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Research Article

Numerical analysis of dual-fuel diesel engines in compression ignition engines: a review

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ABSTRACT

Hydrogen gas is currently used in many daily uses because of its chemical properties that help in combustion and energy generation processes. Hydrogen can be easily used in diesel engines without major design modifications. In additions, its high flame velocity and calorific value make it a desirable option for dual-fuel mode in diesel engines. The trend in developing car engines has become to use alternative fuels to diesel and gasoline. The types of injections currently used, their development technology in diesel engines, and the advantages of using them to develop and raise engine efficiency are discussed. A complete study is being conducted on the use of hydrogen as a dual fuel in diesel engines by changing the engine speed and the amount of hydrogen used in combustion, generating including energy and heat resulting from the use of hydrogen as a dual fuel. This study aims to determine the optimal conditions for using hydrogen as a dual fuel in diesel engines, taking into account both performance and environmental impact. The results of this research could potentially lead to more efficient and sustainable transportation options in the future. Furthermore, the study will also evaluate the emissions produced when using hydrogen as a dual fuel in diesel engines, to ensure that the environmental impact is minimized. By optimizing the use of hydrogen in combustion, this research has the potential to revolutionize the way we power vehicles and reduce our reliance on traditional fossil fuels.

1. INTRODUCTION

An internal combustion engine receives its energy input in three forms: energy lost through the exhaust system, energy used for productive work, and energy lost through the coolant system [1]. Merely one-third of the total energy is transformed into work. Thus, by turning these heat losses into usable work, an internal combustion engine's efficiency and overall performance can be boosted. The technology of insulating the surfaces of the piston, cylinder head, combustion chamber, and valve using thermal barrier coating materials has been introduced to reduce heat transmission and enhance the performance of an internal combustion engine[2]. Since they are the source of more than 24% of the atmosphere's carbon dioxide emissions, cars and other carbon-based vehicles are among the most damaging to the environment. Reducing transportation emissions is essential in the event of a climate emergency. To achieve this goal, cleaner private vehicles as well as the promotion of active and public transportation must be developed. [3]. Alternative fuel research and application are prompted by energy shortages and emission pollution from road transport vehicles. Natural gas, methanol, ethanol, and biodiesel are examples of alternative fuels that are now being extensively researched and utilized in transportation [4]. In a CI engine, conventional fuel is injected through a diesel injector near the end of the compression stroke, when the fuel temperature is substantially lower than the charge temperature, after the air has been compressed. This starts the process of combustion, which ignites a heterogeneous mixture of fuel and air inside the cylinder to produce power for the engine. In the case of a dual-fuel diesel engine, the suction is generally a mixture of air and producer gas known as the charge mixture. A small quantity of conventional fuel is injected into the compressed charge mixture through

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a high-speed diesel injector which then propagates to the surrounding homogeneous mixture inside the cylinder [5] .One of the best fuels is thought to be natural gas. It is an easy fuel to blend with air, has a low carbon content, and is clean. Hydrogen gas is considered one of the most important gases currently used in energy production, as it has many chemical properties that facilitate many processes such as combustion. Hydrogen gas can be produced in many available ways, such as electrolysis, and hydrogen gas can be produced from renewable energy sources. The potential of hydrogen as a reliable, secure, and clean energy source of the future has grown. Less than 3% of the world's end-use energy is made up of hydrogen, however. These are the primary causes: The mismatch between the locations of hydrogen production and demand (2) :the high cost and small volume of transportation for long-distance hydrogen delivery: (3) the absence of infrastructure for hydrogen storage, transmission, and use; and (4) the high cost of constructing pure hydrogen pipelines to facilitate widespread adoption are the first four issues.[6]. An additional benefit of hydrogen is that it can be constructed on top of the natural gas infrastructure already in place in buildings. In the transportation sector, hydrogen-fueled internal combustion engines and fuel cells may be used in conjunction with battery electric vehicles to achieve the full greenization of all land, air, and water transportation.[7] .In addition, research has been conducted on the utilization of hydrogen-methane mixtures in internal combustion engines[8]. A control scheme for producing hydrogen on demand to power an internal combustion engine has been proposed[9]. Studies on the viability of utilizing hydrogen fuel in heavy-duty, long-haul, internal combustion engine trucks have also been conducted. in place of diesel fuel, as a cleaner fuel[10]. Also investigated is the possibility of hydrogen internal combustion engines in 2030[11]. Reviewing the progress made in modeling, in-cylinder heat transfer, combustion strategies, and charting the opportunities presented by direct injection of hydrogen for use as an internal combustion engine fuel[12]. Recent trends point to a rise in the use of natural gas as an internal combustion engine motor fuel[13]. In order to increase efficiency and lower emissions, internal combustion engines have also been using gasification gases made from solid fuels with a higher hydrogen to carbon ratio[14]. Lastly, studies on hydrogen production techniques and its use in engines as a backup fuel in addition to biodiesel have been expanded[15].

2. RELATED WORK

In the realm of internal combustion engines, there has been an increasing amount of interest in the incorporation of hydrogen in dual-fuel systems. The possibility of using hydrogen as a secondary fuel in dual-fuel combustion to get carbon-free combustion and lower emissions has been investigated. Research has looked into combining hydrogen with other fuels, such as diesel, to improve combustion efficiency and environmental sustainability[16]. Since liquefied petroleum gas (LPG) can reduce pollutants and the consumption of fossil fuels, it is a viable alternative to natural gas and hydrogen in dual-fuel systems where combustion stability and knocking prevention have been identified as challenges[17]. It has been investigated whether dual-injection technology may be used in spark ignition engines to efficiently use renewable fuels. Research has been done on several fuel mixtures, such as hydrogen and alcohol, to take use of each fuel's special qualities and enhance engine performance[18][19]. Experiments have shown that adding hydrogen gas to biodiesel in a dual-fuel engine configuration improves combustion, performance, and reduces pollution levels compared to single-fuel operation[20]. This is due to the high cetane number of hydrogen, which enhances ignition and combustion efficiency. Additionally, the presence of hydrogen can also help reduce particulate matter emissions in the exhaust[21].

2.1. Injection of ICE

A fuel injection system is a kind of internal combustion engine system that delivers fuel to the engine's combustion chamber or cylinders precisely and under control using fuel injectors. By atomizing fuel and precisely delivering it into engine cylinders at high pressure, this guarantees effective combustion. In diesel engines, there are various kinds of fuel injection. The injection of compression diesel engines is a critical aspect of engine performance and emissions. Various studies have been conducted to analyze the impact of different fuels and injection systems on compression ignition engines. conducted a comprehensive analysis of the impact of biofuels on the performance and emissions from compression ignition engines, focusing on the use of a common rail injection system and different fuel blends[22]. Similarly, performed emissions studies with different fuels at various static fuel injection timing conditions in a single-cylinder DI diesel engine, providing insights into NOx emissions of alternative diesel fuels[23]. Furthermore, and investigated the compression ignition of directly injected natural gas and the dual-fuel performance of compression ignition diesel engines, respectively, shedding light on the injection of gaseous fuels in compression ignition engines[24]. Moreover, the optimization of injection systems has been a subject of research. Studies by and focused on the effects of injection rate shape and start-of-injection-based software optimization on combustion and emission performance of diesel engines, highlighting the significance of injection control for engine efficiency and emissions[25][26]. Additionally, research by addressed the fuel compensation control of high-pressure common-rail diesel engines, emphasizing the advancements in high-pressure common-rail diesel injection systems[27]. Furthermore, the influence of different factors on injection performance has been explored. investigated the effects of fuel temperature on the injection performance of an electronic unit pump (EUP) system, emphasizing the impact of fuel temperature on injection characteristics[28].

2.2. Throttle Body Injection

The throttle body injection (TBI) system is a critical component of internal combustion engines, influencing air-fuel mixture delivery and combustion. It regulates the flow of air into the engine, thereby affecting the combustion process. 's work on the engineering fundamentals of the internal combustion engine provides valuable insights into the combustion process and the role of the throttle body injection system in delivering fuel to the engine[29]. Furthermore, as essential parts of contemporary fuel injection systems, such as throttle body injection systems, the study highlights the importance of stability analysis and chaos control in electronic throttle dynamical systems[30]. A throttle body assembly's primary job is to regulate engine air flow in response to vehicle demand. The throttle body is situated in the space between the intake manifold and the air cleaner. To lower the air pressure passing through it, it contains a venturi. By lowering the flow area, the input flow is reduced. This is accomplished by installing a throttle shaft, which is a circular shaft, downstream of the venture and equipped with a butterfly valve[31][31]. Additionally, the optimization of fuel injection in gasoline direct injection (GDI) engines is highlighted by the implementation of the economic order quantity (EOQ) and Lambert W function in engine simulation models, as discussed by, highlighting the significance of effective fuel delivery systems like throttle body injection[32].

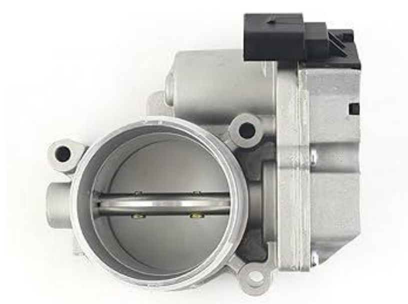

Fig. 1. Throttle Body Injection[33]

2.2 Multi-Point Injection (MPI)

Because hydrogen has the potential to lower emissions and increase efficiency, its application in internal combustion engines (ICEs) has attracted a lot of attention. The use of multi-point injection techniques poses issues regarding pressure levels and needed injector flow rates when contemplating the application of hydrogen in internal combustion engines (ICEs)[34]. In spark-ignited internal combustion engines (ICEs), research has demonstrated that hydrogen direct injection can achieve high engine power output and efficiency with low emissions[35]. An internal combustion engine can be fueled through a number of ports on the intake valve of each cylinder by using a multi-point fuel injection system. Together, these apertures provide each cylinder with the correct amount of fuel at the ideal moment. MPFI units come in three different varieties: sequential, simultaneous, and batched. Fuel is delivered to the cylinders by the ports in batches in the first type of multi-point fuel injection system; the intake strokes are not coordinated. While the fuel release in sequential MPFI systems is timed to occur simultaneously with each engine cylinder's intake stroke, simultaneous MPFI systems release fuel into every engine cylinder simultaneously. A possible area for additional research and development in the field is indicated by the paucity of literature on multi-point hydrogen injection used with natural gas engines[36].

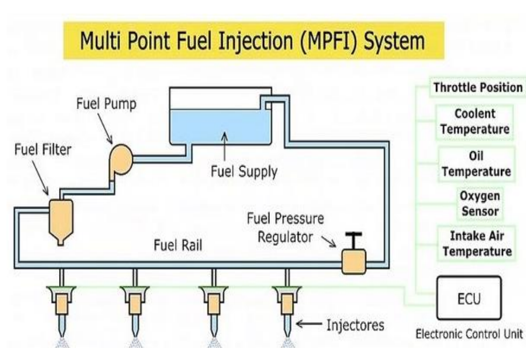

Fig. 2. Multi-Point Injection[37]

2.3 Common Rail Direct Injection (CRDI)

Many studies have been conducted on the common rail direct injection (CRDI) system in the context of diesel engines, especially about the combustion and emission characteristics of biodiesel-fueled engines[38]. examined the impact of injection parameters on the characteristics of combustion and emissions in a common-rail direct injection diesel engine running on biodiesel made from used cooking oil[39]. studied how engine injection strategy affected the biodiesel NOx effect using a common rail turbocharged direct injection diesel engine running at a moderate speed and load[40]. Diesel engine performance and pollution control have greatly improved due to common rail direct injection (CRDI) technology. Fuel injection characteristics, such as injection pressure, start timing, rate, and duration, can be precisely controlled by the CRDI system, improving engine performance and lowering emissions[41]. Research has indicated that the utilization of CRDI technology in diesel engines leads to enhanced combustion and emission properties[42]. pointed out how fuel injection parameters like fuel injection pressure, start of injection (SOI) timing, fuel injection rate, and injection duration can be controlled by CRDI technology to improve engine performance, combustion, and emissions from compression ignition (CI) engines[43].

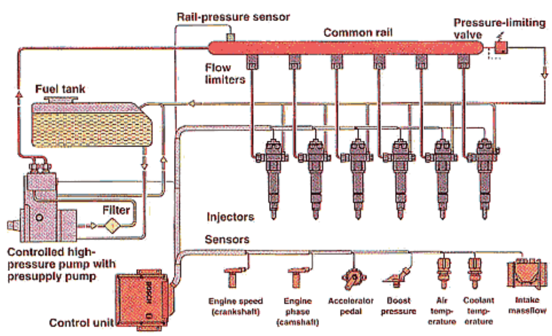

Fig. 3. Common Rail Direct Injection[44]

2.4 Ignition Delay Time

IDT, or ignition delay time, is a crucial metric for characterizing fuels. IDT is a common validation target in fundamental research that is used to assess how well proposed chemical kinetics processes function[45][46]. IDT is typically used in engine studies to interpret abnormal combustion behaviors, such as knocking in internal combustion engines[47]. IDT of ammonia has been studied experimentally since the 1960s, and in the last five years, numerous new research focusing on ammonia and ammonia/fuel blends have been published. Within the review article by Valera-Medina and colleagues[48]. The most significant IDT research up to 2020 has been succinctly outlined. More research on the IDT of ammonia/fuel blends has been published in the last two years, offering a greater variety of data sets and novel blending options for engine-relevant circumstances[49]. The review article also highlights the importance of understanding the chemical kinetics and thermodynamics involved in ammonia combustion. This knowledge is crucial for optimizing engine performance and reducing emissions in future sustainable transportation systems[50][51].

2.5 Natural gas in IC engines

Of all the alternative fuels, natural gas is regarded as being vital for internal combustion engines[52]. It is considered a cleaner and more efficient option compared to traditional gasoline or diesel fuels. Natural gas produces lower emissions of pollutants such as carbon dioxide and nitrogen oxides. Natural gas has many clear and advantageous advantages over other alternative fuels, such as lower capital costs and fewer greenhouse gas emissions. Table 1 lists the attributes of natural gas. Because natural gas has a high-octane rating, it can be used in diesel engines with a high compression ratio. Governments throughout the world have been paying more attention to natural gas as a fuel substitute for heavy-duty diesel engines and stationary engines used in power production and industrial uses in recent years due to the energy scarcity and pollution[53]. This is because fresh air is mixed with natural gas directly into the intake manifold or cylinder, creating a homogenous mixture that is ignited by the spark plug or pilot diesel fuel[54]. This process allows for a more efficient combustion of the fuel mixture, resulting in increased power output and reduced emissions. Additionally, the use of natural gas as a fuel source can help reduce reliance on traditional petroleum-based fuels[55]. Natural gas's ability to increase combustion efficiency and lower emissions has drawn a lot of attention to dual-fuel systems. Since the 1950s, the idea of dual-fuel systems—which blend natural gas with diesel or other fuels—has been developing[56]. One of the main benefits of using natural gas in dual-fuel combustion is its high auto-ignition temperature, which makes it suitable for compression ignition engines[57]. Studies have shown that dual-fuel technology, especially when using natural gas as a supplementary fuel in diesel engines, offers economic and environmental benefits. The combination of natural gas and diesel fuel in engines can reduce emissions of harmful pollutants such as nitrogen oxides and particulate matter. Additionally, the use of dual-fuel technology can also result in cost savings for operators due to the lower price of natural gas compared to diesel fuel[58]. Retrofitting truck engines with dual-fuel kits that replace a portion of the diesel fuel with natural gas can help reduce emissions, such as methane, from the heavy-duty transportation sector[59]. Furthermore, the use of dual-fuel technology in marine engines, such as replacing diesel with liquefied natural gas (LNG), has been discovered to improve ecological parameters and reduce environmental impact[60]. Numerous facets of dual-fuel combustion, such as fuel blend optimization and injection strategy development, have been studied by researchers. For example, research has looked into how different fuel mixtures, including ethanol and gasoline, affect the way dual-fuel engines burn[61]. Recent research has focused on developing dual-injection spark ignition engines with flexible fuel injection strategies[62]. Furthermore, the environmental and cost-effectiveness of dual-fuel propulsion options, particularly those using natural gas fuel, have been evaluated for applications such as LNG carriers[63]. The integration of dual-fuel technology with other systems, such as the Organic Rankine Cycle (ORC) for waste heat recovery in marine engines, has been proposed to improve overall system efficiency[64]. The use of natural gas in dual-fuel systems is a promising way to improve combustion efficiency, reduce emissions, and improve overall environmental sustainability in a variety of industries, including transportation and marine[65][66]. By utilizing natural gas as a cleaner-burning fuel source alongside traditional diesel or gasoline, dual-fuel systems can significantly lower harmful pollutants such as nitrogen oxides and particulate matter. This transition to a more sustainable energy source also helps to diversify fuel options and reduce dependence on fossil fuels[67][68].

TABLE I. COMPOSITION AND PROPERTIES OF NATURAL GAS[69].

Component	**v/v (%)**	**Component**	**v/v (%)**
CH4	91.72 ± 1.7	C5H12	0.03 ± 0.03
C2H6	5.5 ± 1.6	N2	0.322 ± 0.3
C3H8	1.98 ± 0.8	CO2	0.03 ± 0.03
C4H10	0.44 ± 0.5	Lower heating value (MJ/kg)	49.5 ± 0.2
Density(kg/m3)	0.788	Stoichiometric air/fuel ratio	17.20

2.6 Using ammonia in IC engines

Ammonia has been identified as a promising alternative fuel for internal combustion (IC) engines, offering potential benefits in terms of reduced emissions and improved engine performance. Research has explored various aspects of utilizing ammonia in IC engines, particularly in dual-fuel configurations, to effectively leverage its unique properties[70]. Research has investigated using ammonia in IC engines as a primary or supplementary fuel to improve combustion and lower emissions. Ammonia's adaptability in engine applications is demonstrated by its ability to spark combustion in dual-fuel mode with a modest amount of diesel or biodiesel without requiring major engine modifications[71]. Additionally, the use of ammonia in compression-ignition engines in dual-fuel mode with diesel has been discovered to be a viable approach to improving engine performance and reducing carbon emissions[72]. The combustion properties of ammonia in internal combustion engines, including spark-ignition engines, have been investigated through experimental study. According to results, ammonia burns efficiently in SI engines and produces large power outputs, especially when paired with hydrogen enrichment or higher intake pressure[73]. The study of ammonia-hydrogen blends in IC engines has demonstrated their potential to increase efficiency and mean effective pressure, making them suitable fuels for SI engines[74]. Furthermore, these blends have shown promise in reducing emissions of harmful pollutants such as nitrogen oxides, highlighting their potential for improving air quality. Additionally, ongoing research is exploring the optimal blend ratios and combustion strategies to maximize the benefits of using ammonia-hydrogen blends in IC engines[75][76]. The conversion of diesel engines to dedicated ammonia operations has been investigated, highlighting ammonia's potential to improve the traditional energy structure and reduce carbon emissions in internal combustion engines[77]. The use of ammonia in dual-fuel marine engines has also been investigated and showing promising results in terms of performance and emissions[78]. Ammonia is considered a potential alternative fuel for reducing greenhouse gas emissions in the shipping industry, as it can be produced from renewable sources. Further research and development are needed to optimize its use and ensure its safety in marine applications. This research will be crucial in determining the feasibility of using ammonia as a sustainable fuel alternative for marine transportation[79].

2.7 Hydrogen properties in IC engines

Table 2 shows that hydrogen has unique physical and chemical properties in comparison to the conventional fossil fuels widely used in the transportation sector, namely compressed natural gas (CNG), gasoline, and diesel[80]. Throughout the study, engine performance in various engine modes using these fuels is frequently compared to hydrogen. Hydrogen's zero carbon content is one of the numerous benefits of using it as a clean alternative fuel in internal combustion engines. This implies that NOx is the only toxic combustion byproduct remaining when carbon-based pollutants, primarily CO, CO2, and soot, are eliminated. Hydrogen's lower heating value is a result of its high specific energy density, which allows it to supply almost three times as much energy by mass as other fossil fuels[81].

TABLE II. HYDROGEN PROPERTIES COMPARED WITH COMPRESSED NATURAL GAS (CNG), GASOLINE AND DIESEL

Property	**Hydrogen**	**CNG**	**Gasoline**	**Diesel**
Carbon content (mass%)	0	75[e]	84	86
Lower heating value (MJ/kg)	119.7	45.8	44.8	42.5
Density [a,b] (kg/m^3)	0.089	0.72	730–780	830
Volumetric energy content [a,b] (MJ/m^3)	10.7	33.0	33 × 103	35 × 103
Molecular weight	2.016	16.043 [e]	~110	~170
Boiling point [a] (K)	20	111 [e]	298–488	453–633
Auto-ignition temperature (K)	858	813 [e]	~623	~523
Minimum ignition energy in air [a,d] (mJ)	0.02	0.29	0.24	0.24
Stoichiometric air/fuel mass ratio	34.5	17.2 [e]	14.7	14.5
Stoichiometric volume fraction in air (%)	29.53	9.48	~2[f]	-
Quenching distance [a,c,d] (mm)	0.64	2.1 [e]	~2	-
Laminar flame speed in air [a,c,d] (m/s)	1.85	0.38	0.37–0.43	0.37–0.43 g
Diffusion coefficient in air [a,b] (m^2/s)	8.5 × 10−6	1.9 × 10^{-6}	-	-
Flammability limits in air (vol%)	4–76	5.3–15	1 – 7.6	0.6–5.5
Adiabatic flame temperature [a.c.d] (K)	2480	2214	2580	~2300

[a] at 1 bar, [b] at 273 K, c at 298 K, d at stoichiometry, [e] methane ,[f] vapor and [g] n-heptane

2.8 Using hydrogen in spark ignition engines

A lot of research has been done on the use of hydrogen in spark ignition (SI) engines[82]. Fuels enhanced with hydrogen have demonstrated encouraging outcomes in terms of enhancing the efficiency and combustion properties of spark ignition engines. shown that adding hydrogen to gasoline resulted in a rise in peak pressure and a drop in relevant crank angle.[83]. Furthermore, the addition of hydrogen and ethyl alcohol improved all engine performance parameters in a gasoline spark-ignition engine[84]. Furthermore, we investigated the effects of different spark plugs and hydrogen usage at various engine loads, indicating the potential for optimizing engine performance with hydrogen-enriched gasoline[85] Additionally, the use of hydrogen as a fuel additive in gasoline and diesel engines has been considered, but the efficiency of the combustion process and the high costs of additional electrolysis systems for hydrogen production have been cited as limiting factors[86]. Thus, studies on the application of hydrogen in SI engines show that it has the potential to enhance emissions, performance, and combustion. To fully reap the benefits of hydrogen-enriched fuels in spark ignition engines, however, issues like cost-effectiveness and combustion anomalies must be resolved.

3. INJECTION OF DUAL FUELS

The suction in a dual-fuel diesel engine is often a mixture of producing gas and air, referred to as the charge mixture. Through the use of a high-speed diesel injector, a small amount of conventional fuel is introduced into the compressed charge mixture. This fuel then spreads to the surrounding homogeneous mixture inside the cylinder in a manner that is strikingly similar to that of the spark ignition operating mode[87]. Figure 4 illustrates the complicated combustion process of dual-fuel engines and compression ignition diesel engines in terms of pressure rise with respect to crank angle position[88].

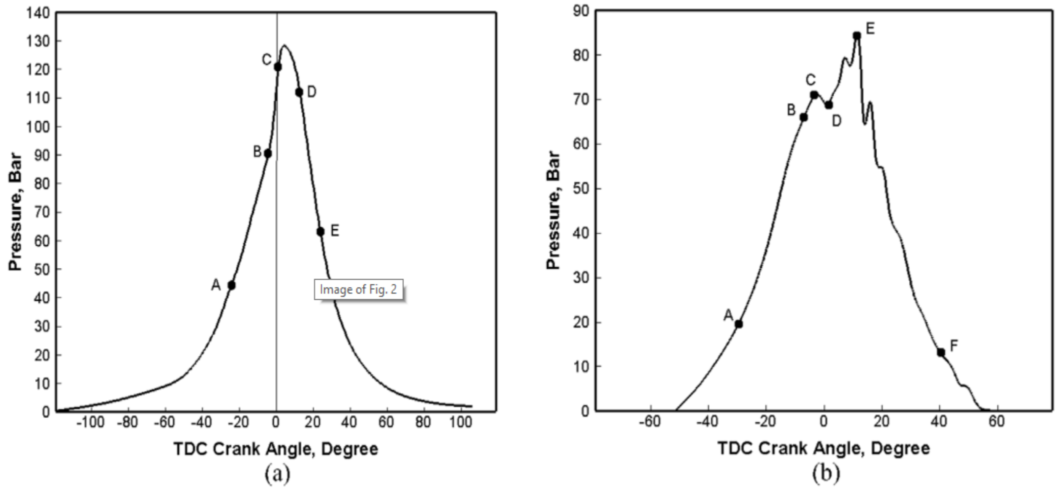

Fig. 4. Combustion process, (a) For diesel engine, and (b) For dual-fuel diesel engine [87].

The four stages of the combustion process in a compressed ignition diesel engine are depicted in Fig. 4, where A-B stands for ignition delay, B-C for premixed combustion phase, C-D for rate of regulated combustion phase, and D-E for post-combustion stage. In a dual-fuel diesel engine, the combustion process can be thought of as five stages: A-B denotes the ignition delay, B-C the pre-mixed combustion phase, C-D the primary fuel ignition delay, D-E the primary fuel's uncontrolled combustion phase, and E-F the post-combustion phase. Compared to normally aspirated mode, it is clear that the ignition delay phase is highest for dual-fuel engines since the concentration of oxygen gradually decreases with the addition of gaseous fuel. This reduction in oxygen concentration prolongs the ignition delay phase[87]. The diesel fuel mode exhibits a better rate of pressure increase when accounting for the pre-mixed phase of combustion[89]. In contrast to traditional diesel engines, new dual-fuel engines have a very short primary fuel igniting delay period (C-D). Furthermore, because the primary liquid fuel spontaneously ignites throughout the combustion period (D–E), it is likewise regarded as unstable [87]. In dual-fuel diesel combustion mode, the nozzle and injector orientation were discovered to be important in improving the combustion process because they defined the interaction between the pilot fuel and gas jets. Figures 5 and 6 depict the schematic of the axial cross section and the top view of the dual-fuel DI jet orientation with a concentric injector, respectively[90]. The angle between the cylinder head and the jet axis in the axial cross-sectional plane is known as the injection vertical angle, and the angle between the diesel and gas jet axes of a concentric injector on the top plane is known as the interlace angle. In Figure 5, it is observed that the interlace angle is diverging from the concentric injector. However, it can be constructed as a parallel or converging array depending on the injector arrangement[90].

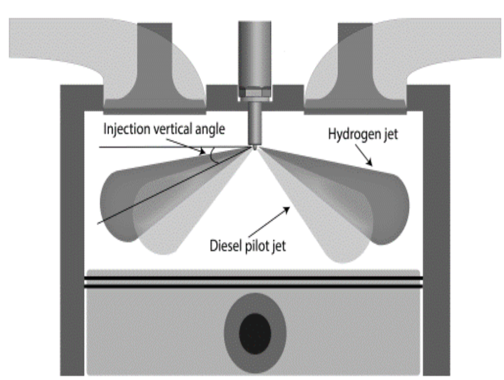

Fig. 5. Schematic of the dual-fuel DI concentric injector jet configuration on the axial cross-sectional plane[35].

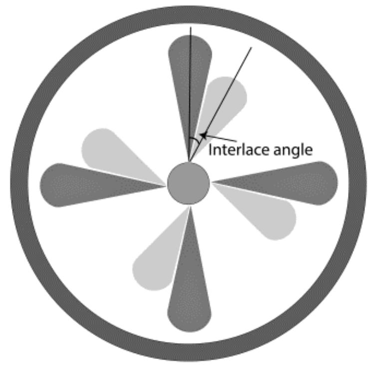

Fig. 6. Schematic of the dual-fuel DI concentric injector jet configuration on the top-plane[35].

Early research conducted in 1983 by Miyake et al [91] showed that the BTE of the CNG-diesel dual-fuel DI engine was higher than that of the then-current diesel engines. The engine was a modified four-stroke single-cylinder diesel with a big bore (420 mm) and two independent injectors. The gas injector was positioned in the middle, perpendicular to the cylinder head, and diesel pilot jets were injected from the cylinder's periphery in a radial pattern. For 85% and 100% of the engine's full load, only 5% of the diesel fuel needed to be added to the total energy input when using CNG injection pressure of 250 bars.

4. EFFECT OF AMOUNT OF HYDROGEN WITH DIESEL

The purity of the hydrogen employed in this investigation was 99.99%. Diesel fuel was a standard EN590-convenient product. The test engine's fuel injection advance was set to 22° crank angle before TDC, while its hydrogen injection advance was set to the beginning of the intake stroke. The speed was adjusted to 750, 900, 1100, 1400, 1750, and 2100 r/min while the engine was run at full load[92]. In pre-engine tests, the engine map was created and brake-specific diesel fuel consumption estimates were determined based on engine load and engine speed. Then, with the lower heating values of hydrogen and diesel fuels, the hydrogen energy fraction may be computed with ease. The amount of hydrogen fuel injected by the injector was simply modified to reach the necessary hydrogen energy percentage by varying the injection amount based on the injection duration. Depending on the hydrogen energy fraction and engine rpm, the LPG injector's injection duration varied from 4 to 12 ms. The hydrogen mass flow rate is dependent on the input hydrogen energy fraction and engine speed, and it ranges from 12.5 to 44.6 slpm. 25% and 50% of the mixture's total energy content was designated as the hydrogen rate. Table 2 contains a list of the test conditions.

TABLE III. TEST CONDITIONS.

Engine speed (r/min)	**H2 energy content (%)**	**Diesel fuel energy content (%)**	**Diesel fuel injection advance (CAD before TDC, degrees)**	**H2 injection advance (CAD before TDC)**
750	0	100	22	At TDC
750	25	75	22	At TDC
750	50	50	22	At TDC
900	0	100	22	At TDC
900	25	75	22	At TDC
900	50	50	22	At TDC
1100	0	100	22	At TDC
1100	25	75	22	At TDC
1100	50	50	22	At TDC
1400	0	100	22	At TDC
1400	25	75	22	At TDC
1400	50	50	22	At TDC
1750	0	100	22	At TDC
1750	25	75	22	At TDC
1750	50	50	22	At TDC
2100	0	100	22	At TDC
2100	25	75	22	At TDC
2100	50	50	22	At TDC

5. EXPERIMENTAL RESULTS

Based on engine speed, Figure 7(a) illustrates how the test engine's brake power varied at various hydrogen energy contents (0%, 25%, and 50%). Based on engine speed, Figure 7(b) illustrates how the test engine's brake torque varies at various hydrogen energy contents (0%, 25%, and 50%). The excess air ratio value in Figure 7(c) was maintained as closely as feasible. The engine injures less air when hydrogen is injected into the intake manifold. The volumetric efficiency of the test engine was lower in the 25% and 50% hydrogen injection experiments over the entire engine speed range, as shown in Figure 6(d). Hydrogen has a higher heating value than diesel fuel, but because of the engine's decreased volumetric efficiency, less torque and power were generated. When 25% energy equivalent hydrogen injection is used, the measured engine power loss ranges from 8.1% to 15.1% across the whole speed range. When 50% energy equivalent hydrogen was injected, the test engine's power output dropped even more, falling between 10.8% and 25.4% below that of neat diesel operation. When 25% hydrogen is added, the braking engine power value decreases by 8.1%–15.1% (on an energy basis), and when 50% hydrogen is added, the brake engine power value decreases by 10.8%–25.4% as compared to solely diesel fuel (0% hydrogen).

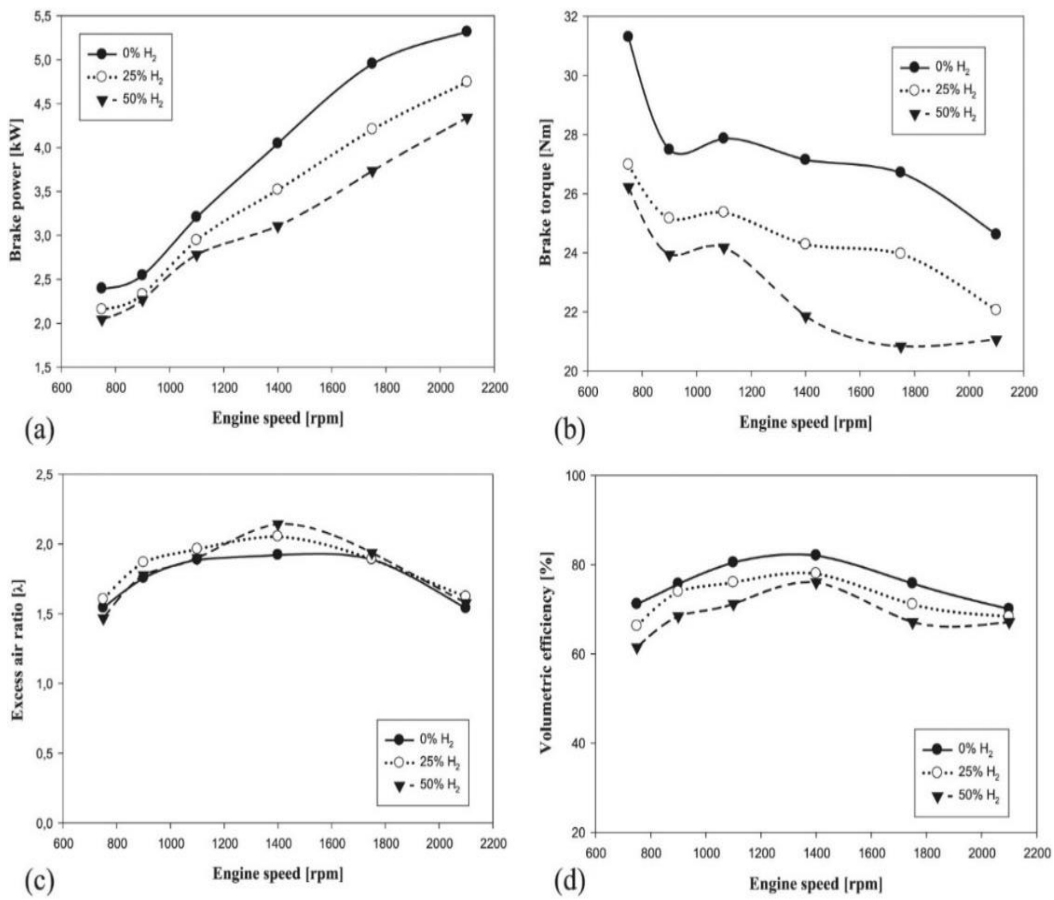

Fig. 7. (a) Variation of brake power, (b) brake torque, (c) excess air ratio (d) and volumetric efficiency depending on engine speed and hydrogen rate[93].

Figure 8(a) shows the variation in the brake thermal efficiency value based on engine speed at different hydrogen quantities, and Figure 8(b) shows the variation in the BSFC value based on engine speed at different hydrogen quantities. The flame speed of hydrogen is nine times faster than that of diesel fuel. 24 The brake thermal efficiency rating decreases by 3.3%–8.1% with a 25% hydrogen addition (the energy content of the overall fuel), and by 8.2%–15.5% with a 50% hydrogen addition as compared to solely diesel fuel. Results are discovered in terms of diesel fuel when the quantity of diesel fuel consumed is multiplied by the BSFC and the equivalent diesel fuel quantity derived from the lower specific value of hydrogen. When 25% of the fuel's energy content is hydrogen, the BSFC value increases 3.4%–8.7%, and when 50% of the fuel is hydrogen, the BSFC value increases 9.0–18.4% when compared to solely diesel fuel. Hydrogen usually improves the combustion efficiency of diesel fuel. According to Varde and Frame's study, the addition of hydrogen alters the combustion phase advance, which has a negative effect on thermal efficiency[94]. The investigation conducted by Christodoulou and Megaritis on a Ford Puma diesel engine revealed a decline in thermal efficiency at low speeds. It is thought to be caused by a drop in hydrogen combustion efficiency that was observed experimentally[95]. Since N2 is often used to simulate EGR in studies, the higher molar thermal capacity of hydrogen relative to N2 dilutes cylindrical gas, which lowers combustion efficiency[91].

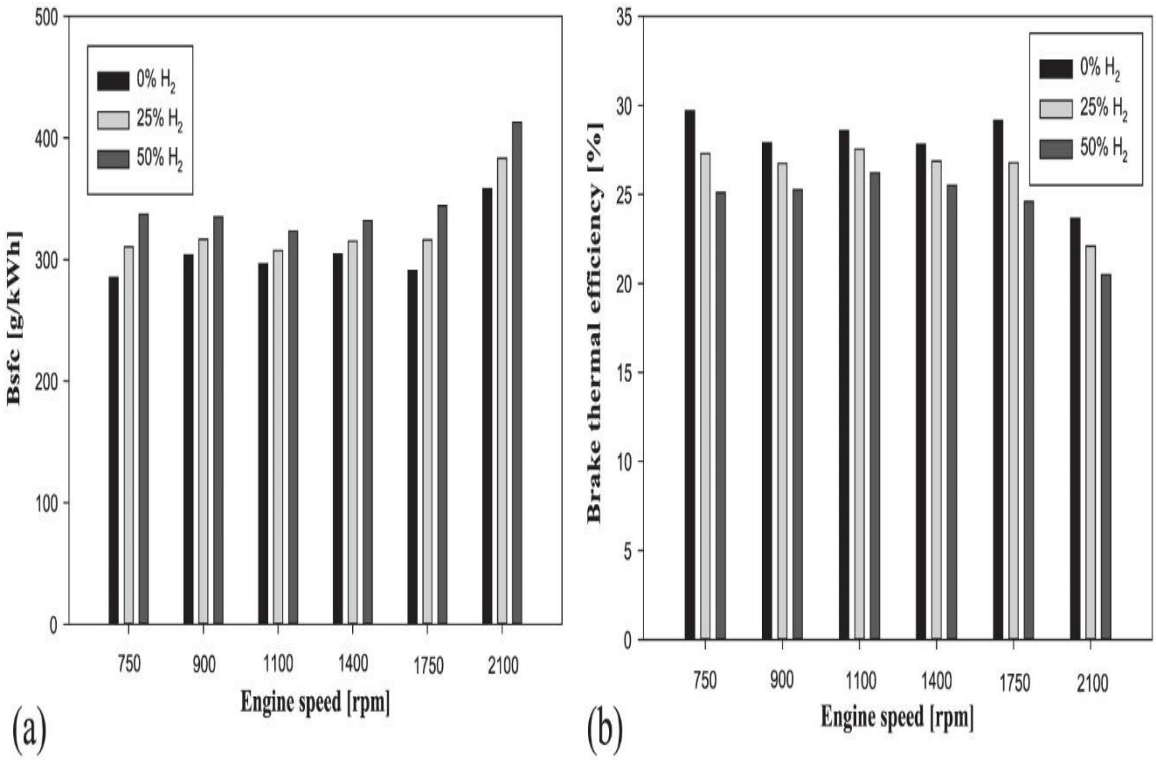

Fig. 8. (a) Brake-specific fuel consumption value variation at different hydrogen quantities based on engine speed and (b) brake thermal efficiency value variation at different hydrogen quantities based on engine speed[88,92].

Figure 9(a) shows the fluctuation in CO emission values depending on engine speed at various hydrogen concentrations. Compared to using only diesel fuel, CO emissions are significantly reduced at all engine speeds when 25% and 50% hydrogen is added. Compared to solely diesel fuel circumstances (0% hydrogen), an improvement of 20.4%–65.3% and 48.5%–66.3% is observed, respectively, with hydrogen addition equivalent to 25% and 50% of total fuel as energy content. Figure 9(b) shows the fluctuation in CO2 emission values depending on engine speed at various hydrogen concentrations. as hydrogen is added, CO2 emissions are significantly reduced across all engine speeds as compared to diesel fuel alone. When 25% hydrogen is added, CO2 emissions improve by 12.7%–25.4%, and when 50% hydrogen is added, CO2 emissions improve by 23.4%–38.7% as compared to diesel fuel alone. Since hydrogen is carbon-free, CO2 emissions are reduced[80]. Combustion efficiency increases and combustion duration shortens with an increase in the H/C rate of the total fuel when hydrogen is added[93]. Conversely, the high diffusion coefficient of hydrogen leads to an improvement in diesel fuel heterogeneity and the formation of a more homogeneous pre-mixed ignitable mixture[94]. Based on these findings, it is clear that the addition of hydrogen reduces specific CO2 emissions [95].

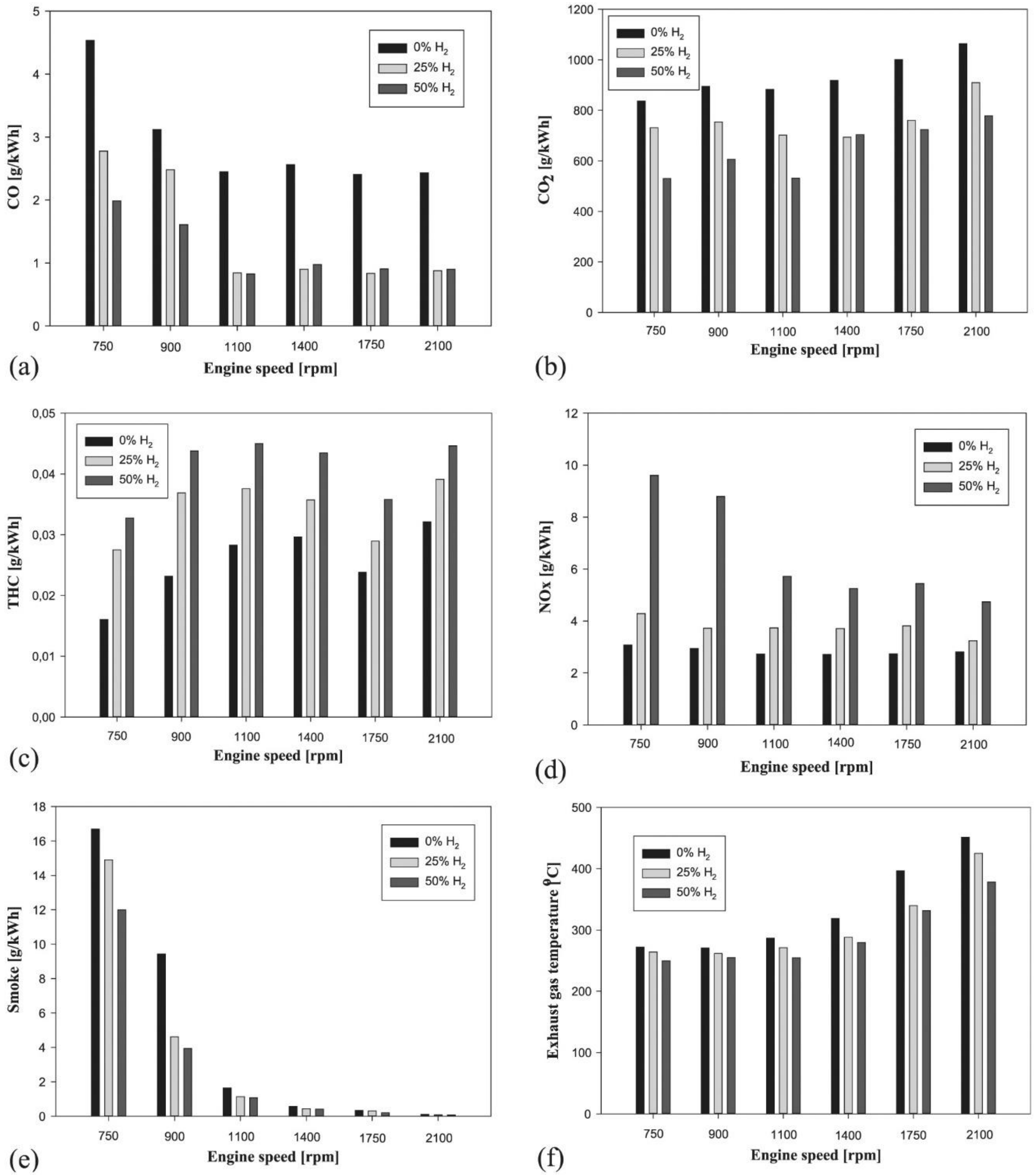

Fig. 9. (a) CO emission value variation, (b) CO2 emission value variation, (c) THC emission value variation, (d) NOx emission value variation, (e) Smoke emission value variation and (f) exhaust gas temperature value variation based on engine speed at different hydrogen quantities[93].

In comparison to solely diesel fuel (0% hydrogen), the power value of the brake engine drops by 8.1%–15.1% with 25% hydrogen addition (as an energy basis) and by 10.8%–25.4% with 50% hydrogen addition. In addition, torque and volumetric efficiency ratings for brake engines have dropped as compared to diesel fuel alone (0% hydrogen). Hydrogen may be introduced into the cylinder in place of some air by keeping the excess air ratio value as close as feasible.

When 25% hydrogen is added (as the energy content of the whole fuel), the brake thermal efficiency value drops by 3.3%–8.1%, and when 50% hydrogen is added, it reduces by 8.2%–15.5% as compared to diesel fuel alone. Results are discovered in terms of diesel fuel when the quantity of diesel fuel consumed is multiplied by the BSFC and the equivalent diesel fuel quantity derived from the lower specific value of hydrogen. At all cycles, the addition of hydrogen raises the BSFC value.

Comparably, at all engine speeds, hydrogen enrichment in filling results in a significant reduction in CO emissions. Compared to simply diesel fuel (0% hydrogen), an improvement of 20.4%–65.3% and 48.5%–66.3% is seen, respectively, with 25% and 50% hydrogen addition as the energy content of the whole fuel. Furthermore, at all engine speeds, CO2 readings drop with the addition of hydrogen.

6. CONCLUSION

Hydrogen can be used in dual-fuel diesel engines to reduce emissions and fuel consumption. With 90% hydrogen enrichment, brake thermal efficiency increases to 29.1%, but knocking occurs. The best results are achieved with 30% hydrogen, achieving 27.9% efficiency without knocking. As hydrogen percentage increases, specific energy consumption decreases. At maximum load, NOx emissions drop from 1806 to 888 ppm and smoke emissions from 6.8 BSN to 2.3 BSN. Under ideal conditions, efficiency rises from 23.59% to 29%. The combustion properties of hydrogen enhance the combustion process, improving energy and pollution performance. The use of hydrogen in dual-fuel diesel engines enhances operational effectiveness and environmental sustainability. Benefits such as lower emissions, improved engine performance, and increased fuel efficiency are supported by evidence from evaluated sources.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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