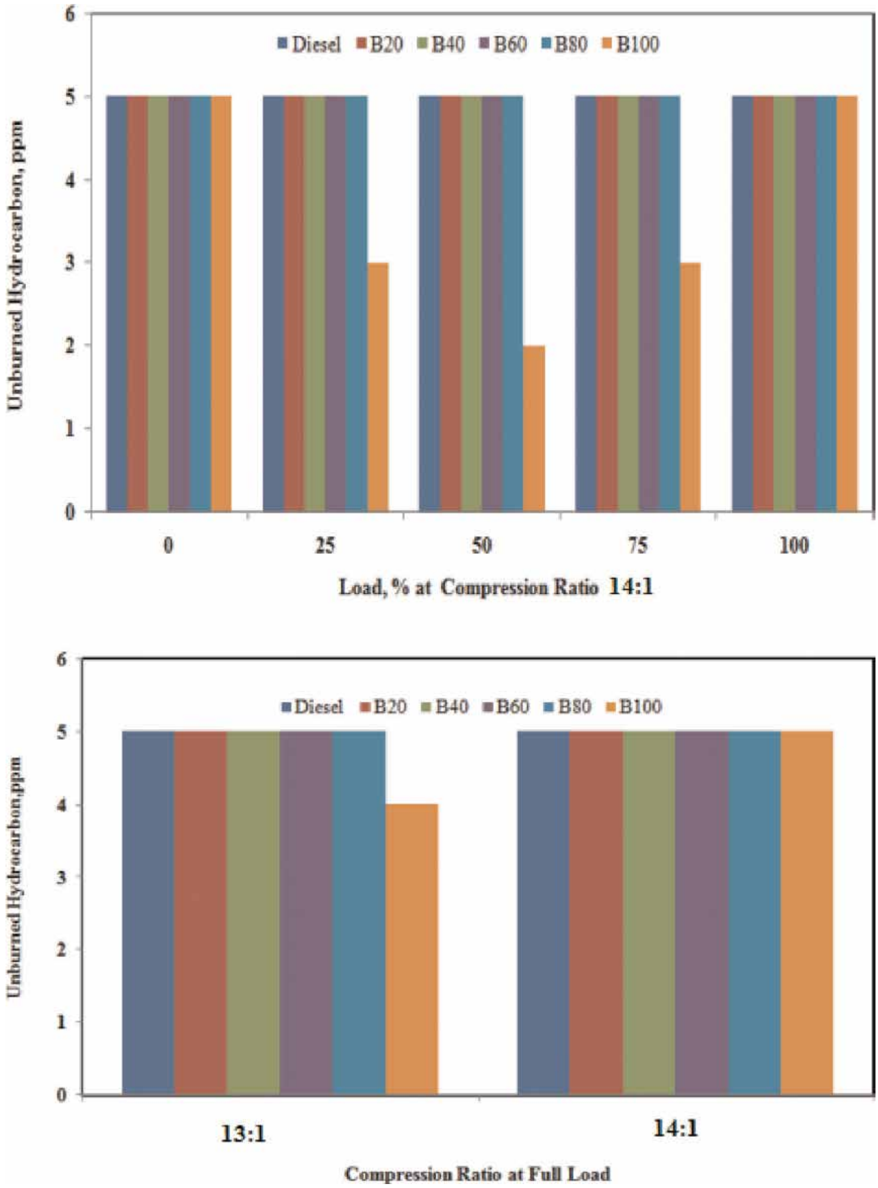

Figure 8.
Variations of unburned hydrocarbon with load and compression ratio.

fuels at full load shows a decreasing trend with regard to compression ratios, it is noticed that combustion is better at higher ratios.

3.6 Oxides of nitrogen

Nitrogen and oxygen react at high temperatures during fuel combustion to produce nitrogen oxide and nitric oxide, which are known as NOx emissions. **Figure 9** displays the changes in NOx emissions with load and compression ratios for the

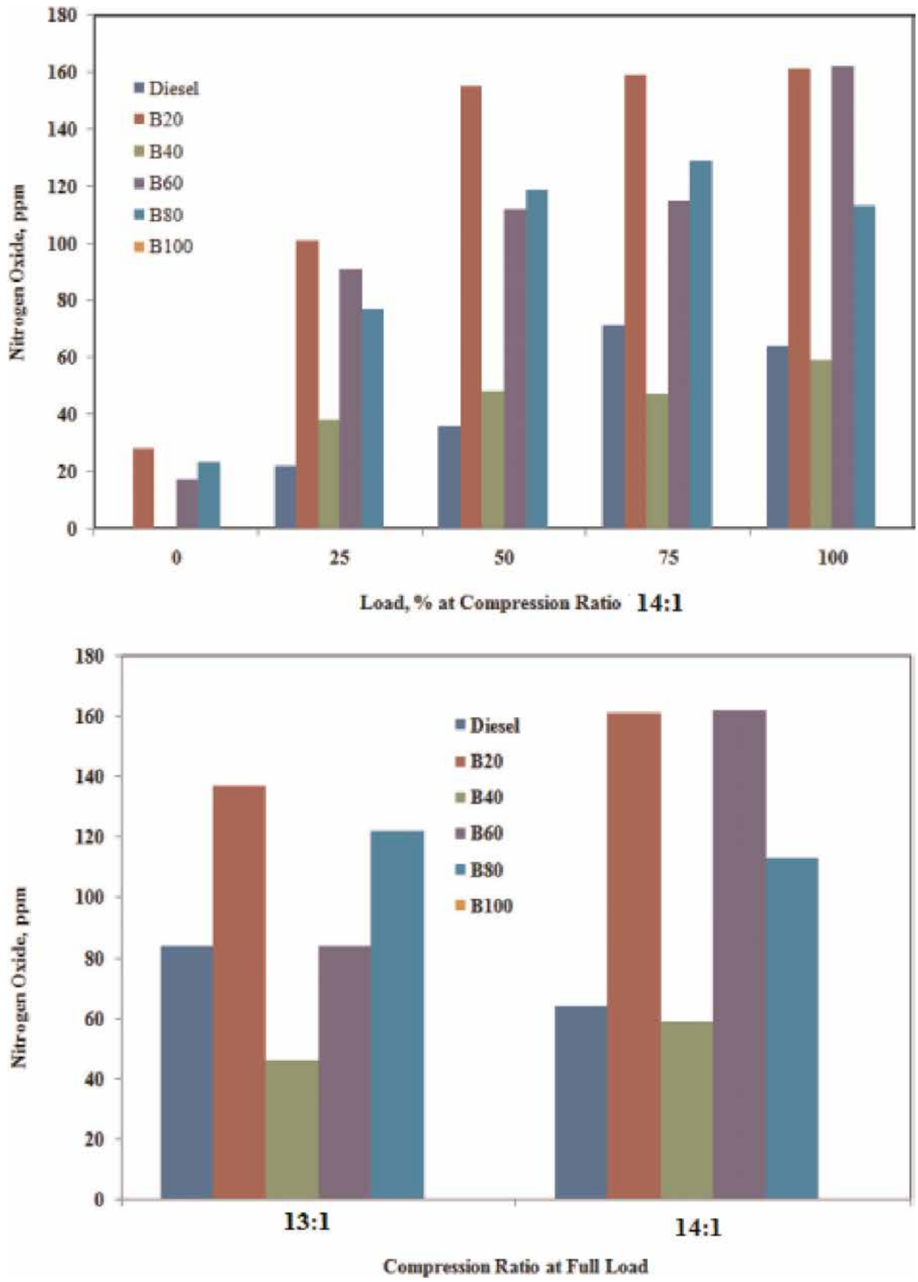

Figure 9.
Variations of nitrogen oxide with load and compression ratio.

different tested fuels. The NOx emissions rise as the load and compression ratio rise for each of the fuels under test.

Diesel and the blends (B40, B60, B80, and B100) were found to have lower NOx emissions as compared to B20. One possible explanation for the decreased amounts of NOx emissions could be the drop in flame temperature. Because of inadequate atomization and vaporization, incomplete combustion is the reason it is high for B20 fuel.

Because to their increased oxygen concentration, which caused complete combustion, B20 blends emitted more NOx into the atmosphere than diesel did. Because of partial fuel combustion at a lower compression ratio, the NOx level is lower. Because of the increased pressure and temperature of the compressed air during the combustion process, which ensures complete combustion, NOx emissions are higher at higher compression ratios.

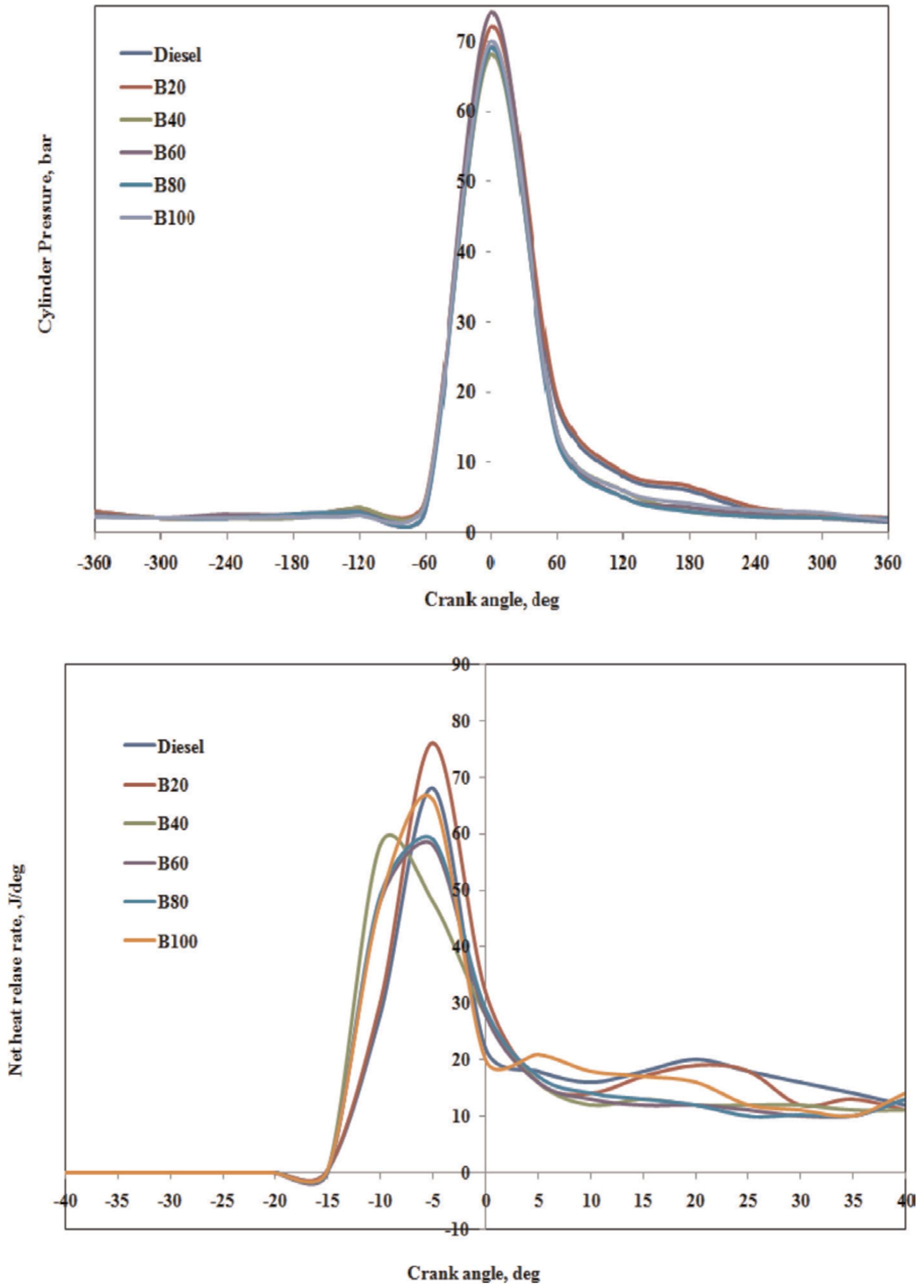

Figure 10.
Cylinder pressure and heat release rate with crank angle at CR of 14.

3.7 Combustion characteristics

The fuels' volatility, viscosity, and rate of combustion all affect how high the cylinder pressure can get. **Figure 10** displays the changes in mean cylinder pressure and heat release rate with crank angle. The graphic shows that the max cylinder pressure is lower at first and rises throughout the subsequent strokes. For the B20, B40, B60, B80, and B100, there is a little deviation in the mean cylinder pressure and heat release rate compared to diesel.

The fuel's energy content has a direct impact on how quickly heat is released. The maximal heat release rate of corn biodiesel lowers as its ingredient content rises. **Figure 10** shows that the heat release rate of diesel is higher (67.85 J/deg) than that of pure corn oil (65.08 J/deg) as a result of the lower flame temperature. Additionally, **Figure 10** shows that B100 releases heat at a slower pace than the other fuels that were evaluated. B100's increased viscosity causes the rates of fuel-air mixing to decrease.

4. Conclusions

In an experiment, different combinations of diesel and corn-based diesel (B20, B40, B60, B80, and B100) are utilized, and the compression ratio is adjusted. Blend B100 reaches a maximum BTE of 22.54%, which is higher than diesel, at full load and a compression ratio of 14:1. Furthermore, under full load, the B100's SFC (0.41 kg/kWh) is higher than diesel's (0.34 kg/kWh). With the lower blends, far less CO is being released. Biodiesel emits 0.02% more CO into the atmosphere than diesel, which emits 0.00% vol. Diesel and corn biodiesel have constant HC emissions across all loads, in contrast to mixed fuels. Compared to B100, diesel generates greater NOx emissions. Diesel releases heat at a faster rate (67.85 J/deg) than pure corn biodiesel (65.08 J/kg) because to its controlled combustion stage. Mixtures of methyl ester and corn biodiesel produce less emissions and better.

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Chapter 7

Diesel-Powered Engine and Agriculture

Ramesh Beerge and Sachin Devarmani

Abstract

Diesel engines have been instrumental in revolutionizing the mechanical, construction, transportation, power generation, and agricultural sectors, providing farmers with the energy efficiency, power, and reliability needed to maximize productivity and ensure consistent operational efficiency. In this chapter, we will explore the various benefits and advancements in diesel engines in agriculture. Diesel engines, due to their proven reliability, cost-effectiveness, and compatibility with alternative fuels, are likely to continue to play a significant role in powering agricultural machinery, enabling farmers to achieve significant savings. As technology advances, diesel engines are evolving to meet stringent emissions standards, ensuring compliance while maintaining high power output. The future of agricultural power solutions lies in integrating various technologies, ensuring that farmers have access to reliable, cost-effective, and sustainable power sources to meet the growing demands of a changing world.

Keywords: diesel engine, diesel cycle, two-stroke engine, four-stroke engine, valve timing diagram, firing order, agriculture engine

1. Introduction

Engines, the mechanical heart of modern machinery and vehicles, have powered human progress for centuries. They are intricate assemblies that convert fuel into kinetic energy, driving everything from automobiles to industrial machinery. Over time, engines have undergone remarkable transformations, aligning with technological advancements and environmental concerns. This section explores the recent developments and significance of diesel engines, a type of internal combustion engine that has played a pivotal role in various sectors. Diesel engines occupy a vital position in various sectors due to their inherent advantages. They are known for their high torque output, making them indispensable for heavy-duty applications such as transportation, construction, and agriculture. The ability to efficiently convert fuel into mechanical power allows diesel engines to excel in scenarios requiring prolonged operation and substantial load-bearing capacities. Moreover, diesel engines have a proven track record in long-distance travel and industrial processes. Their durability and reliability have earned them a place in power generation, where they provide backup electricity during outages and serve as primary sources in off-grid locations.

The significance of diesel engines extends to global economies. They power commercial transportation, facilitating the movement of goods and people across vast distances. Additionally, they enable the operation of critical industries, contributing to economic growth and development. For example, as the agricultural sector continues to evolve and adapt to meet the growing demands of a global population, the role of diesel engines in powering and revolutionizing agricultural operations cannot be overstated. Diesel engines power about 75% of all farm equipment, transport 90% of farm products, and pump about 20% of agriculture's irrigation water in the United States. Ninety-six percent of the large trucks that move agricultural commodities to railheads and warehouses are powered by a diesel engine [1]. Diesel engines have become the lifeblood of the industry, providing farmers with the energy efficiency, power, and reliability needed to maximize productivity and ensure consistent operational efficiency. While diesel-powered engines have revolutionized agriculture, their successful implementation is not without its challenges. Farmers face logistical hurdles, including initial investment costs, fuel availability, and maintenance requirements [2]. However, the ease of access to diesel fuel and the portability of engines make them an attractive choice, particularly in remote or less accessible farming regions.

There are two different kinds of engines, external combustion engines and internal combustion engines, and are well known. Coal or oil-fueled steam engines are examples of external combustion engines, whereas petrol, diesel, and natural gas engines are examples of internal combustion engines. Internal combustion engines burn their fuel within the cylinder instead of external combustion engines, which burn coal or liquid fuel outside the cylinder. Once again, internal combustion engines are split into two groups: spark-ignition engines and compression-ignition engines. Petrol and petrol engines are examples of spark-ignition engines, respectively. An IC engine's primary function is to produce power by burning fuel. Therefore, an engine's ability to burn fuel efficiently and fast is key to its performance. The burning of hydrocarbons is referred to as combustion, which is a chemical reaction (oxidation) that also releases heat and light. Because an electric spark is necessary to ignite the fuel-air combination that is injected as a mixture in the combustion chamber, petrol engines are referred to as spark-ignition engines. Compression ignition engines have a very different combustion process than spark ignition engines. In a diesel engine, just liquid fuel is delivered at extremely high pressure into the combustion chamber's highly heated and compressed air; this heat initiates the combustion process without the need for an external spark plug. The term "Compression Ignition Engine" derives from the fact that the air pulled in during the suction stroke is compressed during the compression stroke to such an extent that the heat produced due to compression rises far above the temperature at which the liquid fuel will self-ignite or automatically ignite [3].

2. Diesel engine

The diesel engine owes its existence to the visionary inventor Rudolf Diesel, a German engineer, who introduced the concept of compression ignition engines in the late nineteenth century in 1892 [4]. Diesel's innovation hinged on the principle of igniting fuel through compression rather than a spark, resulting in higher efficiency and torque. His first successful prototype ran on peanut oil, showcasing the engine's potential to run on a variety of fuels. Diesel engines gained popularity for their fuel efficiency and durability, gradually replacing steam engines and gasoline-powered internal combustion engines in various applications. A compression ignition engine (CI engine), often known as a diesel engine named after Rudolf Diesel, is an internal combustion engine in which the fuel is ignited by use of the heated air in the cylinder brought about by mechanical compression. This is in contrast to engines that ignite the air-fuel mixture using a spark plug, such as petrol or petrol engines (which burn gaseous fuels like natural gas or liquefied petroleum gas). Diesel engine works based on the principle of compression ignition. The principle of working a diesel engine is based on the diesel cycle. During the intake stroke and compression stroke, the air is drawn into the chamber and compressed. For the atomized diesel fuel pumped into the combustion chamber to ignite, this raises the air temperature inside the cylinder. A heterogeneous air-fuel mixture is one in which the fuel disperses unevenly after being introduced into the air right before combustion.

2.1 Diesel cycle

The diesel cycle is a thermodynamic cycle used in diesel engines to convert heat energy into mechanical work. It was first proposed by Rudolf Diesel, which is the basis for the operation of most modern CI engines, commonly known as diesel engines. The diesel cycle is an idealized representation of the actual processes occurring inside a diesel engine.

The diesel cycle consists of four main processes, as shown in **Figure 1** [5].

1. Adiabatic Compression (process 1–2): The cycle begins with the intake stroke, where air is drawn into the cylinder. During the compression stroke, the air is compressed adiabatically (without heat transfer to or from the surroundings) by the rising piston. As the air is compressed, its temperature and pressure increase significantly. Unlike gasoline engines, diesel engines do not mix fuel with the air during the intake stroke; rather, fuel is injected directly into the hot, highly compressed air later in the cycle.

2. Constant Pressure Heat Addition (process 2-3): After the air is compressed to a high temperature and pressure, fuel is injected into the combustion chamber.

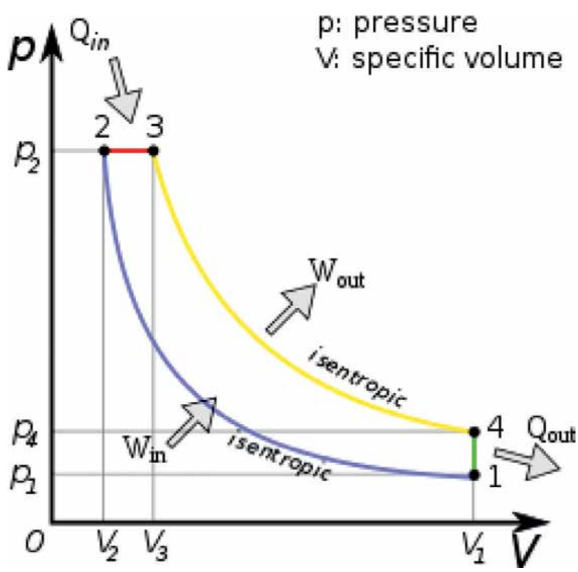

Figure 1.
P–V diagram of diesel cycle.

The heat of the highly compressed air causes spontaneous ignition of the fuel, a process known as auto ignition or self-ignition. The fuel burns rapidly at constant pressure, and the combustion products (hot gases) cause a significant increase in temperature and volume. This process is often referred to as the power stroke, as it generates the mechanical work needed to move the piston.

3. Adiabatic Expansion (process 3-4): During the expansion stroke, the burning gases push the piston down. This expansion process is adiabatic, meaning no heat is exchanged with the surroundings during this phase. As the volume of the gases increases, their temperature and pressure decrease.

4. Constant Volume Heat Rejection (process 4-1): In the final phase of the cycle, the exhaust stroke, the exhaust valves open, and the burned gases are expelled from the cylinder. This process occurs at constant volume, meaning the pressure drops, but the volume remains constant. The heat energy from the exhaust gases is rejected by the surroundings, and the cycle is completed [6].

From **Figure 1**, it is evident that all process of IC engine after suction strokes works accordingly with the diesel, that is,

1. Work in (W_{in}) is done by the piston compressing the air (system), which is called a compression stroke.

2. Heat in (Q_{in}) is done by the combustion of the fuel, and work out (W_{out}) is done by the working fluid expanding and pushing a piston (this produces usable work), which is called a power stroke.

3. Heat out (Q_{out}) is done by venting the air, and this process is termed as exhaust stroke.

4. Network produced = Q_{in} - Q_{out}

2.1.1 Efficiency of diesel cycle

The thermal efficiency of an ordinary diesel engine is from 30–35%. About 65–70% of the effort given to the flywheel is rejected as waste heat rather than being transformed into productive work. Diesel cycle engines are often more effective than Otto cycle engines in most situations. The thermal efficiency of a practical combustion engine is highest for the diesel engine. The thermal efficiency of low-speed diesel engines (such as those used in ships) can be greater than 50%. Peak output for the biggest diesel engine in the world is 51.7% [7].

In general, the thermal efficiency, η_{th} as given in Eq. (1) of any heat engine is defined as the ratio of the work it does, W, to the heat input at the high temperature, Q_H as given in the below equation [6].

$$\eta_{th} = 1 - \frac{1}{C^{K-1}}\left(\frac{\alpha^{K} - 1}{K(\alpha - 1)}\right) \quad (1)$$

where

η_{th}, is thermal efficiency.

α is the cut-off ratio V_3/V_2 (ratio between the end and start volume for the combustion phase).

C is the compression ratio V_1/V_2.

K is the ratio of specific heats (C_p/C_v)

2.2 Principle and working of diesel engine

The principle of a diesel engine is based on the concept of internal combustion, where fuel is burned inside the engine to produce mechanical work. Unlike gasoline engines, which use a spark plug to ignite the air–fuel mixture, diesel engines operate on the principle of compression ignition, where air is compressed to a high temperature and pressure, causing the fuel to ignite spontaneously.

2.2.1 Working principle of four-stroke diesel engine

1. Suction (Intake) Stroke: The diesel engine's cycle begins with the intake stroke. As the piston moves down the cylinder (toward BDC), the intake valve opens, and fresh air is drawn into the combustion chamber. Unlike gasoline engines, diesel engines do not mix fuel with the incoming air during this stage. The air is compressed adiabatically, meaning its temperature increases as it gets compressed.

2. Compression Ignition: In a diesel engine, the air is drawn into the combustion chamber during the intake stroke. During the compression stroke, the air is compressed to high pressure and temperature by the rising piston (toward TDC). This compression causes the air to reach a point where its temperature is high enough to ignite the diesel fuel when it is injected into the combustion chamber.

3. Fuel Injection: Diesel engines do not use a carburetor or a spark plug. Instead, they have a fuel injection system that injects the precisely measured amount of diesel fuel directly into the hot, highly compressed air in the combustion chamber. When the fuel comes into contact with the hot air, it ignites spontaneously due to the heat of compression.

4. Combustion and Power Stroke: The burning of diesel fuel results in a rapid expansion of gases, generating high pressure inside the combustion chamber. This pressure pushes the piston down (toward BDC) the cylinder, converting the heat energy of the burning fuel into mechanical work. This downward movement of the piston is known as the power stroke and is the primary source of the engine's power output.

5. Exhaust Stroke: After the power stroke, the exhaust valves open, and the burned gases are expelled from the combustion chamber during the exhaust stroke. This prepares the engine for a new cycle, drawing in fresh air for the next compression stroke.

Most modern diesel engines operate on a four-stroke cycle, consisting of the intake stroke, compression stroke, power stroke, and exhaust stroke (**Figure 2**) [8].

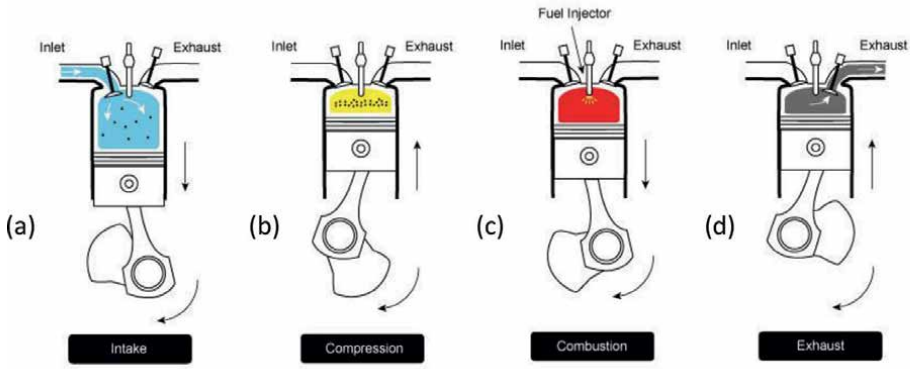

Figure 2.
Four-stroke cycle of diesel engine.

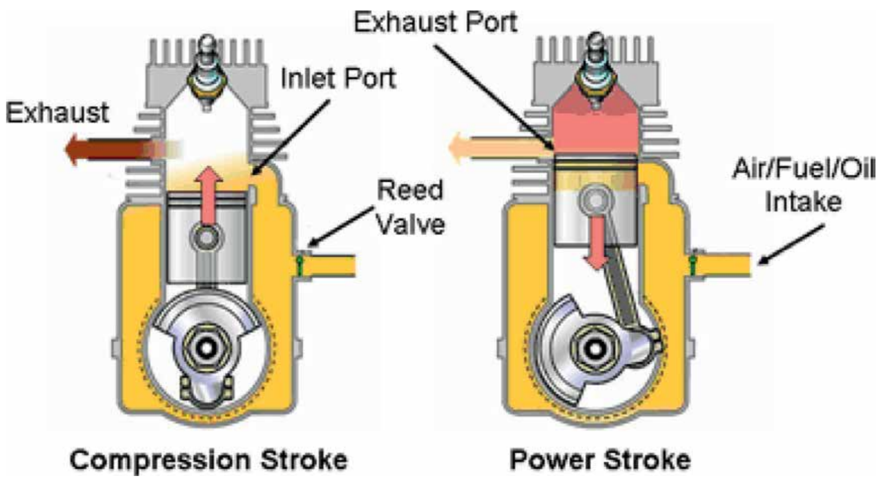

Figure 3.
Two-stroke cycle of diesel engine.

This cycle repeats continuously as the engine runs; hence, it is also called a four-stroke cycle. These are the most common types of IC engines used in various applications, including cars, trucks, busses, industrial machinery, and power generators. It completes one full power cycle in four strokes of the piston [9].

2.2.2 Working principle of two-stroke diesel engine

The two-stroke cycle diesel engine (**Figure 3**) [10] is another type of IC engine that completes one full power cycle in just two strokes of the piston. Two-stroke diesel engines are less common than four-stroke engines due to some inherent disadvantages, but they are still used in certain applications such as marines and locomotives with single crankshaft engines where their simplicity and high power-to-weight ratio are advantageous. Here is how a two-stroke diesel engine works:

1. Intake and Compression Stroke: Unlike the four-stroke diesel engine, which has separate intake and compression strokes, the two-stroke engine combines these

two functions into one stroke. As the piston moves to BDC, the air intake ports on the cylinder walls and/or the bottom of the cylinder are uncovered. Fresh air is drawn into the combustion chamber; simultaneously, the upward-moving piston compresses this air–fuel mixture.

2. Fuel Injection and Power Stroke: As the piston reaches the top of its stroke (TDC), fuel is injected directly into the compressed air in the combustion chamber. The injected fuel mixes with the air, and spontaneous ignition occurs due to the high temperature and pressure from compression. The fuel-air mixture rapidly combusts, generating a high-pressure explosion that forces the piston back to BDC.

3. Exhaust and Scavenging: As the piston moves down, it uncovers the exhaust ports on the cylinder walls and/or the bottom of the cylinder. The high-pressure gases resulting from combustion are expelled through these exhaust ports, and the process of scavenging begins. Scavenging involves the incoming fresh air pushing the remaining exhaust gases out of the cylinder. The momentum of the incoming air, aided by the shape of the cylinder and ports, helps clear the cylinder of exhaust gases and prepare it for the next intake and compression stroke.

4. Repeat Cycle: The piston reaches the BDC, and the exhaust and intake ports are closed. The upward movement of the piston now starts the next cycle by compressing the fresh air drawn in during the scavenging process. The cycle then repeats, with a power stroke occurring every two strokes of the piston [6, 9].

2.3 Valve timing diagram

A valve timing diagram is a graphical representation that illustrates the precise timing of the opening and closing of the intake and exhaust valves in relation to the piston's movement in an internal combustion engine. It shows the events of the engine's intake, compression, power, and exhaust strokes with respect to the positions of the piston and the crankshaft. The valve timing diagram provides crucial information about the engine's performance characteristics, including power output, fuel efficiency, and emissions. It is also essential for optimizing the engine's operation and diagnosing any timing-related issues. The timing of the intake and exhaust valves significantly impacts the engine's efficiency and power delivery. **Figures 4** and **5** [11] show how the valve events are synchronized with the movement of the piston and the rotation of the crankshaft during one complete engine cycle [12].

2.3.1 Valve timing diagram of two-stroke engine

After ignition during an expansion (power) stroke, the piston starts moving toward BDC. When the piston is at 60° before the BDC exhaust valves open, the burned gas will be expelled from the combustion chamber by letting fresh air with the help of the scavenging process by opening the scavenging ports at the piston position 42° before BDC. After the fresh inlet air occupies the place of exhaustible burned gas inside the cylinder, scavenging ports and exhaust valves will be closed at the piston position 42 and 60° after BDC, respectively. At the same time, keeping all the ports and valves closed as the piston moves toward TDC, compression stroke will begin. Piston 15° before TDC fuel will be injected until the piston reaches 20° after TDC.

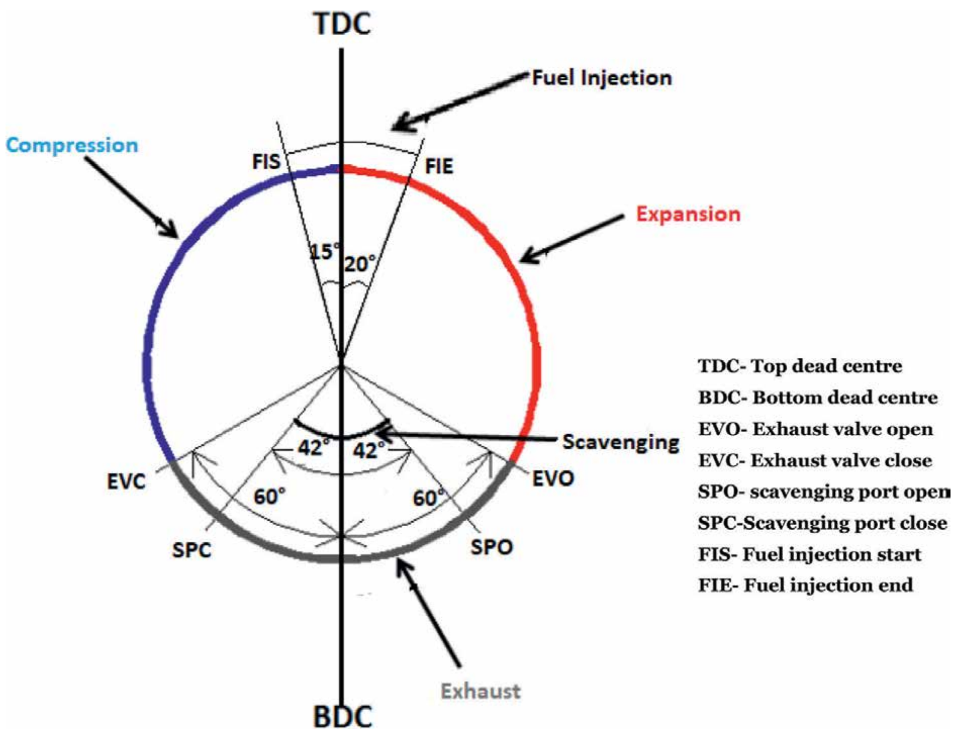

Figure 4.
Valve timing diagram of two-stroke engine.

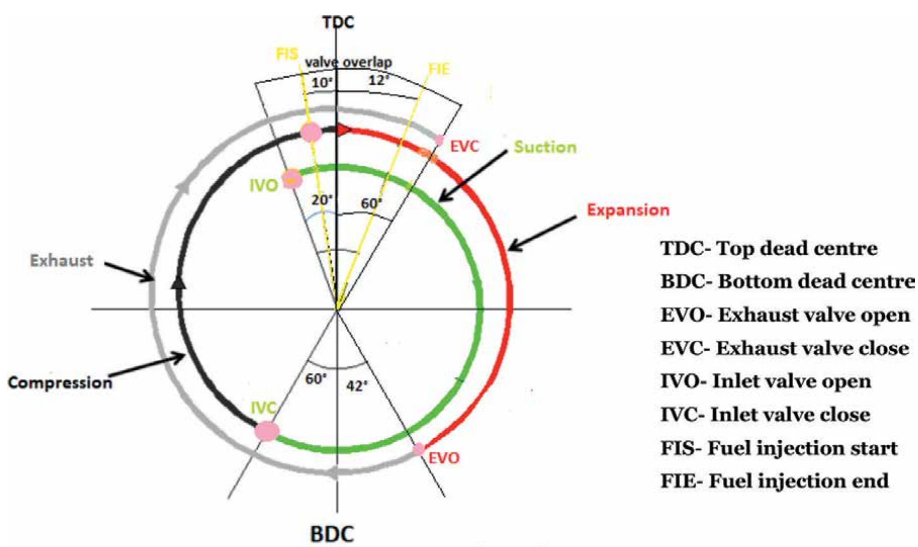

Figure 5.
Valve timing diagram of four-stroke engine.

Just before the ignition occurs, the fuel injection will be stopped. At this stage, due to ignition, high power will be developed, the piston will be pushed again toward BDC, and the cycle will be repeated (**Figure 4**).

2.3.2 Valve timing diagram of four-stroke engine

Figure 5 depicts that the intake valve opens, and fuel injection begins at 20° before the TDC position of the piston during the compression stroke. The typical inlet valve opening (IVO) timing for a four-stroke diesel engine is around 10 to 20° TDC. This early opening allows the intake valve to start admitting fresh air into the combustion chamber before the piston reaches the top dead center, ensuring efficient filling of the cylinder. The intake valve closes at 60° after the BDC position of the piston during the intake stroke. The typical inlet valve closing (IVC) timing for a four-stroke diesel engine is around 40 to 60° after BDC. Closing the intake valve after the piston has passed the bottom dead center ensures that the cylinder is fully charged with air before the compression stroke begins. During the compression stroke, both the intake and exhaust valves remain closed. The piston moves from BDC to TDC, compressing the air in the combustion chamber. For diesel engines, fuel injection occurs at 10° before TDC during the end of the compression stroke and the beginning of the power stroke. The typical Fuel Injection (FI) timing for a four-stroke diesel engine is around 20 to 40° before TDC. Injecting fuel at this time ensures that the fuel mixes with the highly compressed air and spontaneously ignites due to compression ignition. After fuel injection, the air-fuel mixture ignites, and the power stroke begins. The high-pressure explosion pushes the piston downward, generating mechanical work. During this stroke, both the intake and exhaust valves remain closed. The exhaust valve opens at a certain number of degrees before the BDC position of the piston during the power stroke and the beginning of the exhaust stroke. The typical Exhaust Valve Open (EVO) timing for a four-stroke diesel engine is around 20 to 40° before BDC. Opening the exhaust valve before the piston reaches the bottom dead center allows the exhaust gases to start exiting the cylinder while the piston is still moving downward, facilitating efficient gas flow. The exhaust valve closes at a certain number of degrees after the TDC position of the piston during the exhaust stroke. The typical Exhaust Valve Close (EVC) timing for a four-stroke diesel engine is around 20 to 40° after TDC. Closing the exhaust valve after the piston has passed the top dead center ensures that the cylinder is effectively evacuated from exhaust gases before the next intake stroke begins.

2.4 Firing order

The firing order of an engine refers to the specific sequence in which the fuel injectors or cylinders receive fuel and ignite during one complete engine cycle. The firing order ensures that the power strokes in each cylinder are evenly distributed across the engine's crankshaft rotation, resulting in smooth engine operation and reduced vibrations. The firing order is expressed as a numerical sequence that indicates the order in which each cylinder fires [13].

2.4.1 Firing order in 2-stroke diesel engines

In a 2-stroke diesel engine, where one complete cycle is completed in two strokes of the piston (compression stroke and power stroke), the firing order is relatively simple. Since the engine has no separate intake and exhaust strokes, each cylinder fires every revolution of the crankshaft.

For example, in a 3-cylinder 2-stroke diesel engine, the firing order would be 1-2-3. In this case, cylinder 1 fires first, followed by cylinder 2, and then cylinder 3, completing one full cycle in three crankshaft revolutions.

2.4.2 Firing order in 4-stroke diesel engines

In a 4-stroke diesel engine, where one complete cycle is completed in four strokes of the piston (intake, compression, power, and exhaust strokes), the firing order is more complex and varies based on the engine's design and configuration.

For a 4-cylinder diesel engine, the most common firing order is 1-3-4-2. This means that the first cylinder fires, followed by the third, fourth, and second cylinders, respectively. Each cylinder fires every two revolutions of the crankshaft, completing one full cycle.

For example, in a 6-cylinder diesel engine, the firing order could be 1-5-3-6-2-4 or 1-3-5-2-4-6, depending on the engine's design.

The firing order is essential to ensure smooth engine operation, even power delivery, and balanced crankshaft forces. A correct firing order prevents issues like rough running, power imbalance, and excessive vibration, making it a crucial consideration in diesel engine design and tuning. Manufacturers carefully design the firing order to optimize engine performance, minimize stress on engine components, and provide a comfortable driving experience for the vehicle or efficient power delivery for industrial applications [14].

3. Components of diesel engine

Diesel engines are complex machines that power a wide range of vehicles, machinery, and equipment. Understanding the various components that make up a diesel engine is crucial for maintenance, troubleshooting, and performance optimization [6].

1. Cylinder Block and Pistons: The cylinder block (**Figure 6**) [15] is the engine's main structure, housing the cylinders where the combustion takes place.

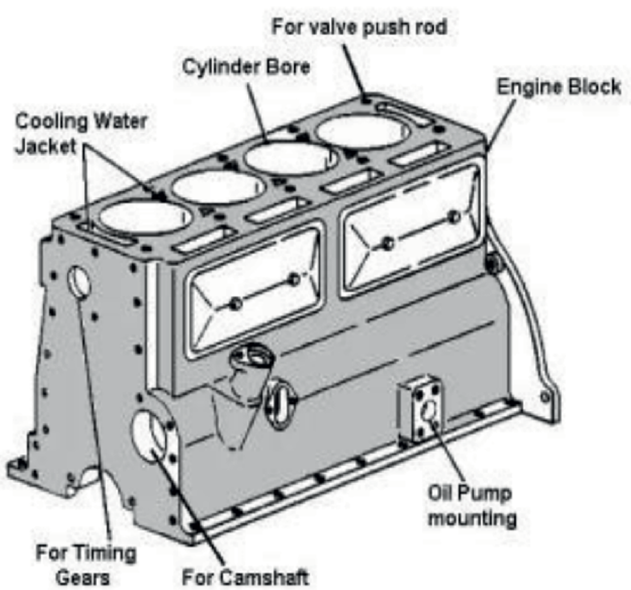

Figure 6.
Parts of cylinder block.

The number of cylinders can vary, with common configurations being 4-cylinder, 6-cylinder, and 8-cylinder engines. The pistons, usually made of aluminum, move up and down inside the cylinders, converting the energy from combustion into reciprocating motion.

2. Cylinder Head and Valves: The cylinder head sits atop the cylinder block and forms the top of the combustion chamber. It contains intake and exhaust valves that control the flow of air and exhaust gases. The valves are actuated by a camshaft, which opens and closes them at precise times during the engine's operation.

3. Crankshaft and Connecting Rods: The crankshaft (**Figure 7**) [16] is a crucial component that converts the reciprocating motion of the pistons into rotational motion. The connecting rods (**Figure 8**) connect the pistons to the crankshaft, transferring the up-and-down motion into a rotary motion that drives the engine's output shaft.

4. Fuel Injection System: The fuel injection system (**Figure 9**) [17] delivers the precise amount of diesel fuel into the combustion chamber at the right moment. Modern diesel engines use electronic fuel injection systems, which employ fuel injectors controlled by the engine's electronic control unit (ECU). This allows for better fuel efficiency, power output, and emission control.

5. Turbocharger: A turbocharger is a forced induction device used in many diesel engines to increase air intake and improve performance. It uses the engine's exhaust gases to drive a turbine that compresses the incoming air before it enters the combustion chamber. This compressed air leads to better combustion and increased power output.

6. Air Intake System: The air intake system (**Figure 10**) [18] brings fresh air from the environment into the engine's combustion chambers. It typically includes

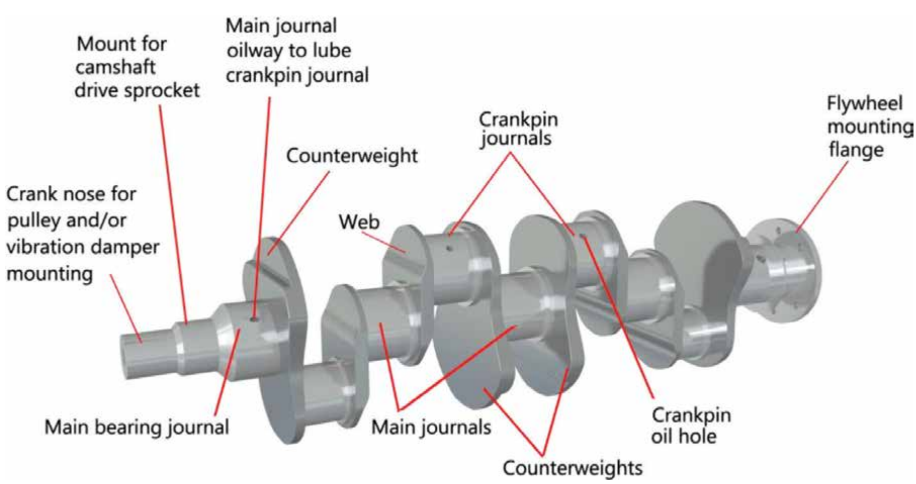

Figure 7.
Crankshaft.

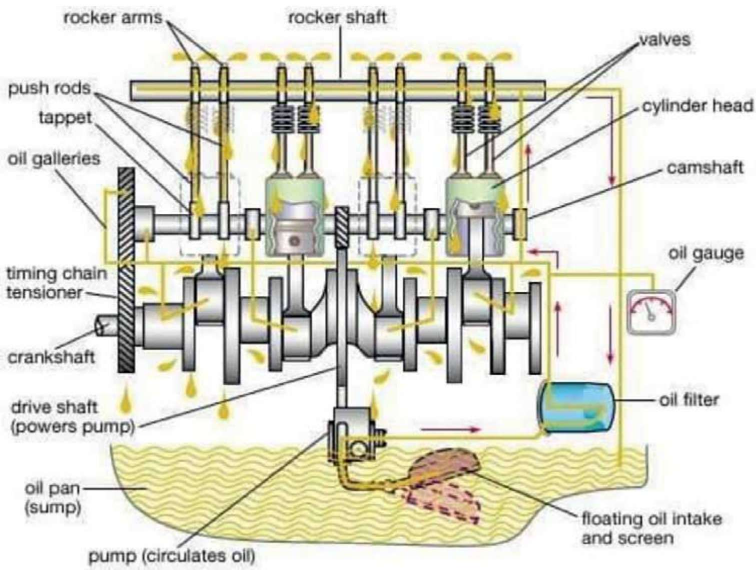

Figure 8.
Diesel engine lubrication system.

an air filter to remove dust and debris and, in some engines, a turbocharger or supercharger to boost air pressure.

7. Exhaust System: The exhaust system (**Figure 10**) directs the burned gases produced during combustion out of the engine. It includes an exhaust manifold, which collects the gases from each cylinder and channels them into the exhaust pipe. In modern diesel engines, emission control devices like the diesel particulate filter (DPF) and selective catalytic reduction (SCR) are often integrated into the exhaust system to reduce harmful emissions.

8. Lubrication System: The lubrication system (**Figure 8**) [19] ensures proper lubrication of moving parts to reduce friction and wear. It includes an oil pump that circulates engine oil through various passages and channels to critical components such as the crankshaft, connecting rods, and camshaft.

9. Cooling System: Diesel engines generate a considerable amount of heat during operation. The cooling system (**Figure 11**) [20] maintains the engine's temperature within an optimal range. It includes a water pump, radiator, and coolant passages to dissipate excess heat.

10. Timing Belt or Chain: The timing belt or chain (**Figure 8**) synchronizes the movement of the engine's camshaft(s) and crankshaft, ensuring precise valve timing for efficient combustion.

4. Classification of diesel engine

A diesel engine is a type of compression ignition engine using diesel fuel. Diesel engines can be classified into various categories (**Table 1**) [21].

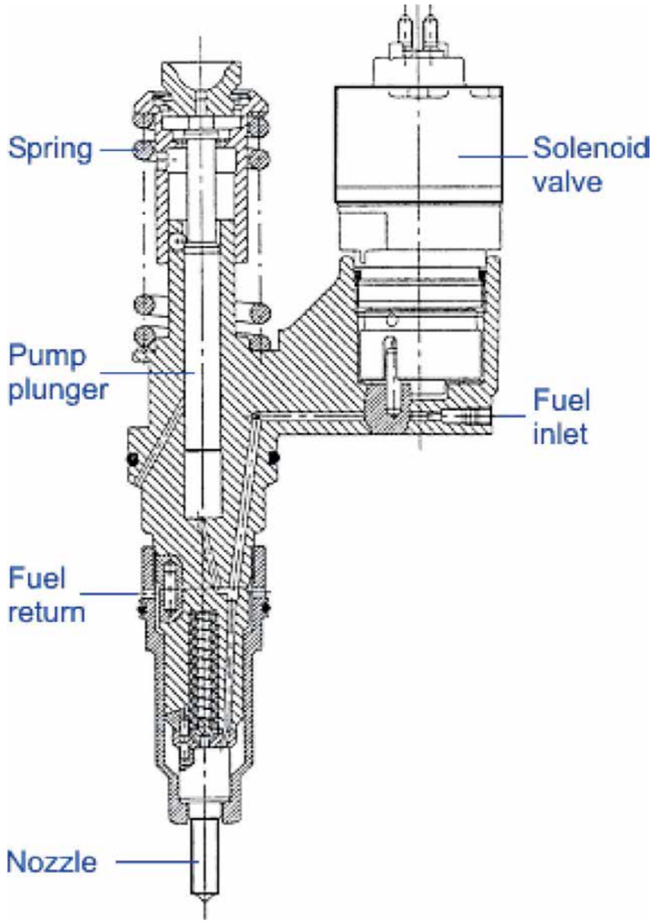

Figure 9.
Cross section of fuel injector.

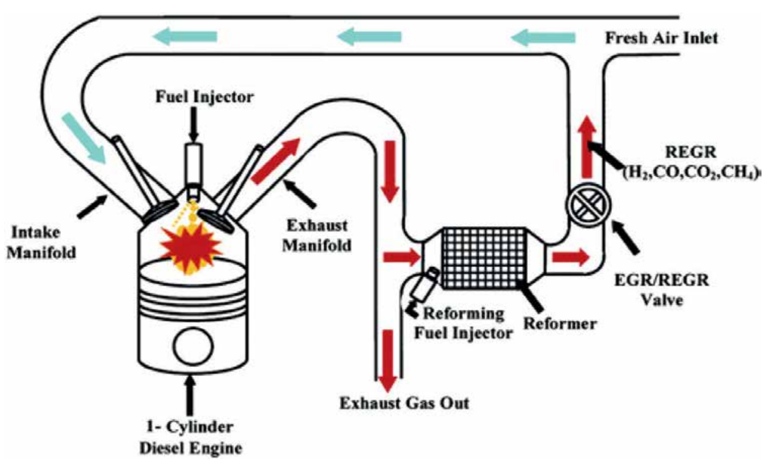

Figure 10.
Air intake and exhaust system.

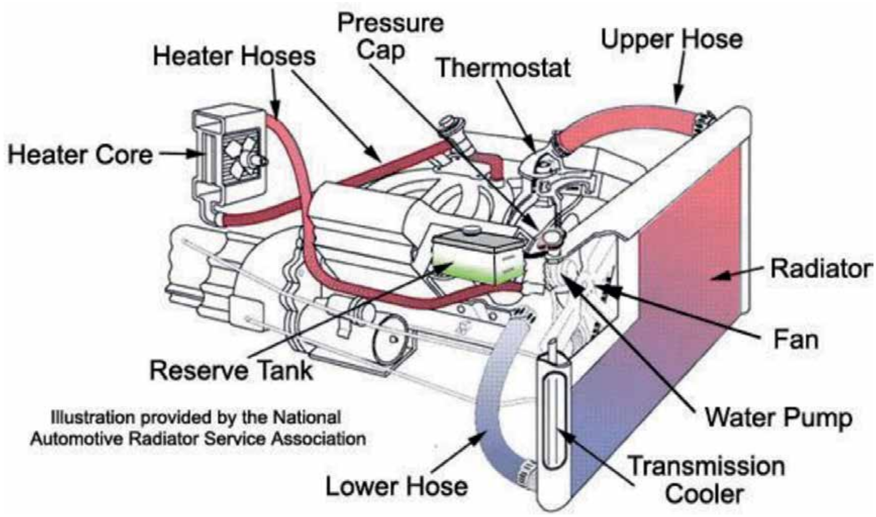

Figure 11.
Engine cooling system.

Classification criteria	Variant 1	Variant 2	Variant 3
Number of strokes	Four-stroke	Two-stroke	
Emissions standard	On-road	Off-road	
Application	On-road (trucks, busses, and automobiles)	Off-road (marine, industrial, construction equipment, agricultural, and locomotive)	Stationary
Emissions certification method for vehicles	Heavy heavy-duty, medium heavy-duty, light heavy-duty	Light duty	
Vehicle weight	Heavy-duty	Medium duty	Light duty
Crankshaft rated speed	High speed (N_E > 1000 rpm or v_{mp} > 9 m/s)	Medium speed (N_E = 300–1000 rpm or v_{mp} = 6–9 m/s)	Low speed (N_E < 300 rpm or v_{mp} < 6 m/s)
Fuel injection	Direct injection	Indirect injection	
Air charging	Turocharged (with or without after cooling)	Mechanically supercharged (with or without after cooling)	Naturally aspirated
Cooling medium	Water cooled	Air-cooled	
Number of cylinders	Single-cylinder	Multi-cylinder	
Fuel utilized	Light-liquid fueled	Heavy-liquid fueled	Multi-fueled (e.g., biodiesel, duel fuel-natural gas and diesel)

Table 1.
Diesel engine classification.

5. Scope of diesel engine

With advancements in technology and growing concerns about environmental sustainability, the scope of diesel engines is continually evolving. The scope of diesel engines includes the following:

5.1 Reliability: the backbone of agricultural machinery

One of the primary reasons why diesel engines have become the preferred choice for machinery is their unmatched reliability [22]. Unlike their petrol counterparts, diesel engines are simpler in design and lack components such as spark plugs and carburetors that are prone to failure. This inherent simplicity translates to reduced maintenance and repair costs for farmers, allowing them to focus on their core operations without worrying about frequent breakdowns or costly repairs. The durability and dependability of diesel engines make them well-suited for the demanding and often harsh conditions.

5.2 Storage: convenience and downtime prevention

Another advantage of using diesel fuel is the ease of storage. Unlike other fuel types, diesel fuel can be stored for extended periods without degradation [23], reducing the risk of downtime resulting from running out of fuel. This storage convenience ensures the readily available fuel source, enabling the maintenance of uninterrupted operations during critical periods such as planting and harvesting seasons.

5.3 Engine commonality: simplifying operations

Diesel engines often share a common platform, offering a range of benefits to end users. This commonality simplifies operations by ensuring that operators are familiar with the various engines and reducing the learning curve associated with different equipment models. Additionally, shared service and maintenance practices across the fleet streamline operations and minimize downtime. Users also benefit from having a single contact point for accessories or parts, simplifying the procurement process and facilitating efficient equipment maintenance [24].

5.4 Advancements in diesel engine technology

Diesel engine technology has continued to advance, further enhancing its efficiency and environmental performance. The introduction of ultra-clean engines, such as Cummins' Performance Series, has significantly reduced emissions while maintaining high power output. These engines achieve near-zero emissions levels, meeting stringent environmental standards and contributing to sustainability efforts in the agricultural sector. Innovative after-treatment technologies, integrated within the engine design, effectively control and reduce harmful emissions, ensuring compliance with regulatory requirements. This commitment to clean technology demonstrates the industry's dedication to reducing its environmental impact while preserving the efficiency and reliability of diesel engines.

5.5 The potential of hybridization

While diesel engines remain the primary power source for heavy-duty machinery, hybridization presents an opportunity to bridge the gap between full-electric and diesel-powered equipment. Hybrid power trains combine the power density of a clean diesel engine with the added flexibility of utilizing batteries when appropriate. These full hybrid power trains offer farmers greater operational flexibility, particularly in areas with limited or no charging infrastructure. While hybrid systems have been successfully implemented in on-road applications, their adoption in off-road industries, including agriculture, has been relatively limited. The longer payback period associated with hybrid technology, coupled with the absence of government subsidies, poses challenges to widespread adoption in the agricultural sector. However, as technology continues to advance and costs decrease, hybridization may become a more viable option for certain agricultural applications [25].

6. Recent developments in diesel engine technology

Diesel engines have evolved significantly over the years, with constant advancements in technology aimed at improving efficiency, reducing emissions, and enhancing overall performance. This chapter delves into the cutting-edge developments in diesel engine technology, focusing on the latest innovations that are shaping the future of this crucial power source.

6.1 Ultra-low-emission standards

One of the most notable recent developments in diesel engine technology is the pursuit of ultra-low-emission standards. Stricter regulations have driven the adoption of advanced exhaust after-treatment systems, such as selective catalytic reduction (SCR) and diesel particulate filters (DPF). These technologies effectively reduce nitrogen oxide (NO_x) and particulate matter (PM) emissions, making modern diesel engines cleaner and more environmentally friendly [26].

6.2 Electrification and hybridization

The integration of electric and hybrid technologies with diesel engines is a significant trend. Hybrid diesel-electric systems combine the efficiency and torque of diesel engines with the benefits of electric propulsion, particularly in urban settings. Mild-hybrid systems use electric power to assist during acceleration, reducing the load on the engine and improving fuel efficiency. Full hybrid systems allow for all-electric operation during low-speed or idling conditions [27].

6.3 Advanced fuel injection

Recent developments in fuel injection technology have enhanced combustion efficiency and reduced emissions. High-pressure common rail systems with multiple injections per cycle optimize combustion, resulting in cleaner exhaust gases and improved fuel economy. Emerging innovations, such as solenoid-controlled piezo injectors, offer even finer control over fuel delivery for precise combustion management [28].

6.4 Advanced air management

Optimizing air intake and exhaust flow has a profound impact on diesel engine performance. Variable geometry turbochargers (VGT) and electric turbochargers adjust boost pressure based on engine conditions, providing better low-end torque and higher top-end power. Combined with exhaust gas recirculation (EGR) and advanced intake designs, these technologies improve combustion efficiency and reduce emissions [29].

6.5 Digitalization and connectivity

Digital technologies are transforming diesel engines into smarter and more connected systems. Sensors and real-time data analysis enable predictive maintenance, optimizing engine health, and uptime. Telematics and remote monitoring allow fleet operators to manage engine performance, fuel consumption, and emissions remotely, leading to better operational efficiency [30].

6.6 Alternative fuels and synthetic fuels

Research into alternative and synthetic fuels is gaining momentum to address the environmental concerns associated with traditional diesel fuel. Biodiesel, derived from renewable sources, offers a cleaner-burning alternative. Synthetic diesel, produced from sources like natural gas or biomass, provides a high-energy-density fuel with lower emissions [31].

6.7 Lightweight materials and design

Advancements in materials science have led to the development of lightweight components without compromising durability. Aluminum, high-strength steel, and composite materials reduce engine weight, contributing to improved fuel efficiency and overall vehicle performance [32].

6.8 Future-proofing with modular designs

Modular engine designs allow for flexibility and adaptability to evolving technological and regulatory landscapes. Diesel engines can be easily integrated with emerging technologies, such as electrification components, without requiring extensive redesigns [33].

7. Key advantages of diesel engines

1. Higher Efficiency: Diesel engines are more thermodynamically efficient than gasoline engines, primarily due to their higher compression ratios ranging from 14:1 to 22:1 and lower losses from pumping losses [34].

2. Torque and Power: Diesel engines during the compression stroke attain high pressure ranging from 30 to 45 kg/cm^2 and high temperatures around 500°C, due to which they are able to produce high torque at low Revolutions per Minute (RPMs), making them well-suited for heavy-duty applications like agricultural operations, trucks, busses, and industrial machinery [35].

3. Fuel Economy: Diesel engines typically offer better fuel economy than gasoline engines, especially in larger vehicles and under heavy loads.

4. Durability: Diesel engines are known for their robust construction and longer service life than gasoline engines [36].

5. Lower Volatility: Diesel fuel has lower volatility than gasoline, reducing the risk of fuel evaporation and vapor lock in hot weather.

6. Safety: Diesel fuel is less flammable compared to gasoline, reducing the risk of fire in case of a spill or accident.

7. Adaptability to Alternative Fuels: Diesel engines can be modified to run on alternative fuels such as biodiesel and synthetic diesel, providing more sustainable options.

8. Limitations of diesel engines

1. Higher Initial Cost: Diesel engines generally have a higher upfront cost than gasoline engines. This is primarily due to their more robust construction and additional components like turbochargers and intercoolers.

2. Noise and Vibration: Diesel engines tend to produce more noise and vibration compared to gasoline engines, particularly at low speeds. Although advancements in engine design and technology have reduced noise levels, diesel engines can still be louder than their gasoline counterparts.

3. Emissions: While diesel engines are more fuel-efficient than gasoline engines, they tend to produce higher levels of certain emissions, particularly nitrogen oxides (NO_x) and particulate matter (PM). This has led to concerns about air pollution and its impact on human health and the environment.

4. NO_x and Particulate Matter: Diesel engines emit nitrogen oxides (NO_x) and particulate matter (PM), which contribute to smog formation and can have adverse health effects. Reducing these emissions requires advanced exhaust after-treatment systems and careful engine tuning.

5. Cold Weather Performance: Diesel engines can experience difficulty starting in extremely cold weather due to the higher compression ratios and lower volatility of diesel fuel. Cold weather starting can be improved with the use of glow plugs or block heaters.

6. Limited Availability of Fuel: In some remote or rural areas, access to diesel fuel may be more limited compared to gasoline. This can be a disadvantage for diesel engine users in such locations.

7. Fuel Ignition and Combustion Noise: Diesel engines use compression ignition, which can result in louder combustion noise compared to spark ignition in gasoline engines. While advancements in fuel injection technology have reduced noise, it can still be an issue in some diesel engines.

8. Fuel Sulfur Content: Diesel engines are sensitive to the sulfur content in diesel fuel. High sulfur content can lead to increased emissions and accelerated wear of engine components. Modern diesel engines require low-sulfur diesel fuel for optimal performance and emissions control.

9. Weight and Size: Diesel engines are generally heavier and bulkier compared to equivalent gasoline engines. This can be a disadvantage in certain applications where weight and size constraints are critical, such as in smaller vehicles or portable equipment.

9. The evolution of diesel engines

The evolution of diesel engines traces a remarkable journey of innovation, efficiency, and adaptability. From their inception in the late nineteenth century by Rudolf Diesel to their present-day prominence in various industries, diesel engines have undergone transformative changes that have shaped modern transportation, power generation, and beyond. The early diesel engines were characterized by their compression ignition principle, where fuel ignited due to the heat generated by compressing air within the cylinder. These engines quickly gained attention for their fuel efficiency and torque, making them suitable for heavy-duty applications. However, they were also known for their noise, vibration, and emissions. As time progressed, diesel engine technology saw substantial improvements. Advancements in fuel injection systems, turbocharging, and combustion controlled to enhance efficiency and reduce emissions. Turbochargers, for instance, boosted air intake, resulting in better combustion and increased power output. Fuel injection systems became more precise, optimizing fuel delivery for improved performance and reduced pollution.

The automotive industry saw the integration of diesel engines into passenger cars, offering increased fuel efficiency over gasoline engines. Yet, environmental concerns arose due to higher emissions of nitrogen oxides and particulate matter. In response, diesel engine manufacturers worked on exhaust after-treatment technologies like selective catalytic reduction (SCR) and diesel particulate filters (DPF), drastically reducing harmful emissions.

The twenty-first century brought further transformation. Diesel engines embraced digitalization, incorporating advanced sensors and control systems for optimized performance and predictive maintenance. Hybridization and electrification entered the scene, leading to hybrid diesel-electric powertrains that combined diesel's efficiency with electric's low-emission capabilities, ideal for urban driving.

Alternative fuels also gained attention, with research into biodiesel, synthetic fuels, and hydrogen as potential replacements for conventional diesel fuel. These innovations mitigate environmental concerns while maintaining diesel engines' practicality and versatility. The evolution of diesel engines is an ongoing narrative, driven by the need for cleaner, more efficient, and sustainable power sources. Today, diesel engines are essential in sectors such as commercial transportation, construction, and power generation. Their ability to evolve with the times, embracing new technologies and cleaner fuel options, underscores their enduring importance in a rapidly changing world as they continue to power progress while aligning with environmental and efficiency goals.

10. Alternative power options to replace the diesel engines

As the world moves toward sustainability and reducing greenhouse gas emissions, there is an increasing focus on alternative power options for the mechanical industry to replace diesel engines. Several renewable and cleaner energy sources are being explored to make the globe more environmentally friendly and reduce the carbon footprint of polluting operations. Some of the promising alternative power options include:

1. Electric Tractors and Machinery: Electric tractors and agricultural machinery are gaining traction as viable alternatives to diesel-powered equipment. Electric motors provide instant torque, making them suitable for various farming tasks. Battery-powered electric tractors are already available in the market, offering emissions-free operation and reduced noise levels. Additionally, advancements in battery technology are extending the range and capacity of electric agricultural equipment.

2. Biofuels: Biofuels, such as biodiesel and bioethanol, are derived from renewable biomass sources such as crops, agricultural residues, and animal fats. Biodiesel can directly replace diesel in conventional diesel engines without significant modifications. Bioethanol can be used as a blend with gasoline in spark-ignition engines. These biofuels offer a cleaner-burning alternative to fossil fuels, reducing greenhouse gas emissions and promoting sustainable solutions.

3. Hydrogen Fuel Cells: Hydrogen fuel cells are an emerging technology that holds promise for modern mechanical applications. Fuel cells produce electricity by reacting hydrogen with oxygen, with the only byproduct being water vapor. Hydrogen can be produced from renewable sources through electrolysis or from bio-based feedstocks. Hydrogen-powered engines and machinery have the potential to provide long-range operation with zero emissions, making them environmentally friendly options.

4. Solar Power: Solar power can be harnessed to generate electricity applications. Solar panels can be installed on buildings or mounted on automobile equipment to power electric motors or charge batteries. Solar energy can provide a sustainable and reliable power source for irrigation systems, electric fencing, and other farm operations, reducing dependence on diesel generators.

5. Wind Power: Wind energy can be harnessed through wind turbines to generate electricity for on-farm use. Small-scale wind turbines can be installed on farms to power electric pumps, lighting, and other equipment. Wind power complements solar power, providing renewable energy options that suit different weather conditions.

6. Biogas: Biogas is produced from the anaerobic digestion of organic materials, such as agricultural residues, animal manure, and crop waste. It can be used as a fuel for generating electricity or as a replacement for natural gas in engines. Biogas digesters can be integrated into farms to not only provide renewable energy but also manage organic waste and produce nutrient-rich biofertilizers.

11. The future of power solutions

The future of global power solutions in relation to diesel-powered engines is undergoing a transformative shift driven by technological advancements, environmental considerations, and the growing demand for efficient and reliable energy sources. While the landscape is evolving, diesel engines are poised to continue playing a significant role in providing power solutions, albeit in a more sustainable and integrated manner. The future of global power solutions involving diesel-powered engines is characterized by a transition toward sustainability and integration with emerging technologies. While diesel engines face challenges related to emissions, they also offer a pathway to cleaner and more efficient power solutions through hybridization, alternative fuels, and advanced emissions reduction technologies. As the world strives for a balance between reliable energy sources and environmental stewardship, diesel engines are set to play a dynamic role in shaping the future of global power solutions.

12. Conclusion

The diesel engines have played a significant role in shaping various industries and applications, offering a plethora of advantages such as high fuel efficiency, torque, reliability, and durability needed to maximize productivity. They have revolutionized transportation, agriculture, construction, and power generation, providing reliable and efficient power for a wide range of tasks. The evolution of diesel engines has seen advancements in technology, emission control, and alternative fuel options, making them more environmentally friendly and sustainable. However, challenges like emissions and noise continue to be addressed through ongoing research and innovation. As we move forward, a balanced approach to harnessing the benefits of diesel engines while minimizing their drawbacks is crucial for a greener and more efficient future.

Abbreviations

BDC	bottom dead center
CI	compression ignition
DPF	diesel particulate filter
ECU	electronic control unit
EGR	exhaust gas reduction
IC	internal combustion
NO_x	nitrogen oxide
PM	particulate matter
SCR	selective catalytic reduction
TDC	top dead center
VGT	variable geometry turbocharger

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This book discusses the current technology and future status of diesel engines. While gasoline engines are preferred for speed and jet engines, diesel engines are widely used in vehicles and machinery that require torque, such as ships, trains, tanks, unmanned ariel vehicles (UAVs), and heavy-duty vehicles. Some recent research on global climate change has focused on obtaining zero carbon, zero emissions, and decarbonization via clean combustion technologies. For this reason, restrictive emission regulations have forced engine manufacturers and research centers to turn to different technologies to achieve clean combustion in diesel engines. This book focuses on different combustion technologies, from artificial intelligence applications in diesel engines to alternative fuels. It discusses the roles of artificial intelligence in the design of diesel engines, the use of different fuels in diesel engines, and the effects of these on the performance and emission values of diesel engines. Solving the challenge of hydrogen storage in hydrogen-fed diesel engines will open a new era for internal combustion engines. In particular, the use of hydrogen fuel produced by the reaction of chemical ingredients with water in diesel engine cycles will have a significant impact on the industry. This book, which brings together the latest studies on clean combustion technologies, is an interesting resource for both industry and research centers.

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