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Utilization of Ammonia Hydroxide /Diesel Fuel Blends in Partially Premixed Charge Compression Ignition (PPCCI) Engine: A Technical Review

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Abstract*- Compression ignition engines have gone through periods of ups and downs in recent decades. Almost 50% of new car registrations in Europe at the turn of the century were diesel. However, reports of harmful NOx emissions have been corroborated by diesel emissions scandals, which have sent the diesel engine market into a tailspin and raised concerns about the diesel engine's long-term viability. The development of diesel cars with low NOx emissions has been announced by major automakers. Modern posttreatment systems can be installed, and they will result in decreased NOx emissions for heavy-duty, marine, or power production applications. Despite attempts to lower NOx emissions, the automobile, marine, and power generation industries must decarbonize if we are to reach greenhouse gas emission objectives and prevent global warming. Using fuels with low carbon, like ammonia, can help decarbonize a diesel engine. Using ammonia as a fuel for diesel engines is discussed at length in this work. To drastically lower carbon emissions, Ammonia could be burned when mixed with diesel or another low-temperature fuel in a dual-fuel system. Creating advanced injection technologies can improve overall emissions while also improving performance. However, due to the coupling of nitrogen to the fuel, dual fuel combustion of ammonia currently has relatively large emissions of ammonia and nitrogen oxides. As a result, post-processing mechanisms need to be put in place. With the introduction of modern combustion systems like HCCI, PCCI, and RCCI systems, ammonia is currently only a practical alternative in specific applications including maritime, power generating, and maybe heavy duty.

***Keywords*- RCCI engine, HCCI engine, NOx emissions, Ammonia Hydroxide, Diesel engine.**

I. INTRODUCTION

The engineering community worked to enhance manufacturing, industrial, and power generation technology during the Second Industrial Revolution. Compression ignition (CI) engines were invented in 1892 by the brilliant engineer and inventor Rudolf Diesel [1]. On June 16, 1897, Diesel defended his internal combustion theory in a lecture to assure more heat utilization and boost economic efficiency in comparison to the formerly most well-known contemporary steam engines. The development of diesel has stood the test of time, as seen by the diesel engine's continued dominance in the automotive, maritime, and industries that generate power.

During this time, the Compression ignition engine has gone through growth, turbulence, and bust stages. The number of vehicles fueled by diesel has considerably expanded since the 1990s, largely due to European governments' encouragement of the purchase of diesel vehicles through reductions in road and diesel fuel taxes. As compared to gasoline-powered engines, diesel engines burn fuel more efficiently, they were then considered the greatest alternative for minimizing carbon dioxide emissions. Diesel-powered vehicles accounted for 50% of all new vehicle's registrations in the European market in 2005, and this number has climbed over time [2]. The future of the compression engine wasn't as clear as imagined, despite a period of expansion for diesel engines at the conclusion of the previous century and the start of the current one. Due to their propensity to run at high ignition temperatures, diesel engines produce more nitrogen oxides (NOx) than petrol engines that use spark ignition [3]. The rumors that dangerous diesel engines cause fatal breathing issues, which were supported by scientific investigations [4], began to circulate. Countries that had previously backed diesel-powered automobiles quickly began to oppose them, either by raising taxes or by outlawing diesel vehicles in large cities [5]. It was at this time that the diesel era was supposedly ending. When the "Dieselgate" scandal broke in 2015, the murky future of diesel engines got even worse. Another stunning piece of information regarding the diesel engine was the requirement that major automakers submit fabricated test results in order to comply with the strict emissions legislation. Since then, the number of new diesel-powered vehicle registrations has drastically decreased, and the passenger car diesel engine market is in decline [6].

Major automakers continue to support the idea of compression ignition engines despite the bad news for diesel engines. Over the past few years, major modifications in the compression ignition engine's operation have been brought about by technology developments and ongoing diesel engine improvements [7].

Early in 2019, encouraging research showing that diesel-powered cars release nearly no NOx emissions were sufficient to reignite interest in clean diesel engines. Diesel engines are among the most efficient types of internal combustion engines, which makes them the best choice for the energy and maritime industries, aside from the vehicle industry. The Department of Energy predicts that over the next few decades, diesel fuel consumption for heavy-duty applications will continue to rise [8]. Diesel powered vehicles burn fuel more efficiently than gasoline models,

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making them more environmentally friendly, but more steps must be taken to decarbonize the world economy due to the urgent need to reduce greenhouse gas emissions. In the coming decades, compression ignition engines are expected to play a large role in a number of important industries, necessitating significant carbon emission reductions.

Using alternative, without emissions fuels seems to be the solution to this issue. To reduce carbon emissions in a diesel engine, hydrogen fuel has a small quantity of carbon, and may be utilized in addition to diesel fuel. Dimitriou and Tsujimura have reviewed the advantages and drawbacks of using hydrogen (H2) as diesel fuel for engines [9]. The scientists reached that storage technology is a major barrier to hydrogen diffusion in spite of the excellent performance and emission advantages of hydrogen vaporization. Because hydrogen has a low density, compressing it at high pressures can be expensive and occasionally dangerous [10]. At this time, it seems that hydrogen energy carriers, maintained at low or even atmospheric pressures, are a practical alternative to diesel engines. A hydrogen fuel carrier, such as methanol, can either be burnt directly inside the cylinder or utilized as a reduced transport medium prior to combustion [11].

Due to traditional diesel engine's short ignition delay time and the fuel's higher viscosity and volatility, a fuel-air mixture that isn't uniform forms prior to Initial stages of combustion (SOC), which increases the rate of NOx and soot formation [12]. Pre-mixed fuel-air mixes and lower equivalent ratios, those increase the fuel's physical processes and reduce the cylinder's internal temperature, are provided by low-temperature combustion (LTC) techniques to get around these problems [13]. (PCCI) is an approach of the LTC approaches that shows the most promise for reducing greenhouse emissions and increasing thermal efficiency.

The good and bad sides of using ammonia (NH3), a fuel with a high gravity hydrogen density, as in the current study, a substitute fuel for engines with compression ignition is evaluated. With a focus on the technical details of (PCCI) engines, the purpose of this research is to give a complete check of historical and current ammonia fuel study efforts that have been made to power compression ignition engines [14]. The next, a full explanation of NH_3 and its manufacturing procedures is given. Then a thorough evaluation of ammonia ignited by compression's combustion behavior follows.

The primary focus of the review research is how ammonia is burned in cylinders either as the only fuel source or in a multi fuel system with diesel or other fuels. The influence of injection techniques, combustion strategies, and ammonia treatment technology on the emission and combustion characteristics of a multi-fuel engine is comprehensively explored. To their knowledge, this first evaluation strategy focuses on premixed charge compression ignition (PCCI) engines and includes ammonia usage for compression ignition in its entirety [15]. This paper's goals are to collect the information that is now available for easy access and to examine whether it would be feasible to run compression ignition engines on this renewable fuel in the future.

II. AMMONIA IS DEFINITION

The ammonia molecule is made up of a nitrogen atom attached to an unshared pair of electrons, three atoms of hydrogen, and a trigonal pyramidal shape. Alkaline gas, ammonia has a strong, offensive smell and is colorless. The substance has a density of 730 g/m^3, a point of boiling of -33 ^{0}C, a freezing point of -77.5 ^{0}C, and an auto ignition temperature of 651 ^{0}C when exposed to the atmosphere [16]. Ammonia is used as fertilizer in agriculture in about 80% of the world's production. The remaining 20% of workers do tasks including water purification, refrigeration, and industrial production [17]. For example, synthetic fibers such as nylon and rayon are manufactured using ammonia in the clothing industry.

The rubber industry uses ammonia to prevent coagulation of raw latex [18]. In order to balance the acidic byproducts in petrol refineries, it is also used. In the industrial production of acidic solution (Ostwald process) and sodium bicarbonate (ammonia soda process, also known as the Solvay process), ammonia is frequently used. It is also in a lot of home and commercial cleaning products [19]. Ammonia solutions for cleaning purposes in the home have moderate concentrations of 5–10% ammonia in the water, but ammonia solutions for use in industry have corrosive concentrations of 25–35%. In terms of safety, breathing ammonia could be risky. Low quantities (0.6-53 ppm) of it are easily noticed due to its overpowering, strong fragrance [20], significantly below its harmful limits.

The "Immediately Harmful to Life or Health (IDLH)" ammonia concentration is 300 ppm. Ammonia also quickly evaporates into the atmosphere above in the event of an accident since it is lightweight than air. Ammonia is a different potential carrier of hydrogen energy. It has 17.6-wt% hydrogen as opposed to 12.5 wt% methanol. Liquid anhydrous ammonia has a substantially higher volumetric hydrogen energy density than liquid hydrogen and other common liquid fuels (such as methanol, ethanol, and petrol). [21]. Ammonia may be easily split to create hydrogen for usage in fuel cells and other hydrogen-based devices. When employed as an energy source, its direct burning could only produce nitrogen as well as water at low combustion temperatures, which makes it a carbon-free fuel that is environmentally friendly. Ammonia can be used as a direct fuel for combustion engines or high-temperature, alkaline fuel cells that are very resistant to leftover ammonia. Even though concentrations of ammonia as little as 0.1 ppm can quickly damage low temperature fuel-cell devices with acidic membranes. Liquid ammonia is more readily available and safer to store, transport, and distribute than hydrogen. At room temperature, ammonia is easily liquid and may be maintained at low pressures (1030 kPa) and low temperatures (240 K).

Contrarily, hydrogen must be kept either as liquid at ambient temperature or at much greater pressure (24,821 kPa) when cooled to a minimum temperature of 20 K. As a result, hydrogen storage systems are more expensive than the ammonia storage tanks needed. Another benefit of using ammonia as fuel is that there are well-established and documented processes for handling big volumes, and in many countries, there is infrastructure for the movement of goods by pipelines, roads, and trains. Compared to other types of Conventional fuel, ammonia is a competitive fuel.

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For instance, ammonia operates efficiently at higher compression ratios (CR) than petrol and natural gas because it has a higher-octane number [22]. Although stored ammonia has a higher energy density than gaseous or liquid hydrogen and compressed natural gas, it has a lower energy density than petrol and diesel. Ammonia is being used more frequently as a potential low carbon fuel, and in the next ten years, its market is expected to rise by up to 3% while still being classified as a conventional fuel source [23]. Table 1 compares ammonia's fuel characteristics to those of other fuels.

Ammonia is the second most common chemical produced worldwide [24]. There are numerous methods for creating ammonia. The two most common strategies are described in the following explanations.

III. THERMO-CATALYTIC PRODUCTION OF NH3:

Using a Carl Bosch and Alwin Mittasch-discovered iron catalyst, Fritz Haber created the first thermocatalytic ammonia synthesis method that was used commercially. A lower temperature and greater pressure are more favorable for the exothermic process that produces ammonia from hydrogen and nitrogen. The Haber Bosch method predominates in industrial ammonia production [24]. In this method, ammonia is produced using a catalyst made of iron and a hydrogen-to-nitrogen ratio of three to one, operating between 723 and 873 K and 10 to 25 MPa [25]. Every run of the Haber Bosch process results in a 15–25% conversion of reactants to ammonia, but because the unaffected gases are recycled, a final convert of 97% is achieved [26].

$$N_2 + 3H_2 \quad \leftrightarrow \quad 2NH_3 \qquad (1)$$

Equation 1 depicts the thermocatalytic process for the Haber-Bosch process. Due to the presence of an extremely stable $N \equiv N$ nitrogen structure with an abnormally high binding energy of 911 kJ/mol, the method for creating ammonia is kinetically constrained [27]. The nitrogen molecules need a lot of energy to break down on the catalyst's surface; hence, a high temperature is required. because the reaction is reversible, High pressure is employed to encourage equilibrium in the direction of the product, enhancing reaction conversion and decreasing the breakdown of NH3 to N2 in the opposite direction. Ammonia under rather benign reaction circumstances. Over the preceding century, extreme conditions of pressure and temperature were necessary for the commercial Haber-Bosch production of ammonia over Febased catalysts. Ruthenium (Ru) based on carbon was thought to be a more efficient catalyst than iron (Fe) up until 197 [28]. Ru-based catalysts, the second version of catalysts, have high activity at lower temperatures (573-723 K) and pressures (40-150 bar), have received extensive research, demonstrating the benefits of energy conservation, enhancing equipment dependability, and ultimately lowering operating costs [29]. Ru-based catalyst was used in several procedures. The BP and Kellogg Companies developed the KAAP (Kellogg Advance Ammonia Technology) technology, which used a Fe-catalyst reactor followed by a Ru-catalyst reactor to reduce the artificial pressure and energy consumption to roughly 1 bar [30]. A method for producing ammonia was also devised by Zhu et al. [31] using multiple reactors connected in series, which increased conversion while reducing gas recycling and power usage. Consequently, the ammonia industry's development tendency was to adopt an energy-saving catalyst that operates at lower temperatures and pressure levels. In the Haber-Bosch method, methane from a natural gas source is steam reformatted to produce hydrogen, while air separation as shown in equation 2 produces nitrogen.

$$CH4 + 2H2O \leftrightarrow \; 4H2 + CO2 \qquad (2)$$

Countries have several options for hydrogen sources. More than 72% of the ammonia produced worldwide is made using natural gas, and ammonia prices are directly correlated with natural gas prices.
China, in contrast, produces ammonia mostly from coal, which leads to greater greenhouse gas emissions and energy use than anywhere else in the world [32].

Carbon dioxide (CO2) and other greenhouse gases are released when fossil fuels are used as feedstock. The production of CO2 free ammonia has been the subject of recent study. By employing renewable energy to electrolyze water, H2 may be created, which can then be used to synthesis this green ammonia [33]. The Haber Bosch synthetic cycle is being used in two pilot plants to test the power-to-ammonia concept, one in Minnesota, USA, and the other in Oxfordshire, UK.[34]. According to estimates of 50–60%, power-to-ammonia efficiency is less than that of the most recent conventional Habere Bosch ammonia manufacturing plant. Due to increased energy needs and energy losses during the electrolysis of water, efficiency has declined [35].

IV. ELECTROCHEMICAL AMMONIA SYNTHESIS:

Electrochemical ammonia production is the other broadly applicable technique. According to the electrolyte type that is used, this procedure can be divided into three groups. According to the sort of electrolyte membrane being used, the different kinds of electrolytes include (i) liquid electrolytes which operate close to 25 ºC.(ii) composite electrolytes made of a solid electrolyte and a low melting salt that operate at 300-700 ºC and (iii) molten salt electrolytes that depend at 300-500 ºC [36]. For various electrode, electrolyte, and operating circumstances, each electrolyte system provides a selection. Solid electrolyte membrane-based electrochemical methods are more adaptable since they can operate under a variety of circumstances and make it simple to separate hydrogen feed from the ammonia product [37]. Ammonia may be manufactured using either Equation (3) or Equation (4) in the electrochemical method [36].

$$N_2 + 3H_2 \quad \leftrightarrow \quad 2NH_3 \qquad (3)$$

$$NH3 + O_2 \quad \leftrightarrow 2NH_3 + 1.5O_2 \qquad (4)$$

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Table 1: Main differences between hydrogen, natural gas, ethanol, and petrol and diesel

Used fuel	Energy content (LHV)		Octane number	300 Mile range - tank size (30mpg gasoline equivalent)	Tank size for a 500 km range (12.75 km/litre petrol equivalent)	Maximum particle at compression ratio
	Btu/gallon	MJ/litre		Gallons	Litres	
Diesel fuel	129500	36.1	8_15	8.8	34.5	23:1
Biodiesel	118300	32.98	25	9.6	37.8	23:1
Gasoline	114100	31.81	86-94	10	39.2	10:1
LPG [Propane]	84300	23.5	120	13.5	53.1	17:1
Ethanol	76100	21.21	109	15	58.8	19:1
Methanol	56800	15.83	109	20.1	78.7	19:1
NH3	41700	11.62	130	27.4	107.3	5:1
CNG [3600psi]	41000	11.43	120	27.8	109.1	17:1
Hydrogen[10Kpsi]	16000	4.46	130	71.3	279.5	
Hydrogen[5Kpsi]	6500	1.81	130	175.5	688.1	
Lithium-ion Battery	3870	1.08	NA	98.3	385.2	NA

Purified hydrogen and nitrogen are typically used in the electrosynthesis of ammonia, which typically exhibits high conversion rates but necessitates high temperatures (>473 K). Natural gas and water electrolysis, used in the manufacture of Haber-Bosch ammonia, are two possible sources of hydrogen. In addition to creating ammonia that is free of CO2, hydrogen produced from water electrolysis using wind or solar energy sources would also remove the risk of the catalyst becoming poisoned by traces of sulphur compounds or carbon monoxide (CO), which are typical impurities in hydrogen produced through the steam reforming of natural gas [38]. In a typical electrochemical reaction, the anode receives hydrogen, which is followed by protons forming at the electrode/electrolyte interface, protons moving through the electrolyte, and the cathode interacting with nitrogen to produce ammonia while absorbing protons. However, electrochemical reactions that take both nitrogen and water as input produce ammonia by converting water into electrons, protons and oxygen, and at the anode of an electrical circuit and providing protons and electrons for mixing with nitrogen at the cathode. Research in this area has increased because it is necessary to more effectively and carefully manufacture ammonia in controlled environments. Regarding its capacity to generate ammonia at a lower price under various temperature conditions, the Haber-Bosch process is contrasted with the electrochemical approach. The electrochemical process' effectiveness is affected by the temperature conditions at operation.[39]. The development of electrochemical infrastructure for ammonia generation is the subject of current study. The electrochemical method has been stated to have a minimum energy efficiency of 60%. This technique is still being examined because it is unclear how quickly materials deteriorate and how long most materials will last, as well as how electrochemical cells will perform in surroundings with ammonia.[40].

V. CONVENTIONAL INTERNAL COMBUSTION ENGINES:

Internal combustion (IC) reciprocating engines burn fuel and oxygen internally to produce heat energy, which is then converted into mechanical work. Direct injection (DI) engines are those that inject gasoline directly into the combustion chamber before the cylinder's intake ports of the engine. When the fuel's autoignition temperature is achieved, compression is used to ignite the fuel and air, which are referred to as CI engines. Gasoline engines use a spark as their ignition source [41]. Because of this diesel engines run at relatively high compression ratios to make sure the fuel can reach the autoignition temperature. However, this frequently results in higher NOx emissions and higher combustion temperatures [42]. Alternative combustion approaches, such as lean operation or low combustion temperature methods, have been created to reduce NOx emissions from CI engines. The air and fuel benefit from a prolonged mixture generation outside the cylinder chamber in a low combustion approach like homogenous charge compression ignition (HCCI) [43]. In cylinder, Air fuel combination is introduced and compressed to autoignition. The fuel is delivered into the cylinder early in the intake stroke in the premixed charge combustion ignition (PCCI), on the other hand, to allow enough time for a homogenous mixture before combustion. When the piston hits the top dead center, a brief fuel injection may be used to start the homogenous mixture burning [44]. Despite these methods' advantages, such as reduced NOx emissions, they frequently have low combustion efficiency with unburned fuel, poor combustion phasing control, and constrained operating ranges. Higher intake pressure and lower equivalency ratios

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are used to operate an engine in a lean manner. The use of boosting equipment, such as a turbocharged engine or supercharger, may result in excessive intake pressures. With only a slight increase in the engine's breathing while keeping a low air-to-fuel ratio, the same amount of power output may be generated. Exhaust gas recirculation (EGR) is often used in diesel engines to reduce the formation of NOx by increasing the heat capacity of the intake gas and lowering the oxygen content of the intake charge [45].

VI. Premixed Charged Compression Ignition (PCCI):

Premixed Charge Compression Ignition (PCCI), also referred to as partially premixed compression [PPC] or gasoline direct injection compression ignition [GDCII], has the potential to develop into a promising combustion technique that can be applied as a remedy to the operational issues that the HCCI strategy has encountered. Between PCCI and HCCI combustion, there is a variation in the way the air-fuel combination is made. Like PCCI, just a portion of the fuel is necessary to create the homogeneous mixture [46]. Therefore, mixing in Premixed Charge Compression Ignition is less complicated than mixing in Homogeneous charge compression ignition. The Partially premixed charge compression ignition engine is also restricted to medium loads despite having a greater operational range than the Homogeneous charge compression ignition engine. To create an appropriately longer ignition delay and enhance the air-fuel mixture, the Premixed Charge Compression Ignition technique separates fuel injection from the commencement of combustion. Homogeneous charge compression ignition and traditional CI engines are combined in this hybrid combustion technology [47]. Charge Compression with Premixing Because the charge is premixed, ignition engines resemble SI engines to some extent. Additionally, they are similar to CI engines in that the fuel-air mixture auto-ignites because of compression, resulting in good thermal efficiency under partial load circumstances. Because the PPC method requires little modification to the hardware and software of a typical engine, the premixed charge is initially formed in the premixed charge compression ignition by dividing the fuel quantity into two parts [47]. The remaining portion's injection timing was utilized to manage the fuel ignition while the minor portion's injection timing was used to advance the injection time in order to prepare the homogeneous mixture. On the other side, early injection timing results in wall impingements, which reduces thermal efficiency and mandates the use of multiple or split injection modes for the fuel injection. This results in inadequate combustion and substantial amounts of hydrocarbon and carbon dioxide emissions. Three fuel delivery methods—port fuel, late direct injection of fuel and advanced direct injection—are employed in premixed charge compression ignition mode. It has been suggested that premixed charge compression ignition might improve performance and exhaust emissions given the right amount and duration of injection [48], as well as the right EGR settings for two-stage injection. Also, by extending the initial injection time and placing the second injection time near to TDC, it is possible to obtain much improved thermal efficiency at lower emission levels and mild pressure increase rates at large loads. Another investigation was conducted to learn more about the emission and combustion characteristics of a diesel PCCI engine with different start of injection and Intake valve closing timings [49]. In this work, a full-cycle, three-dimensional computational fluid dynamics [CFD] model was employed, together with exact kinetics of chemicals. They stated that reducing the combustion temperature, delaying Intake valve closing (IVC) timing, and optimizing start of injection (SOI) timing resulted in fewer Nitrogen oxide emissions. However, in instances of early SOI and late IVC, the substantial wall-wetting zone brought on by low ambient pressure causes an increase in HC and CO. ISFC is reduced in cases with advanced start of injection sequence around -25 0CA After top dead center and delayed Intake valve closing timing because the use of late Intake valve closing timing successfully delayed the ignition timing at top dead center, lowering compression work. For cases with advanced start of injection timing of -15 ^{0}CA after top dead center and early Intake valve closing (IVC) timing, ISFC is decreased because the ignition timing and combustion efficiency were optimized. Therefore, it is important to properly modify the start of injection (SOI) and Intake valve closing timings. A high injection pressure and different exhaust gas recirculation (EGR) rates are necessary to improve the air-fuel mixing process and produce enough delay in ignition to achieve effective premixed charge compression ignition combustion because the low volatility of the diesel fuel injected at the start of the compression stroke makes it simple for the fuel to stick to the cylinder. Using a premixed charge compression ignition diesel engine with early and late injection timings, the effects of injection parameters and exhaust gas recirculation on combustion characteristics and exhaust emissions were studied [50]. Higher injection pressure increased indicated mean effective pressure [IMEP] and indicated thermal efficiency [ITE] with late and early injection timings because quicker combustion increases heat release rate. In addition, the increased injection pressure reduced Nitrogen oxide, smoke, and Hydrocarbon emissions while mostly maintaining Carbon monoxide emissions. The application of EGR decreased soot and Nitrogen oxide while increasing stated thermal efficiency and indicated mean effective pressure but increased Hydrocarbon and Carbon monoxide emissions instead. a result of the spray hitting the piston wall at an optimal aiming point, which increased fuel-air mixing, the injection timing = 20 Before top dead center (BTDC) with EGR was the best injection timing that delivered simultaneously low soot and Nitrogen oxide emissions [51]. Additionally, by examined and contrasted the impacts of fumigated ethanol and EGR on premixed charge compression ignition performance, greenhouse emissions and combustion characteristics. At various loads, the engine was run with various blends of EGR, diesel, and ethanol. They claimed that at 15% ethanol fumigation, Brake thermal efficiency (BTE) displayed its highest value. In comparison to pure diesel combustion, Nitrogen oxide and soot emissions were decreased at 15% ethanol fumigation. Higher hydrocarbon and Carbon monoxide emissions have been observed with the use of EGR and ethanol fumigation, although performance and exhaust emissions remained unaffected. Similar to this, an open electronic control unit (ECU) was used in a study by. It was configured to run the

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engine in premixed charge compression ignition combustion mode up to middle engine loads and then automatically transition to conventional diesel combustion [CDC] mode at higher engine loads [52]. This electronic control unit (ECU) was used to mode switch between conventional diesel combustion [CDC] and premixed charge compression ignition combustion modes. In this study, the performance and emissions characteristics of the mode switching were investigated using a 2-cylinder,4-stroke direct injection engine run by mineral diesel and B20. When compared to conventional diesel combustion [CDC], premixed charge compression ignition combustion mode dramatically reduced particle and NO$_X$ emissions while modestly increasing CO and HC emissions for both test fuels. According to the conventional diesel combustion [CDC], B20 had much reduced Carbon monoxide and particle emissions. For mineral diesel, on the other hand, marginally lower NO$_X$ emissions were observed. According to the findings, biodiesel and mineral diesel blends have identical engine performance, but they greatly improve both modes' engine emission characteristics. This investigation demonstrates that premixed charge compression ignition [PCCI]combustion is appropriate up to medium loads and traditional conventional diesel combustion [CDC]at larger loads [53].

VII. FUEL PROPERTIES' IMPACT ON PCCI ENGINES:

The quality of the fuel has an immediate influence on the engine's starting time, rate of pressure, heat release, and temperature profile. This affects the emission, performance, and combustion properties of the premixed charge diesel engine simultaneously [51]. Density has a big influence on spray pattern and spray tip penetration (STP); because fuel has more velocity at lower densities, the spray pattern is bigger and the STP is shorter. Low viscosity fuels yield fewer fuel droplets, which results in greater spray and atomization being produced. This makes it easier for the fuel injection system to transfer gasoline into the cylinder. The viscosity of the petrol affects the penetration and atomization of the fuel spray. In general, fossil fuels have a greater calorific value than fuels made from renewable sources since they have lower calorific values overall than fuels with more carbon and hydrogen molecules. With increasing latent heat of vaporization, a liquid fuel requires more thermal energy to transform into a vapor or gas [54] as a result, they can only be utilized in engines that have undergone certain engine modifications, such as adding external heaters, raising the compression ratio, adding thermal insulation, and blending fuels. Alcohol and other fuels with greater ON have higher auto-ignition temperatures. They have been rated an amazing blend for the extension in ID because they enhance premixing and spray-driven combustion but may negatively affect the diffusion phase of the combustion. Due to these factors, choosing the right fuel type can improve engine performance and characteristics. Several studies have been done to look at the effects of utilizing different fuels under various conditions in order to increase thermal efficiency and reduce pollutants during combustion [55]. Before wheat germ oil is pumped directly into the combustion chamber, a mixture of bioethanol (10, 20, and 30%) is delivered into the inlet port. The findings indicated that the fuel (WGO) has a decreased volatility, increased density, and viscosity, which results in poor atomization and a gradual release of heat. This increases the temperature of the exhaust gas and lengthens the ignition delay [56]. Peak pressure is reduced because of a lower calorific value. The lowest braking thermal efficiency of WGO is produced by these combustion circumstances for all loads. Furthermore, while HC and CO emissions may increase under these combustion conditions, NOx emissions may decrease. Because of its favored characteristics, the early injection of bioethanol delivers a more homogeneous charge than the early injection of primary fuel wheat germ oil. At the end of the compression phase, when the main fuel source is injected, combustion commences. Because bioethanol burns more quickly than other fuels, these results in premixed combustion lasting longer, which reduces diffusion combustion time. According to the findings, increasing by adding bioethanol due to the biofuel's high flame rate, premixed combustion improves (more heat flows out near top dead Centre, converting to more work output), the ignition delay period decreases, and the combustion duration increases due to the biofuel's high latent heat of vaporization, resulting in increased brake thermal efficiency [57]. Due to its extremely low volatile and viscosity, bioethanol efficiently combines with air to form a uniform mixture throughout the intake & compression process, which increases peak pressure and heat release. For these reasons, adding bioethanol also reduces the production of greenhouse emissions.

Elkelawy and associates ran the tests on 1-cylinder diesel engine at 17CRand1500 rpm. They created two blends: one with 40%biodiesel and 60% diesel (B40-D60), and the other one with 20%biodiesel and80%diesel (B20-D80), to study the impacts of combining biodiesel and diesel fuel blends. However, there were three separate changes to the premixed fuel blends that vaporized 20%, 25%, and 30%. The Brake thermal efficiency values of B40-D60 blend increased from 19.34% to 29.91%, according to the results. The B40-D60 engine produces the lowest levels of Carbon monoxide and Hydrocarbon emissions when it is running because of the high oxygen content of the fuel and the adjustable timing of the injection for the intake manifold charge. Nitrogen oxide and smoke pollutants are at their lowest when using B40-D60. For the mix with higher biodiesel content, this led to a larger BTE and a noticeable reduction in Carbon monoxide, Hydrocarbon, Nitrogen oxide, and soot emissions.[58]

Hildngsson et al. studied the effects of gasoline octane number [ON] using a one -cylinder light-duty CI engine at low loads & speeds (4barIMEP/1200rpm) without EGR aswellas at higher loads & speeds (10barIMEP/ 2000and3000rpm) with Exhaust gas recirculation [EGR]. The experiments utilized four petrol fuels with RONs of 72, 78, 84, and 91 as well as a standard diesel engine fuel with a fixed entry temperature of 60°C. They stated that under low load, soot rates for all fuels were quite low. High RON petrol emits much less Nitrogen oxide than diesel fuel because of a slightly longer delay in ignition and better air-fuel mixing. At large loads, all the fuels showed little Nitrogen oxide below0.3g/kWh and sufficient Exhaust gas recirculation. Diesel fuels have considerable levels of smoke, whilst petrol had comparatively moderate levels. Lean fuel burning at low temperatures causes incomplete combustion, which increases the amount of carbon monoxide and

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hydrocarbons in petrol fuels. With petrol fuels, however, the amount of hydrocarbon and carbon monoxide might be reduced by lowering the injection pressure. The testing showed that in order to boost mixing rates and overcome the short delay in diesel ignition, tiny nozzles and significant injection pressures are needed. With bigger nozzle diameters & lower injection pressures, the ideal Research octane number (RON) range may be between 75 & 85. Another study examined the impact of Research octane number on engine performance using a one-cylinder engine operating at15:1CR, three naphtha fuels with Research octane number (RON) values of 60, 70, and 80, as well as E10 petrol. The standard test fuel was "RON 91". As a consequence of optimal combustion phasing and duration, little unburned fuel, and minimum heat transfer, the RON80 naphtha had the lowest specific fuel consumption and maximum indicated thermal efficiency (ITE) of all the fuels at 800RPM and low loads, according to the data. Thermal efficiencies increased from RON80 to RON60at1500RPM and medium loads, while RON60 naphtha had better-indicated thermal efficiency (ITE) equivalent to E10 fuel [59]. However, large loads are limited for the naphtha fuels (RON80 at 1.42MPa IMEP, RON70 at 1.1MPa Indicated mean effective pressure (IMEP), and RON60 at 0.76MPa IMEP) due to the demand of higher Exhaust gas recirculation rates, which replaced injected fresh air. Only E10 petrol was allowed to operate at 1.5MPa Indicated mean effective pressure (IMEP) because it had very low specific fuel consumption (SFC) and a high indicated thermal efficiency (ITE). The impact of fuel characteristics on the combustion, performance, and emissions characteristics of premixed charge compression ignition (PCCI) engines are outlined in Table 2. [60]. Increased octane fuels, like petrol, ethanol, butanol, etc., promote better air-fuel mixing that lowers soot emissions & Nitrogen oxide due to higher latent heat of vaporization and lower combustion temperatures, but results in higher carbon dioxide and Sulphur dioxide emissions due to incomplete combustion [61]. Therefore, to improve combustion and reduce carbon monoxide and hydrocarbon, wider nozzles, earlier injection timing, and lower injection may be necessary for lower reactivity fuels. However, fuels with a higher viscosity and density, such as diesel, biodiesel, and others. To prevent fuel from being trapped in the cracks, a later pilot injection with a smaller fuel ratio was necessary, and a greater injection pressure was needed for improved atomization. For improved air-fuel mixing, a larger exhaust gas recirculation ratio is also necessary.

Table 2: Impact of fuel qualities on PCCI engine efficiency

Author	Test rig engine	Type of fuel	Condition of test	Results on performance and emissions
Viollet et al. [62]	diesel engine with single cylinder, CR = 12:14, Vd = 499 cc	M.O.N. = 40& 63& 84, R.O.N. = 40& 68 and 93	$P_{inj.}$ = 4 & 15 MPa RPM between 1000-3000 Max. load = 10 bar	NOX is Increased, Hydrocarbon and CO are decreased. RON 40 at 14 CR
Kaya et al [63].	CI engine with single Cylinder V_d = 1498 cc CR = 16	Biodiesel B100 Diesel B0 B30	Power = 0 to 5 kW RPM = 2000 EGR = 22 to 60 % Pinj. = 65 MPa	with the addition of biodiesel ID, BTE and Soot are decreased, NOX is increased
Cardone et al. [64]	CI engine with single Cylinder Vd = 477 cc CR = 16.5	LPG - Diesel blends with 20% & 35% by mass	Injector hole =7 RPM= 2000 Nozzle diameter = 0.141 mm, $P_{inj.}$ = 75 & 85 MPa Spray angle = 148^{O} IMEP = 2 & 5 bar	ID, NOX are increased and Hydrocarbon, CO are decreased with increasing the LPG fraction & Soot has a 95% reduction with the use of LPG
Ahmed Mohammed Elbanna et al. [65]	Highly premixed dual fuel. direct injection (TDI) triple-combustion model	Diesel and ethanol of RON 80	Intake air temp. = 38°c RPM= 1500 Injector hole = 8 diameter = 0.124 mm Nozzle hole cone angle = 120◦	↑ ITE, ↓ NOX, ↑BTE
Ahmed Mohammed Elbanna et al. [66]	PCCI engine with Direct Dual Fuel Stratification (DDFS)	25% ethanol + 75% diesel by volume	RPM= 1500 Intake air temp. (◦C) = 38 the fast Fourier transform of the cylinder vibration statistics was used	↓ vibration intensity, controllability of the start of combustion and burning period, ↓NOX, ↓ CO and ↓UHC
Jing-zhou Yu et al. [67]	Homogeneous charge compression ignition (HCCI) engine	DME/diesel blends in the the blend of 25%, 50% and75% DME by mass	RPM= 1200 Intake air temp.(◦C) =25,60,100 nominal injection timing (TDC) = -20 ^{0}CA Needle open pressure (Mpa) =7,10,15,20	50% DME mass fraction in the blended fuel is the optimum ratio under injection pressure= 15MPa and 20MPa.
Medhat Elkelawy et al [15]	PCCI-DI engine brand DEUTZ FL 511/W with one cylinder	Diesel, biodiesel (B20, B40)	Compression ratio =17& Bore- Stroke = 100 mm-105 mm& Weight= 116 kg Displacement= 825 cm3 & Power=7.7Hp =5.7kW& Inlet valve opens= 32◦	↓the peaks of the in-cylinder pressure, ↓ heat release, ↓ BTE, ↓ NOX, ↓ CO_2

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			BTDC& Exhaust valve opens= 71◦& BBDC Inlet valve closes= 59◦ ABDC& Exhaust valve closes= 32◦ATDC& Injection pressure= 115 bar	

VIII. EARLY RESEARCH YEARS:

The 1940s were an important period for the ammonia-fueled IC engine. There were dangerously low oil reserves because of the Allies' oil campaign during World War II against the occupiers, which involved eliminating any oil refineries and storage facilities. Ammonia appeared to be the most practical and available alternative fuel at that time to power armoured battle vehicles and other military vehicles. Kroch [68] published the results of a yearlong research conducted by the S. N. C. F. V. (Societ e Nationale des Chemens de Fer Vicinaux, the Belgan State-supervised system of suburiban and rural transport by rail and road) in collaboration with Belgian experts in 1945. According to the author, liquid anhydrous ammonia was utilized as a motor bus fuel for the first time in 1943. Kroch focused a lot of his research on the advantages of burning ammonia with coal gas. According to the author, liquid anhydrous ammonium was utilized as a motor bus fuel for the first time in 1943. In Kroch study, noting that there was no power loss, no corrosion, and no additional lubricating oil usage when compared to the vapor oil engine. The author's last claim in the description of his work was that other gases, including hydrogen, might simply substitute the coal gas employed as the ignition promoter, resulting in a fully coal independent operation. Ammonia has been used as a fuel for vehicular purposes since as early as 1822. Thurston's book claims that Sir Goldsworthy Gurney became the first to propose and develop ammonia-powered engines for a miniature locomotive [69], These details the growth of the engine using steam over time. At the beginning of the 19th century, it was believed that using ammonia, as an anti-knock agent would allow internal combustion engines to run at high speeds with perfect combustion and high average pressures. This was a few decades later. Norsk Hydro became one of the first companies to use a pick-up vehicle with an altered engine that operate with ammonia-hydrogen in 1933. Ammonia Casale Ltd. received a patent for an engine with an internal combustion system that burns hydrogen and ammonia in 1938, and by the beginning of the 1940s, it had been put into around 100 vehicles. Ammonia was used less often as a power mover after the 2nd World War and the restart of oil supply. In order to address any possible fuel logistical issues, the US Military launched a sizable initiative (the Energy Depot project) in the 1960s to research alternate energy producing technologies [70]. For this research, multiple fuels, including hydrogen, ammonia, and hydrazine, were tested in a one-cylinder Waukesha engine using local resources (such as soil, air, and water). The analysis performed by the researchers showed that using ammonia as an alternative for fossil fuels in civilian applications is feasible. In 1967, Pearsall and Garabedian studied and tested two distinct methods for the creation of an IC engine that runs on anhydrous ammonia. In their initial approach, the scientists tested the engine in a diesel condition utilizing a double-fuel strategy and diesel fuel. The 2nd method involved converting the engine to another that runs by gasoline. The authors came to the conclusion that there are numerous applications where the ammonia idea would be workable, even though the price of ammonia might be five to ten times larger than the price of the quantity of HC fuels needed to create the same amount of energy. This may be done to produce ammonia locally, get ready for an oil crisis such as the one that occurred during World War II, or run military operations in remote locations where it's hard to get hydrocarbon fuels. Starkman et al. reported the findings of a study on the use of ammonia for gasoline engines that was carried out under contract to the United States (US) Army Materials Command in 1968. The results showed that the SI engine performed satisfactorily as ammonia was supplied as a vapor after being first broken down to hydrogen and nitrogen at the applied compression ratios. When ammonia was used in place of the hydrocarbon engine, a power output shortfall of between 70 and 77% was observed [71]. The inclusion of liquid ammonia, however, could fix the observed power output deficit, according to the scientists' calculations. A few occasional investigations on the use of ammonia for IC engines have been published in the literature since the Energy Storage Project's closure [72], However, no substantial actions have ever been done to put this idea into practice. The global economy critically needs to decarbonize, though, and ammonia has recently sparked renewed attention in this regard. Due to its lack of carbon emissions and ease of storage and transportation, ammonia seems to be the best alternative for lowering fossil fuel usage and assisting in the reduction of emissions of greenhouse emissions.

IX. RECENT DEVELOPMENT:

Numerous businesses and research teams have investigated the idea of using ammonia for autos over the past few decades. Greg Vezina of the business that is presently known as Hydrofuel Inc. displayed his modified Chevrolet Impala that ran on ammonia fuel in 1981. On July 31, 2007, a pickup truck running on a mixture of ammonia and petrol set out from Michigan's Detroit to San Francisco to show the practicality of ammonia-powered vehicles. The Marangoni Toyota GT86 ECO was the first racing car to run on ammonia fuel, and it was displayed at the 2013 Geneva Motor Show [73]. The ammonia fuel for the car had a 180 km range and permitted 2800-rpm engine speeds. Direct-injected petrol was used to drive the engine at greater velocities. The Hydrogen Energy Centre, a Nevada-based business known as "HEC Inc.", said in November 2014 that it has developed a tractor run by ammonia that is free carbon. In 2014, researchers from the Korean Academy of Energy Research demonstrated a functional car that utilized 70% petrol (direct injection) and ammonia (port injection) [74].

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Ezzat and Dincer have suggested creating a unique integrated carbon-free fuel system specifically for automobiles that run on hydrogen and ammonia [75].

The system suggests a novel way to generate hydrogen on board using ammonia's electrochemical splitting. The power generation and maritime sectors also benefit from using ammonia as a fuel. Power generating and maritime applications, which are not space-constrained like the automobile industry, can use catalytic technology to reduce NOx levels. Ammonia has recently been proposed as a viable Power-to-liquid technology to create a hydrogen economy. According to a recent statement from the international corporation MAN Energy Solutions, the 3000 B&W bi fuel engines for marine that burn both diesel and LPG (liquefied petroleum gas) currently serve as the power source for 50% of global commerce activities [76].

X. ENGINE SYSTEM MODIFICATIONS:

Ammonia is used in a standard IC engine without significantly altering the engine's geometrical characteristics. In pertinent experimental tests, ammonia is frequently port-fuel injected into the engine's intake system or close to the intake valves. Alternative methods such cooling ammonia liquid injection, ammonia-fuel mixes, and directly in-cylinder injection are also discussed in the literature but are less common [77]. To keep the engine's operational capability intact & small adjustments to the compression ratio & gasoline system and fuel line materials may be necessary. The minimal compression ratio for smooth engine performance is largely reliant on the source of ignition for the air-fuel combination and the cetane number of the other fuel in the event of continuous ignition operation because ammonia is particularly resistant to auto-ignition. Additionally, ammonia must be avoided because it corrodes some materials like copper, nickel, and plastics. The ammonia can be more evenly distributed from cylinder to cylinder with the aid of a mixer, and the engine's boosting mechanism can avoid corrosion by having ammonia added after the compressor outlet. By flashing the fuel pump and injector with the engine's normal fuel (such as diesel or gasoline) before turning the engine down for a considerable amount of time (such as at the end of each experimental day), engine corrosion can be avoided in a laboratory study environment [78]. It could be necessary to alter the ignition substance and spark plug mechanism when ammonia fuel undergoes catalytic conversion into hydrogen before being fed to the engine to prevent backfiring. A typical reason for backfiring is any electrical energy left in the spark cable, which results in a second discharge during the intake stroke and a mix of air and fuel ignition at the intake port since hydrogen has a low ignition energy.

Two key times may be used to split the ammonia research activity for internal combustion engines. The most recent period, which began with the turn of the millennium, and the early era, which spanned the 1960s and 1970s, the precise study goals represent the major distinction between the two periods. Engineers and scientists concentrated on creating engines that could use alternate fuels in the early years, shortly after the conclusion of World War II, to be ready for any impending oil crisis [79]. By (partially) replacing fossil fuels with carbon-free alternatives, the main research objectives for the next period are to lower greenhouse emissions. Ammonia is a dependable fuel for these sorts of engines, as demonstrated by several tests on ammonia-fueled spark ignition engines. A high-octane rating for ammonia is advantageous since it might enhance combustion properties and lessen engine knocking and other detrimental combustion effects found in gasoline engines. However, due to the fuel's high autoignition resistance, ammonia combustion in diesel engines is a difficult operation. This study is primarily concerned with the use of ammonia in reciprocating compression ignition engines for power production, heavy-duty, and nautical purposes. If the reader is curious, they may look at a number of studies that focus on the use of ammonia as a fuel for gas turbines and fuel cells, as well as for internal combustion engines and a wider range of applications [80].

The early year study period on ammonia produced negative results for diesel engines because of the fuel's poor combustion properties, which include a high autoignition temperature, a low flame speed and limited range flammability, and a high heat of vaporisation. The only engine types that could use ammonia compression ignition were those with extremely high compression ratios, ranging from 35:1 to 100:1. The lengthy hiatus noted in the literature might be explained by the first period's failure to function. The research goals for the second term are instead mainly focused on minimising greenhouse gas output by partially substituting diesel fuel in a dual fuel operation with a variety of carbon-free alternatives [81].

XI. AMMONIA-ONLY OPERATION:

Wagner T.O. of American Oil Co. stressed the significance of transferring the Energy Storage project's work in ammonia combustion to diesel engines in his assessment notes on paper publications from 1965 [82]. Since many of the vehicles used by the Armed Forces were operated by compression ignition engines, Mitchel H.R. and Huellmantel L.W. of General Motors Corp. agreed with Wagner's conclusion [74]. In his declaration, the engine can be operated on both pure ammonia and ammonia combined with different additives. Wagner stated that the engine might only be started on diesel and that when the engine had warmed up, ammonia replaced kerosene at a 35:1 compression ratio. The third and final stage of the Army Laboratory project then looked into how well the current injection systems worked together and studied different ways to use ammonia in CI engines. Wagner T.O. of American Oil Co. stressed the significance of transferring the Energy Storage project's work in ammonia combustion to diesel engines in his assessment notes on paper publications from 1965 [81]. Ammonia could only burn at a 35:1 compression ratio and a 423 K intake gas temperature, according to the study. High-temperature flame coils were shown to be superior sources of ignition to traditional glow plugs and noncombustible spark plugs. Proof was provided by Starkman et al. that altering a spark plug to ignite the injected fuel was necessary for liquid ammonia to be properly burnt in a diesel engine at standard compression ratios [83]. This is primarily explained by how challenging it is to ignite and burn ammonia. Pearsall attempted to run an AVDS-1790 Vee Twin CI engine with injection directly of

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liquid ammonia and a 30:1 CR without success [84]. Using ammonia in a single-fuel design is challenging due to the unusually high compression ratios (CR) required, even though some researchers have had experience operating ammonia-only conventional engines with diesel in particular engine settings [85].

XII. Dual-fuel operation using ammonia with diesel:

The idea of using ammonia in a dual-fuel engine is plausible since another fuel with a low autoignition temperature may be used to light the combination. In contrast to the 35:1 they employed for the ammonia-only operation; the researchers were able to operate a diesel with ammonia dual-fuel diesel engine [86]. The lowest CR (compression ratio) at which effective combustion was seen decreased to 12:1 and 13.7:1, respectively, when amylnitrate (100CN) and dimethylhydrazine (67CN) were employed in place of diesel. The researchers found that the secondary fuel's cetane rating had a significant impact on the low compression ratio needed for a stable operation. Additionally, the authors found that for satisfactory combustion to occur, before the end of the diesel injection, ammonia must be supplied into the combustion chamber no later than 40 crank angles. On the other hand, a late ammonia injection that took place just before the final stage of the diesel injection produced misfiring. The effects of the cetane rating of diesel fuel were also studied by Pearsall & Garabedian [87]. The author ran studies to see what would occur if the amount of petrol fed to the engine was modified while maintaining the status quo for all other variables. According to the authors, the increase in power produced for the lean condition was quadruple the heat content of the diesel fuel, demonstrating a requirement for substantially greater ignition energy. The modified spark plug ammonia-only engine performed significantly worse than the authors' mixed-fuel engine even while operating in optimal conditions. The flexibility to function at partial throttle, the increased reliability of the ignited source, and the decreased system complexity caused by the lack of auxiliary fuel storage are only a few of the advantages of spark ignition operation that the authors highlightedAmmonia gas was compared against methanol, ethanol and methane for appropriateness in Bro and Pedersen's study of the dual-fuel compression ignition operation with diesel pilot injection [88]. Ammonia was found to be the least suitable of the gaseous fuels under study by the researchers, primarily because it emits relatively large amounts of unburned ammonia. Because ammonia burns rather slowly, the ammonia-diesel engine had the biggest increase in ignition delay in addition to the lowest combustion efficiency and power output gain. Although it produced a lot of NOx, ammonia fumigation decreased the engine's smoke emissions. Reiter and Kong showed off the dual-fuel capability of an ammonia-powered diesel engine in 2008 [89]. The source of the pilot ignition was diesel fuel, and the engine was successfully operated at a variety of engine speeds, loads, and ammonia energy sharing ratios up to95% by the authors. For ammonia rates between40and80%, a combustion efficiency of approximately 95% was achieved, and for ammonia rates between 40 and 80%, a combustion efficiency of about 95% was achieved. According to the scientists, this is brought about by reduced combustion flame temperatures and the effect that ammonia has on the effectiveness of after-treatment systems in reducing emissions. Unburned ammonia emissions between 1000 and 3000 ppm were found at the engine's exhaust, and the hydrocarbon emissions deteriorated due to the combustion temperatures' comparatively low levels. However, the high ammonia content at the exhaust substantially exceeded that objective. Due to the fuel's slow flame speed and extensive quenching distance, low ammonia combustion efficiency is usually seen; this might cause petrol to become stuck in the crevice volume [90]. The engine was equipped with SCR (selective catalytic reduction) technology to cut back on Nitrogen oxide and unburned NH_3 emissions [91]. It was found that increasing the ammonia feed rate while maintaining the engine's power output caused lower compression, higher levels of pressure, and a longer ignition delay. The objective of another investigation by Niki et al. was to lessen the amount of unburned ammonia and nitrous oxide (N_2O), a gas that damages the ozone layer and has around 300 times the potency of CO_2 [92].

XIII. Ammonia and alternative fuels:

As was previously mentioned, Grey et al. were among the first research teams to think of using alternate fuels to ignite an ammonia dual fuel compression ignition engine. Instead of diesel, pilot fuels like amylnitrate and dimethyl hydrazine were utilized. Dimethyl hydrazine was selected as a secure lab alternative for hydrazine because it may be manufactured locally and is comparable to ammonia. The main factor causing the high level of observed dependence of the engine combustion characteristics on the pilot ignition source was discovered to be the cetane content of the tested fuels. When utilized with ordinary compression ratios, acetylene produced the greatest results of the additives tested, but hydrogen was favored when utilized with greater ratios of compression [93]. Tay et al. assessed the performance of an ammonia-fumigated compression ignition engine utilizing diesel, diesel-kerosene and kerosene pilot injections in a numerical simulation setup [94]. They found that switching from diesel to kerosene as the pilot fuel resulted in an earlier ignition that benefited from full ammonia combustion. Dimethyl ether requires pressurization to maintain its liquid state since it is similar to ammonia in that it has a high vapour pressure and a high cetane number [94]. Due to the mixed nature of ammonia and dimethyl ether (DME), the researchers employed a newly built injector to directly inject stable mixes of ammonia DME solutions into the cylinders of a diesel engine. Performance evaluations were done on three distinct 20%NH_3+ 80%DME, 40%NH_3+ 60%DME, and 60%NH_3+ 40%DME and pure DME operating combinations. The findings, which included considerable ignition delays, low combustion temperatures, and higher CO and HC emissions, were in line with earlier studies on diesel ammonia [95]. Recently, Pochet et al. tested an ammonia-hydrogen-fueled homogeneous charge compression ignition (HCCI) engine [96]. The hydrogen induction system was designed to make engine operation more straightforward and stable when the mixture burned between 428 and 473 K at an intake gas pressure of 0.15MPa. The researchers recommended employing higher

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compression ratios and intake pressures with ammonia to lessen the requirement for intake gas heating and increase engine efficiency. However, as hydrogen has a propensity to pre-ignite, a variable compression ignition mechanism could be helpful for extending the engine's operation for various ammonia with hydrogen rates [97].

XIV. RECOMMENDATION FOR THE FUTURE WORK

Working to reduce carbon emissions is a major goal in the engine and power generation industries using carbon-neutral fuels such as ammonia and hydrogen, despite the difficulties they pose in production, storage, and transportation processes.

The use of one of the modern injection systems such as PCCI and HCCI is one of the most important research proposals in the task of reducing carbon and other emissions by making minor changes in the internal combustion engine.

Ammonia can be burned in the dual fuel system by injecting it with diesel, but it currently suffers from large emissions of unburned nitrogen oxides, despite the global view of it as a practical alternative to diesel fuel in applications that are not restricted to large areas, such as marine and heavy applications.

Recently, it is expected that more research will be conducted on the use of ammonia and how to burn it in internal combustion engines due to its carbon-free nature, and that this research will be combined with studies of advanced injection systems.

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REFERENCES

[1] K. Mollenhauer and K. Schreiner, "History and Fundamental Principles of the Diesel Engine," in Handbook of Diesel Engines, K. Mollenhauer and H. Tschöke, Eds., ed Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 3-30.
[2] E. Helmers, J. Leitão, U. Tietge, and T. Butler, "CO2-equivalent emissions from European passenger vehicles in the years 1995–2015 based on real-world use: Assessing the climate benefit of the European “diesel boom”," Atmospheric Environment, vol. 198, pp. 122-132, 2019.
[3] S. Bari and R. Marian, "Evolution of risk of diesel engine emissions on health during last 4 decades and comparison with other engine cycles: An innovative survey," p. V012T15A004.
[4] S. Anenberg, J. Miller, D. Henze, and R. Minjares, "A global snapshot of the air pollution-related health impacts of transportation sector emissions in 2010 and 2015," International Council on Clean Transportation: Washington, DC, USA, 2019.
[5] H. Carvalho, "The end of diesel-powered cars?" The Lancet Respiratory Medicine, vol. 4, pp. e2e3, 2016.
[6] R. Dua, S. Hardman, Y. Bhatt, and D. Suneja, "Enablers and disablers to plug-in electric vehicle adoption in India: Insights from a survey of experts," Energy Reports, vol. 7, pp. 3171-3188, 2021.
[7] N. A. Ishak, A. Sapit, and H. Salleh, "Prospective of ammonia as fuel in internal combustion engine."
[8] R. S. Abate, " FOOL ME ONCE, SHAME ON YOU": PROMOTING CORPORATE ACCOUNTABILITY FOR THE HUMAN RIGHTS IMPACTS OF CLIMATE WASHING," Intercultural Human Rights Law Review, vol. 18, 2023.
[9] P. Dimitriou and R. Javaid, "A review of ammonia as a compression ignition engine fuel," International Journal of Hydrogen Energy, vol. 45, pp. 7098-7118, 2020.
[10] P. Dimitriou and T. Tsujimura, "A review of hydrogen as a compression ignition engine fuel," International Journal of Hydrogen Energy, vol. 42, pp. 24470-24486, 2017.
[11] P. Dimitriou, T. Tsujimura, and Y. Suzuki, "Hydrogen-diesel dual-fuel engine optimization for CHP systems," Energy, vol. 160, pp. 740-752, 2018.
[12] M. Elkelawy, E. A. El Shenawy, H. A. E. Bastawissi, and I. A. El Shennawy, "The effect of using the WCO biodiesel as an alternative fuel in compression ignition diesel engine on performance and emissions characteristics," p. 012023.
[13] M. Elkelawy, H. Alm ElDin Mohamad, E. Abd Elhamid, and M. A. M. El-Gamal, "A Critical Review of the Performance, Combustion, and Emissions Characteristics of PCCI Engine Controlled by Injection Strategy and Fuel Properties," Journal of Engineering Research, vol. 6, pp. 96-110, 2022.
[14] J. Lee, L.-L. Tan, and S.-P. Chai, "Heterojunction photocatalysts for artificial nitrogen fixation: fundamentals, latest advances and future perspectives," Nanoscale, vol. 13, pp. 7011-7033, 2021.
[15] M. Elkelawy, H. A.-E. Bastawissi, E. A. El Shenawy, M. M. Shams, H. Panchal, K. K. Sadasivuni, and A. K. Choudhary, "Influence of lean premixed ratio of PCCI-DI engine fueled by diesel/biodiesel blends on combustion, performance, and emission attributes; a comparison study," Energy Conversion and Management: X, vol. 10, p. 100066, 2021/06/01/ 2021.
[16] A. Valera-Medina, H. Xiao, M. Owen-Jones, W. I. F. David, and P. J. Bowen, "Ammonia for power," Progress in Energy and combustion science, vol. 69, pp. 63-102, 2018.
[17] H. J. M. van Grinsven, L. Bouwman, K. G. Cassman, H. M. van Es, M. L. McCrackin, and A. H. W. Beusen, "Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050," Journal of environmental quality, vol. 44, pp. 356-367, 2015.
[18] D. E. Canfield, A. N. Glazer, and P. G. Falkowski, "The evolution and future of Earth’s nitrogen cycle," science, vol. 330, pp. 192-196, 2010.
[19] I. Čorić, B. Q. Mercado, E. Bill, D. J. Vinyard, and P. L. Holland, "Binding of dinitrogen to an iron– sulfur–carbon site," Nature, vol. 526, pp. 96-99, 2015.
[20] P. Jha, N. S. Ramgir, P. K. Sharma, N. Datta, S. Kailasaganapathi, M. Kaur, S. P. Koiry, V. Saxena, A. K. Chauhan, and A. K. Debnath, "Charge transport and ammonia sensing properties of flexible polypyrrole nanosheets grown at air–liquid interface," Materials Chemistry and Physics, vol. 140, pp. 300-306, 2013.
[21] R. Lan, J. T. S. Irvine, and S. Tao, "Ammonia and related chemicals as potential indirect hydrogen storage materials," International Journal of Hydrogen Energy, vol. 37, pp. 1482-1494, 2012.
[22] G. E. Zacharakis-Jutz, "Performance characteristics of ammonia engines using direct injection strategies," 2013.
[23] A. Yapicioglu and I. Dincer, "Performance assesment of hydrogen and ammonia combustion with various fuels for power generators," International Journal of Hydrogen Energy, vol. 43, pp. 21037-21048, 2018.
[24] Q. Wang, J. Guo, and P. Chen, "Recent progress towards mild-condition ammonia synthesis," Journal of Energy Chemistry, vol. 36, pp. 25-36, 2019.
[25] X.-F. Li, Q.-K. Li, J. Cheng, L. Liu, Q. Yan, Y. Wu, X.-H. Zhang, Z.-Y. Wang, Q. Qiu, and Y. Luo, "Conversion of dinitrogen to ammonia by FeN3-embedded graphene," Journal of the American Chemical Society, vol. 138, pp. 8706-8709, 2016.
[26] C. Smith, A. K. Hill, and L. Torrente-Murciano, "Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape," Energy & Environmental Science, vol. 13, pp. 331-344, 2020.
[27] G. Qing, R. Ghazfar, S. T. Jackowski, F. Habibzadeh, M. M. Ashtiani, C.-P. Chen, M. R. Smith Iii, and T. W. Hamann, "Recent advances and challenges of electrocatalytic N2 reduction to ammonia," Chemical reviews, vol. 120, pp. 5437-5516, 2020.
[28] J. Polanski, D. Lach, M. Kapkowski, P. Bartczak, T. Siudyga, and A. Smolinski, "Ru and Ni— Privileged Metal Combination for Environmental Nanocatalysis," Catalysts, vol. 10, p. 992, 2020.
[29] P. Kumar, S. Dua, R. Kaur, M. Kumar, and G. Bhatt, "A review on advancements in carbon quantum dots and their application in photovoltaics," RSC advances, vol. 12, pp. 4714-4759, 2022.
[30] N. Saadatjou, A. Jafari, and S. Sahebdelfar, "Ruthenium nanocatalysts for ammonia synthesis: a review," Chemical Engineering Communications, vol. 202, pp. 420-448, 2015.

doi: 10.21608/ERJENG.2023.234219.1229

[31] Z.-Y. Wu, M. Karamad, X. Yong, Q. Huang, D. A. Cullen, P. Zhu, C. Xia, Q. Xiao, M. Shakouri, and F.Y. Chen, "Electrochemical ammonia synthesis via nitrate reduction on Fe single atom catalyst," Nature communications, vol. 12, p. 2870, 2021.

[32] H. Zhao, L. M. Kamp, and Z. Lukszo, "The potential of green ammonia production to reduce renewable power curtailment and encourage the energy transition in China," International Journal of Hydrogen Energy, vol. 47, pp. 18935-18954, 2022.

[33] J. A. Faria, "Renaissance of ammonia synthesis for sustainable production of energy and fertilizers," Current opinion in green and sustainable chemistry, vol. 29, p. 100466, 2021.

[34] R. Nayak-Luke, R. Bañares-Alcántara, and I. Wilkinson, "“Green” ammonia: impact of renewable energy intermittency on plant sizing and levelized cost of ammonia," Industrial & Engineering Chemistry Research, vol. 57, pp. 14607-14616, 2018.

[35] K. H. R. Rouwenhorst, P. M. Krzywda, N. E. Benes, G. Mul, and L. Lefferts, "Ammonia production technologies," Techno-Economic Challenges of Green Ammonia as Energy Vector, pp. 41-84, 2020.

[36] M. Anandkumar and E. Trofimov, "Synthesis, Properties, and Applications of High-Entropy Oxide Ceramics: Current Progress and Future Perspectives," Journal of Alloys and Compounds, p. 170690, 2023.

[37] Q. Xu, L. Zhang, J. Zhang, J. Wang, Y. Hu, H. Jiang, and C. Li, "Anion exchange membrane water electrolyzer: electrode design, lab-scaled testing system and performance evaluation," EnergyChem, p. 100087, 2022.

[38] S. Ghavam, M. Vahdati, I. A. Wilson, and P. Styring, "Sustainable ammonia production processes," Frontiers in Energy Research, vol. 9, p. 34, 2021.

[39] Y. Li, Q. Zhang, Z. Mei, S. Li, W. Luo, F. Pan, H. Liu, and S. Dou, "Recent advances and perspective on electrochemical ammonia synthesis under ambient conditions," Small Methods, vol. 5, p. 2100460, 2021.

[40] H. Iriawan, S. Z. Andersen, X. Zhang, B. M. Comer, J. Barrio, P. Chen, A. J. Medford, I. E. L. Stephens, I. Chorkendorff, and Y. Shao-Horn, "Methods for nitrogen activation by reduction and oxidation," Nature Reviews Methods Primers, vol. 1, p. 56, 2021.

[41] M. Elkelawy, S. E.-d. H. Etaiw, H. A.-E. Bastawissi, H. Marie, A. Elbanna, H. Panchal, K. Sadasivuni, and H. Bhargav, "Study of diesel-biodiesel blends combustion and emission characteristics in a CI engine by adding nanoparticles of Mn (II) supramolecular complex," Atmospheric Pollution Research, vol. 11, pp. 117-128, 2020/01/01/ 2020.

[42] M. Elkelawy, S. E.-d. H. Etaiw, M. I. Ayad, H. Marie, M. Dawood, H. Panchal, and H. A.-E. Bastawissi, "An enhancement in the diesel engine performance, combustion, and emission attributes fueled by diesel-biodiesel and 3D silver thiocyanate nanoparticles additive fuel blends," Journal of the Taiwan Institute of Chemical Engineers, vol. 124, pp. 369-380, 2021/07/01/ 2021.

[43] H. A. El-Din, M. Elkelawy, and Z. Yu-Sheng, "HCCI engines combustion of CNG fuel with DME and H 2 additives," SAE Technical Paper 0148-7191, 2010.

[44] A. M. Elbanna, C. Xiaobei, Y. Can, M. Elkelawy, and H. A.-E. Bastawissi, "A comparative study for the effect of different premixed charge ratios with conventional diesel engines on the performance, emissions, and vibrations of the engine block," Environmental Science and Pollution Research, 2022/09/17 2022.

[45] A. E. Kabeel, E. A. ElShenawy, M. Elkelawy, H. Alm ElDin Mohamad, and M. M. Elshanshoury, "Numerical Investigation of Combustion in HCCI Diesel Engine Fuelled with Biodiesel Blends," Journal of Engineering Research, vol. 3, pp. 1-10, 2019.

[46] A. M. Elzahaby, M. Elkelawy, H. A.-E. Bastawissi, S. M. El-Malla, and A. M. M. Naceb, "Effect of Ethanol–Diesel Fuel Blends on Autoignition and Combustion Characteristics in HCCI Engines," pp. 1-15.

[47] X. Liang, Z. Zheng, H. Zhang, Y. Wang, and H. Yu, "A review of early injection strategy in premixed combustion engines," Applied Sciences, vol. 9, p. 3737, 2019.

[48] N. Horibe, S. Harada, T. Ishiyama, and M. Shioji, "Improvement of premixed charge compression ignition-based combustion by two-stage injection," International Journal of Engine Research, vol. 10, pp. 71-80, 2009.

[49] M. Jia, M. Xie, T. Wang, and Z. Peng, "The effect of injection timing and intake valve close timing on performance and emissions of diesel PCCI engine with a full engine cycle CFD simulation," Applied Energy, vol. 88, pp. 2967-2975, 2011.

[50] R. Kiplimo, E. Tomita, N. Kawahara, and S. Yokobe, "Effects of spray impingement, injection parameters, and EGR on the combustion and emission characteristics of a PCCI diesel engine," Applied Thermal Engineering, vol. 37, pp. 165-175, 2012.

[51] M. Krishnamoorthi, R. Malayalamurthi, Z. He, and S. Kandasamy, "A review on low temperature combustion engines: Performance, combustion and emission characteristics," Renewable and Sustainable Energy Reviews, vol. 116, p. 109404, 2019.

[52] S. Leblanc, L. Jin, N. S. Sandhu, X. Yu, and M. Zheng, "Combustion Characterization of DMEFueled Dual Fuel Combustion with Premixed Ethanol," SAE Technical Paper 0148-7191, 2022.

[53] N. Ganesan, T. H. Le, P. Ekambaram, D. Balasubramanian, and A. T. Hoang, "Experimental assessment on performance and combustion behaviors of reactivity-controlled compression ignition engine operated by n-pentanol and cottonseed biodiesel," Journal of Cleaner Production, vol. 330, p. 129781, 2022.

[54] A. K. Agarwal and V. H. Chaudhury, "Spray characteristics of biodiesel/blends in a high-pressure constant volume spray chamber," Experimental thermal and fluid science, vol. 42, pp. 212-218, 2012.

[55] F. J. J. S. Bai, K. Shanmugaiah, A. Sonthalia, Y. Devarajan, and E. G. Varuvel, "Application of machine learning algorithms for predicting the engine characteristics of a wheat germ oil– Hydrogen fuelled dual fuel engine," International Journal of Hydrogen Energy, vol. 48, pp. 2330823322, 2023.

[56] M. Nibin, J. B. Raj, and V. E. Geo, "Experimental studies to improve the performance, emission and combustion characteristics of wheat germ oil fuelled CI engine using bioethanol injection in PCCI mode," Fuel, vol. 285, p. 119196, 2021.

[57] M. Pan, W. Qian, R. Huang, X. Zhou, H. Huang, X. Pan, and Z. Ban, "Effects of EGR dilution on combustion and emission performance of a compression ignition engine fueled with dimethyl carbonate and 2-ethylhexyl nitrate additive," Energy & Fuels, vol. 33, pp. 8683-8693, 2019.

[58] M. Elkelawy, E. A. El Shenawy, S. k. A. Almonem, M. H. Nasef, H. Panchal, H. A.-E. Bastawissi, K. K. Sadasivuni, A. K. Choudhary, D. Sharma, and M. Khalid, "Experimental study on combustion, performance, and emission behaviours of diesel /WCO biodiesel/Cyclohexane blends in DI-CI engine," Process Safety and Environmental Protection, vol. 149, pp. 684-697, 2021/05/01/ 2021.

[59] M. I. Jahirul, M. G. Rasul, D. Schaller, M. M. K. Khan, M. M. Hasan, and M. A. Hazrat, "Transport fuel from waste plastics pyrolysis–A review on technologies, challenges and opportunities," Energy Conversion and Management, vol. 258, p. 115451, 2022.

[60] S. Bhurat, S. Pandey, V. Chintala, M. Jaiswal, and C. Kurien, "Effect of novel fuel vaporiser technology on engine characteristics of partially premixed charge compression ignition (PCCI) engine with toroidal combustion chamber," Fuel, vol. 315, p. 123197, 2022.

[61] G. Li, T. H. Lee, Z. Liu, C. F. Lee, and C. Zhang, "Effects of injection strategies on combustion and emission characteristics of a common-rail diesel engine fueled with isopropanol-butanol-ethanol and diesel blends," Renewable energy, vol. 130, pp. 677-686, 2019.

[62] Y. Viollet, J. Chang, and G. Kalghatgi, "Compression ratio and derived cetane number effects on gasoline compression ignition engine running with naphtha fuels," SAE International Journal of Fuels and Lubricants, vol. 7, pp. 412-426, 2014.

[63] T. Kaya, O. A. Kutlar, and O. O. Taskiran, "Evaluation of the partially premixed compression ignition combustion with diesel and biodiesel blended diesel at part load condition," Engineering Science and Technology, an International Journal, vol. 24, pp. 458-468, 2021.

[64] M. Cardone, R. Marialto, R. Ianniello, M. Lazzaro, and G. di Blasio, "Spray analysis and combustion assessment of diesel-LPG fuel blends in compression ignition engine," Fuels, vol. 2, pp. 1-15, 2020.

[65] A. M. Elbanna, X. Cheng, C. Yang, M. Elkelawy, H. Alm-Eldin Bastawissi, and H. Xu, "Statistical analysis of ethanol/diesel dual-fuel combustion of compression ignition engines in RCCI mode using multi-injection strategies," Sustainable Energy & Fuels, vol. 7, pp. 2749-2763, 2023.

[66] A. M. Elbanna, X. Cheng, C. Yang, M. Elkelawy, and H. A.-E. Bastawissi, "Investigative research of diesel/ethanol advanced combustion strategies: A comparison of Premixed Charge Compression Ignition (PCCI) and Direct Dual Fuel Stratification (DDFS)," Fuel, vol. 345, p. 128143, 2023.

[67] J.-z. Yu, Y. S. Zhang, M. Elkelawy, and Q. Kui, "Spray and Combustion Characteristics of HCCI Engine Using DME/Diesel Blended Fuel by Port-Injection," SAE Technical Papers, 2010.

[68] E. Koch, "Ammonia–a fuel for motor buses," J. Inst. Pet, vol. 31, p. 213, 1945.

doi: 10.21608/ERJENG.2023.234219.1229

[69] R. H. Thurston, A History of the Growth of the Steam-Engine vol. 24: D. Appleton, 1878.

[70] D. Eckardt, "Turbomachinery and Aero-Related Activities at BBC and in International Context up to 1935," in Jet Web: CONNECTIONS in the Development History of Turbojet Engines 1920-1950, ed: Springer, 2023, pp. 87-213.

[71] T. C. Fubara, Techno-economic modelling of sustainable energy future scenarios with natural gas as a transition fuel to a low carbon economy: University of Surrey (United Kingdom), 2016.

[72] J. J. MacKenzie and W. H. Avery, "Ammonia fuel: the key to hydrogen-based transportation," Inst. of Electrical and Electronics Engineers, Piscataway, NJ (United States)1996.

[73] W. David, "Ammonia: zero-carbon fertiliser, fuel and energy store," Policy Briefing, 2020.

[74] J. S. Cardoso, V. Silva, R. C. Rocha, M. J. Hall, M. Costa, and D. Eusébio, "Ammonia as an energy vector: Current and future prospects for low-carbon fuel applications in internal combustion engines," Journal of Cleaner Production, vol. 296, p. 126562, 2021.

[75] G. Chehade and I. Dincer, "Progress in green ammonia production as potential carbon-free fuel," Fuel, vol. 299, p. 120845, 2021.

[76] N. De Vries, "Safe and effective application of ammonia as a marine fuel," 2019.

[77] C. Lv, H. Xu, J. Chang, Y. Wang, R. Chen, and D. Yu, "Mode transition analysis of a turbine-based combined-cycle considering ammonia injection pre-compressor cooling and variable-geometry ram-combustor," Energy, vol. 261, p. 125324, 2022.

[78] D. Lisi, "Preliminary modeling of a plasma gasification system for marine transportation," 2021. A. Paykani, H. Chehrmonavari, A. Tsolakis, T. Alger, W. F. Northrop, and R. D. Reitz, "Synthesis gas as a fuel for internal combustion engines in transportation," Progress in Energy and combustion science, vol. 90, p. 100995, 2022/05/01/ 2022.

[79] M. Bednarski, M. Sikora, J. Lasocki, P. Orliński, and M. Wojs, "Ammonia as a fuel for compressionignition engines," Zeszyty Naukowe Instytutu Pojazdów/Politechnika Warszawska, 2018.

[80] C. Xu, A. Zhong, C. Wang, C. Jiang, X. Li, K. Zhou, and Y. Huang, "Combustion Characteristics and Laminar Flame Speed of Premixed Ethanol-Air Mixtures with Laser-Induced Spark Ignition," Biofuels Engineering, vol. 2, pp. 63-72, 2017.

[81] N. De Vries, E. Okafor, M. Gutesa-Bozo, H. Xiao, and A. Valera-Medina, "Use of Ammonia for Heat, Power and Propulsion," Techno-Economic Challenges Green Ammon as an Energy Vector; Elsevier: Amsterdam, The Netherlands, pp. 105-154, 2020.

[82] Z. Liu, Z. Guo, X. Rao, Y. Xu, C. Sheng, and C. Yuan, "A comprehensive review on the material performance affected by gaseous alternative fuels in internal combustion engines," Engineering Failure Analysis, vol. 139, p. 106507, 2022.

[83] C. Mounaïm-Rousselle and P. Brequigny, "Ammonia as Fuel for Low-Carbon Spark-Ignition Engines of Tomorrow's Passenger Cars," Frontiers in Mechanical Engineering, vol. 6, p. 70, 2020.

[84] Y. Wu, Y. Zhang, C. Xia, A. Chinnathambi, O. Nasif, B. Gavurová, M. Sekar, A. Anderson, N. T. L. Chi, and A. Pugazhendhi, "Assessing the effects of ammonia (NH3) as the secondary fuel on the combustion and emission characteristics with nano-additives," Fuel, vol. 336, p. 126831, 2023.

[85] D. Zhu and B. Shu, "Recent Progress on Combustion Characteristics of Ammonia-Based Fuel Blends and Their Potential in Internal Combustion Engines," International Journal of Automotive Manufacturing and Materials, pp. 20-20, 2023.

[86] C. Tornatore, L. Marchitto, P. Sabia, and M. de Joannon, "Ammonia as Green Fuel in Internal Combustion Engines: State-of-the-Art and Future Perspectives," Frontiers in Mechanical Engineering, vol. 8, p. 944201, 2022.

[87] A. Saud, J. Havukainen, P. Peltola, and M. Horttanainen, "Environmental Performance of Nitrogen Recovery from Reject Water of Sewage Sludge Treatment Based on Life Cycle Assessment," Recycling, vol. 8, p. 43, 2023.

[88] J. Zhu, D. Zhou, W. Yang, Y. Qian, Y. Mao, and X. Lu, "Investigation on the potential of using carbon-free ammonia in large two-stroke marine engines by dual-fuel combustion strategy," Energy, vol. 263, p. 125748, 2023/01/15/ 2023.

[89] K. Tay, W. M. Yang, J. Li, D. Zhou, Y. Wenbin, F. Zhao, S. K. Chou, and B. Mohan, "Numerical investigation on the combustion and emissions of a kerosene-diesel fueled compression ignition engine assisted by ammonia fumigation," Applied Energy, vol. 204, 2016.

[90] M. Gallucci, "The Ammonia Solution: Ammonia engines and fuel cells in cargo ships could slash their carbon emissions," IEEE Spectrum, vol. 58, pp. 44-50, 2021.

[91] Y. Niki, D.-H. Yoo, K. Hirata, and H. Sekiguchi, Effects of Ammonia Gas Mixed into Intake Air on Combustion and Emissions Characteristics in Diesel Engine, 2016.

[92] Z. Zhang, H. Liu, Z. Yue, Y. Wu, X. Kong, Z. Zheng, and M. Yao, "Effects of Multiple Injection Strategies on Heavy-Duty Diesel Energy Distributions and Emissions Under High Peak Combustion Pressures," Frontiers in Energy Research, vol. 10, 2022.

[93] S. Smv and A. Agarwal, "Experimental validation of accuracy of dynamic hydrogen-compressed natural gas mixing system using a single cylinder spark ignition engine," International Journal of Hydrogen Energy, vol. 41, 2016.

[94] G. Pontikakos, "Modeling of Ammonia Combustion Emissions in a Dual-Fuel Engine," 2023.

[95] L. Liu, F. Tan, Z. Wu, Y. Wang, and H. Liu, "Comparison of the combustion and emission characteristics of NH3/NH4NO2 and NH3/H2 in a two-stroke low speed marine engine," International Journal of Hydrogen Energy, vol. 47, pp. 17778-17787, 2022/05/08/ 2022.

[96] M. Pochet, I. Truedsson, F. Foucher, H. Jeanmart, and F. Contino, "Ammonia-hydrogen blends in homogeneous-charge compression-ignition engine," SAE Technical Paper 0148-7191, 2017.

[97] S. Oh, C. Park, J. Oh, S. Kim, Y. Kim, Y. Choi, and C. Kim, "Combustion, emissions, and performance of natural gas–ammonia dual-fuel spark-ignited engine at full-load condition," Energy, vol. 258, p. 124837, 2022.

[98]

doi: 10.21608/ERJENG.2023.234219.1229