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Overview Biodiesel-hydrogen as a Combined Fuel Resource in Dual Fuel Diesel Engine

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Abstract— **Rising concerns about energy consumption and the environmental impact of fossil fuels are driving the search for alternative, cleaner energy sources. Extensive research has been conducted to explore alternative fuels as a means of optimizing energy requirements. This review provides a comprehensive analysis of how alternative fuels affect the combustion process in compression ignition (CI) engines, focusing on various combinations of diesel fuel with biodiesel, hydrogen, ammonia, LPG, and CNG. These fuels were combined to determine the most effective option. In the case of biodiesel-hydrogen mixtures, a 13-22% decrease in brake thermal efficiency (BTE) was observed. Conversely, using natural gas as an alternative fuel in dual-fuel engines resulted in a substantial increase in brake specific fuel consumption (BSFC), reaching up to 250 g/kWh.**

Keywords— Alternative fuels, combustion process, compression ignition engines, brake thermal efficiency, brake specific fuel consumption.

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I. INTRODUCTION

The rapid growth of technology and modern business practices has led to environmental problems, despite the economic benefits. This has caused worry about building a future that is both sustainable and environmentally friendly. Renewable energy sources like biomass, geothermal, solar, wind, and hydro-wave offer promising solutions. These sources are plentiful and often more affordable than traditional energy options.

The world's need for energy is increasing quickly because of population growth, better living conditions, and more industrial activity. The International Energy Agency (IEA) expects the world's energy demand to double by the year 2050. Currently, more than 80% of the world's energy comes from fossil fuels like oil, coal, and natural gas [1]. Besides using up fossil fuels, extracting, processing, and burning them has also caused serious environmental pollution. To solve these problems, energy-efficient and environmentally friendly technologies must be developed and used in all different industries.

Energy is essential for societal sustainability and development. Fossil fuels, a major energy source, are used extensively in daily life. However, the conservation of these fuels is becoming increasingly problematic, especially in developing countries like India. There's a growing concern that future fuel demand may outpace supply. The global expansion of power sectors has accelerated the depletion of conventional energy sources [2]. People are more interested in alternative fuels because they need to find replacements for traditional energy sources. Another important reason is environmental pollution. Air pollution and global warming, mainly caused by nitrogen oxides, particulate matter, and carbon dioxide, are serious problems that have.

Diesel is the primary widely used petroleum fuel, and its use is increasing steadily around the world [1]. Diesel engines have several advantages over gasoline engines, such as improved thermal efficiency, better fuel economy, enhanced durability, increased reliability, and lower emissions of carbon dioxide and unburned hydrocarbons [4]. The Organization of the Petroleum Exporting Countries (OPEC) predicts that global demand for diesel and gas-oil will rise from 28.6 to 31.6 million barrels per day between 2017 and 2040[5]. (fig.1)

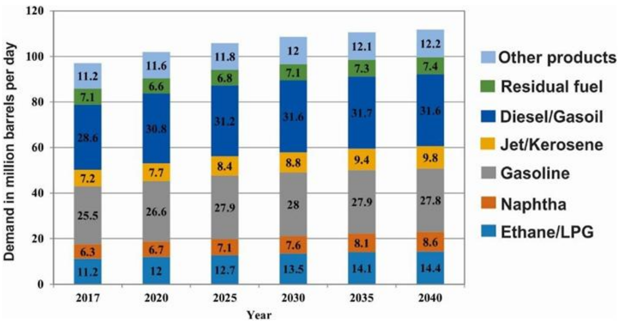

Figure 1. Global petroleum-derived fuel demand projection from 2017 to 2040. Redrawn from Ref [5].

The growing need for middle distillates will probably lead to a significant increase in the number of diesel-powered light and heavy-duty vehicles used in manufacturing, agriculture, and services. As shown in Figure 2, the global market for diesel engines is expected to grow from 8.1 billion USD in 2018 to 11.02 billion USD in 2026 [5]. (Fig.2).

Apart from the advantages mentioned above, diesel engines have several disadvantages, such as high nitrogen oxide (NOx) emissions, particulate (PM) materials, and smoke. Many researchers have

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investigated and leveraging alternative fuels for diesel engines is a sustainable solution to address current challenges. In this regard, various gas fuels have been extensively studied as potential clean and efficient combustion fuels. This review examines the use of biodiesel and hydrogen as alternative fuels in compression ignition (CI) engines, with a focus on optimizing engine performance through their application.

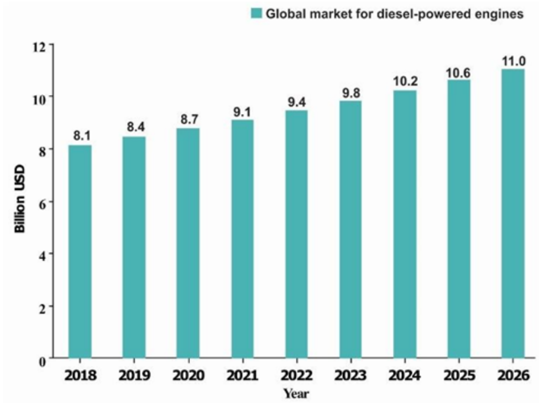

Figure 2. The global market for diesel-powered engines from 2018 to 2026 [5].

II. Literature Review

2.1 Diesel Machine

A diesel engine is an internal combustion engine that utilizes the heat generated by compressing air to ignite fuel. Unlike gasoline engines, which use spark plugs for ignition, diesel engines rely on the high temperatures reached during compression to spontaneously ignite the injected fuel [6]. The idea of compression ignition engines was first introduced by Rudolf Diesel, a famous engineer and inventor, in 1892. In 1897, Diesel suggested that internal combustion engines could use heat better and be more efficient than the popular steam engines of that time [7].

Advantages of Diesel Engines [6]:

- Fuel Efficiency: Diesel engines generally use fuel more efficiently than gasoline engines.
- High Torque: Diesel engines produce a lot of torque at low speeds, making them perfect for vehicles that need a lot of power, like trucks, buses, or other heavy vehicles.
- Long Engine Life: The parts in diesel engines are usually stronger and last longer than those in gasoline engines.

Disadvantages of Diesel Engines [6]:

- Emissions: Diesel engines produce higher levels of nitrogen oxides (NOx) than gasoline engines.
- Price: Cars with diesel engines usually cost more.
- Noise: Diesel engines tend to be rougher and noisier.
- Vibration: Diesel engines produce more noticeable vibrations.
- Fuel Sensitivity: Diesel engines are very sensitive to the quality of the fuel used.

2.1.1 Diesel dual fuel

Diesel dual fuel engine is an engine that can run on a combination of diesel fuel and another fuel, usually natural gas. This ability to use both fuels offers several benefits that address the shortcomings of using diesel fuel alone [6]. One of the ongoing challenges with diesel dual fuel engines is their reduced combustion performance and increased emissions of carbon monoxide and hydrocarbons, especially at lower operating levels. [8], [9].

2.2 Fuel

2.2.1 Biodiesel

Crude palm oil or biodiesel is an alternative fuel that can be made from plant-based materials found in nature, like palm oil (Crude Palm Oil) [10]. The process of making biodiesel involves a transesterification process where plant oils with short-chain alcohol are mixed together. Alcohol is added to Crude Palm Oil (CPO), and glycerol will settle at the bottom while methyl ester (biodiesel) floats to the top. The methyl ester is then washed with distilled water to create biodiesel [11]. Biodiesel made from coconut oil or palm oil has several advantages, such as being readily available in Southeast Asia, particularly in Malaysia and Indonesia. There is great potential for using coconut oil as a main ingredient for producing biodiesel in Indonesia. Additionally, in 2020, Indonesia was listed as the world's largest palm oil producer [12]. The area of oil palm plantations in Indonesia has continued to grow over 10 years, reaching 11.67 million hectares in 2016 [12]. When used in diesel engines, biodiesel can be used as a mixture with diesel fuel or as a full biodiesel fuel. Biodiesel made from CPO is known to be environmentally friendly [9]. The high oxygen content in biodiesel affects gas emissions. Biodiesel has an oxygen content of 9-12% [13], [14]. The high oxygen content in biodiesel has several advantages, including: reducing smoke emissions, CO, HC, CO2, and Exhaust Gas Temperature [14],[15] and [16]. Another advantage of biodiesel is its high cetane number, which is around 58. A higher cetane number indicates a shorter ignition delay, meaning the fuel ignites more quickly after it's injected into the cylinder. Ignition delay is the time between fuel injection and the start of combustion in the cylinder. A higher cetane number means a shorter ignition delay and a smoother running diesel engine [13].

2.2.2 Hydrogen

Hydrogen is considered one of the future fuels in the automotive industry. It's a clean fuel and can be obtained from nature as a renewable resource [4]. Hydrogen is a fuel that has received a lot of attention for development because it's an environmentally friendly fuel with the potential to replace fossil fuels. In terms of production, hydrogen is a secondary energy source that can be produced using various primary energy sources like fossil fuels, nuclear energy, and chemical reactions [17]. In addition, hydrogen production can be done independently using the electrolysis reaction of water with electricity. Hydrogen gas can be used in internal combustion engines as an additional fuel or the primary fuel, with diesel fuel used as a pilot fuel. The auto-ignition temperature of hydrogen fuel is 5850 degrees Celsius, so it can be used in engines with high compression, like a diesel engine [18].

2.2.3 CNG

Several studies have shown that using compressed natural gas (CNG) in dual-fuel diesel engines can lead to reduced engine performance and increased emissions. When CNG is introduced into the cylinder, it can displace some of the incoming air, resulting in a higher specific heat ratio for the air-CNG mixture compared to pure air. This increase in specific heat ratio affects the decrease in temperature at the end of the compression stroke [17].

2.3 Performance Analysis

Performance analysis of an engine includes the utilization of fuel energy to produce the required power. This chapter includes the analysis of various operating parameters such as brake thermal efficiency (BTE) and Specific fuel consumption (SFC).

2.3.1 Brake thermal efficiency

Brake thermal efficiency is a measure of the extent to which the thermal energy stored in the fuel is converted into effective power by an internal combustion engine. The less energy required to produce the same power, the better the thermal efficiency [8], [9].

$$\eta bth = \frac{P}{\dot{m}_f \times CV} \qquad [8], [9].$$

- P is the effective power output of the engine (usually in Watts or kW).
- $\dot{m}_{fuel}$ is the mass flow rate of the fuel (usually in kg/s).
- CV is the calorific value of the fuel (usually in J/kg or MJ/kg).

2.3.2 Specific fuel consumption (SFC).

Specific fuel consumption (SFC) is a measure of fuel efficiency, defined as the rate of fuel consumption per unit of power output. SFC is influenced by the quality of the air-fuel mixture in the combustion chamber. Higher SFC values indicate less efficient fuel utilization, as more fuel is required to produce a given amount of power [8], [9].

$$SFC = \frac{\dot{m}_f}{P} \qquad [8], [9].$$

- $\dot{m}fuel$ is the mass flow rate of the fuel (usually in kg/s).
- P is the effective power output of the engine (usually in Watts or kW).

2.4 Review Paper

TABLE 1.
STANDARD VOLTAGE AND FREQUENCY VARIATIONS FOR AC DISTRIBUTION SYSTEMS

No	Author	Year	Variety problem	Performance	Reference
1	Al-Dawody et al	2023	Diesel and NH3 (aq)	BTE, power, BSFC	[21]
2	Anandavelu	2023	1-hexanol with diesel/biodiesel	BTE, BSEC	[32]
3	Arulkumar and Vijayaragavan	2023	H2-diesel/Calophyllum inophyllum oil	BTE, BSFC	[33]
4	Barik et al	2023	DDEE and H2 in dual fuel	BSFC, BTE	[34]
5	Bhagat et al (review)	2023	H2 in dual fuel	BTE	[35]
6	Bora et al	2023	Biodiesel - H2	BTE	[24]
7	Das and Das	2023	Waste cooking palm biodiesel - H2	BTE, BSFC	[36]
8	Elbanna et al	2023	Diesel - ethanol	BSFC	[37]

CONTINUED - TABLE 2.

STANDARD VOLTAGE AND FREQUENCY VARIATIONS FOR AC DISTRIBUTION SYSTEMS

No	Author	Year	Variety problem	Performance	Reference
9	Farzam and McTaggart- Cowan	2023	H2 in dual fuel (common rail 4 cyl)	IMEP, BTE, BSFC	[38]
10	Gurusamy and Ponnusamy	2023	H2 - champor oil/diesel/DEE	HES, BTE, BSEC, BSFC, VE	[39]
13	Lalsangi et al	2023	H2 injection timing in biodiesel - H2	BTE	[30]
14	Lawrence et al	2023	H2/acetylene gas - jojoba biodiesel	BTE, BSEC	[42]
15	Nguyen et al	2023	PG- biodiesel/diesel	BSFC, BTE	[43], [44]
16	Nguyen et al (review)	2023	diesel and gaseous fuel	BTE, BSFC, BSEC	[33]
17	Pinto et al	2023	biodiesel and H2 port injection	HES, BTE	[23]
18	Pullagura et al	2023	Biodiesel- alcohol/diesel - H2	BTE, BSFC	[27]
19	Thiruselvam et al	2023	H2 - palm biodiesel	BSFC, BTE	[37]
20	Vasanthakumar et al	2023	H2-diesel/ethanol	HES, DES, BTE, BSFC, BSEC	[45]
21	Wang et al (review)	2023	H2-diesel/biodiesel	BTE, BSFC,	[46]

2.5 Methodology

TABLE 2.

PROPERTIES OF FUEL

Properties	Diesel [47], [48]	Biodiesel [49]	Hydrogen [1], [5], [9], [13], [17], [19], [20], [27], [38], [48], [50], [51]	CNG [28]	Biogas [3], [20], [22], [23], [24], [25], [26]	Acetylene [26], [42]
Density @15°C and 100 kPa (kg/m³)	848	960	0.008	0.717	0.75-0.85	0.771

CONTINUED - TABLE 2.
PROPERTIES OF FUEL

Properties	Diesel [47], [48]	Biodiesel [49]	Hdrogen [1], [5], [9], [13], [17], [19], [20], [27], [38], [48], [50], [51]	CNG [28]	Biogas [3], [20], [22], [23], [24], [25], [26]	Acetylene [26], [42]
Diffusivity in air (cm²/s)	0.004	10^-5 to 10^-4	0.63	0.22	0.15-0.20	0.23
Heating value (MJ/kg)	42.7	38 to 42	119.8	55.5	20-25	22.4
Auto- ignition temperature (K)	535	500 – 600	858	870	500 - 600	650
Flammability limit (%vol in air)	0.7-5	3.5 – 12	4-75	5- 15	5-15	15-28
Energy density @15°C and 100 kPa (MJ/m3)	35.8	37-39	10.3	39.8	15-19	17.2

2.5.1.Diesel-Biogas dual fuel operation (DBG) and Diesel-biogas-acetylene dual fuel operation (DBGA)

Internal combustion engines typically get heat energy from hydrocarbon fuels. Brake thermal efficiency is used to measure how well an engine converts heat energy into mechanical energy. The brake thermal efficiencies from the experiments performed are shown in Figure 3, which indicates that at engine brake power, the BTE of DBG and DBGA modes are significantly lower than that of the diesel fuel mode. However, at high torques, all BTEs converge.

In DBGA dual-fuel operation, adding acetylene at 10 Nm and 20 Nm engine torque did not positively impact thermal efficiency. This was due to the low in-cylinder temperatures at low loads and the fact that acetylene, which was present in a lower concentration than biogas in the air-fuel mixture, was expelled from the cylinder before it could be completely burned. However, the effect of adding acetylene became more noticeable at 30 Nm engine torque, and the thermal efficiency of DBGA dual-fuel operation reached that of diesel fuel.

In another study using hydrogen instead of acetylene, it was similarly found that as the load increased, the BTE of the dual-fuel mode was higher than the BTE of diesel.

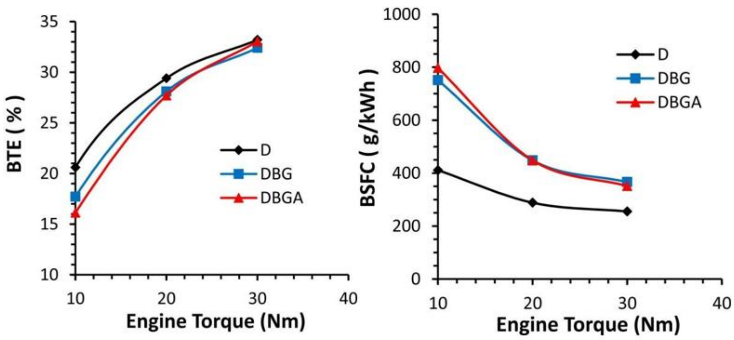

Figure. 3. BTE and BSFC for Diesel, DBG (diesel+biogas) and DBGA (diesel+biogas+acetylene) [26].

Brake Power (kW) = (Torque (Nm) * Speed (RPM)) / (60 * 1000) example = 10 Nm*3000RPM/(60*1000)=0.5 kW
20 Nm*3000RPM /(60*1000)=1 kW
30 Nm*3000RPM/(60*1000)=1.5 kW

In DBGA dual fuel operation, adding acetylene at 10 Nm and 20Nm torques did not have a positive effect on thermal efficiency. This was because in-cylinder temperatures were low at low loads and acetylene, which was present in a lower concentration than biogas in the air-fuel mixture, was expelled from the cylinder before it could be completely burned [19]. However, the effect of adding acetylene became more noticeable at 30Nm engine brake power, and the thermal efficiency of DBGA dual-fuel operation reached that of diesel fuel. It was similarly found that as the load increased, the BTE of the dual-fuel mode was higher than the BTE of diesel + ammonia and diesel + ammonia + CNG [20], [21]. In another study using hydrogen instead of acetylene, it was similarly found that as the load increased, the BTE of the dual-fuel mode was higher than the BTE of diesel [20]. Acetylene has a higher flame speed than all fossil fuels used in internal combustion engines (ICEs), so a small amount of acetylene can improve the combustion of biogas [3], [20], [22], [23], [24], [25], [26].

BSFC of the fuels used in the experiments are shown in Fig. 3. As shown in the figure, the lowest fuel consumption amounts in all operating conditions were undoubtedly obtained with pure diesel fuel. For this reason, BSFC was high in both DBG and DBGA dual fuel modes. At 10Nm engine brake power, specific fuel consumption was very high because some of the biogas and acetylene did not participate in combustion. The inclusion of biogas and acetylene in combustion at 20 Nm and 30 Nm torque engine brake power led to a significant reduction in specific fuel consumption. The BSFC values obtained in this study are also consistent with the BSFC values reported in the literature [24], [27].

2.5.2. Diesel-Amonia dual fuel operation and Diesel-Amonia-CNG dual fuel operation

Figure 4 shows the difference in BTE for pure diesel and a mixture (diesel - ammonia hydroxide) with a volumetric ratio (7.5% - 92.5%) and another with the addition of compressed natural gas in volumetric quantities respectively. It is clear from the figure that thermal efficiency increases with increasing load under all operating conditions due to decreased heat loss. The resulting energy increases because of the quality of combustion, and with the increase in the percentage of ammonia in the mixture, the thermal efficiency of the brakes increases. Adding natural gas and injecting it into the PCCI system works to increase thermal efficiency [8], [28].

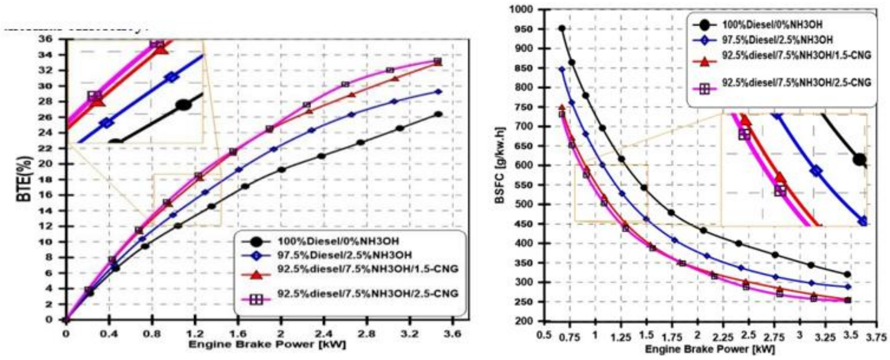

Figure 4. BTE and BSFC for Diesel, Diesel+Amonia, and Diesel+Amonia+CNG [28]

Figure 4 shows that in the case of pure diesel, it is clear from the figure that at the same loads, the consumption rates in the presence of ammonia hydroxide are lower than in pure diesel, and in the case of adding natural gas, the consumption rate decreases further [7], [21], [28].

2.5.3. Diesel-Hydrogen dual fuel operation (DH)

This study tested diesel-biodiesel fuel blends on a three-cylinder, water-cooled, indirect diesel engine at various loads (15, 30, 45, and 60 Nm) and a constant engine speed of 2200 rpm. The goal was to observe the effects of these test fuels on combustion, performance, and emissions characteristics of the diesel engine.

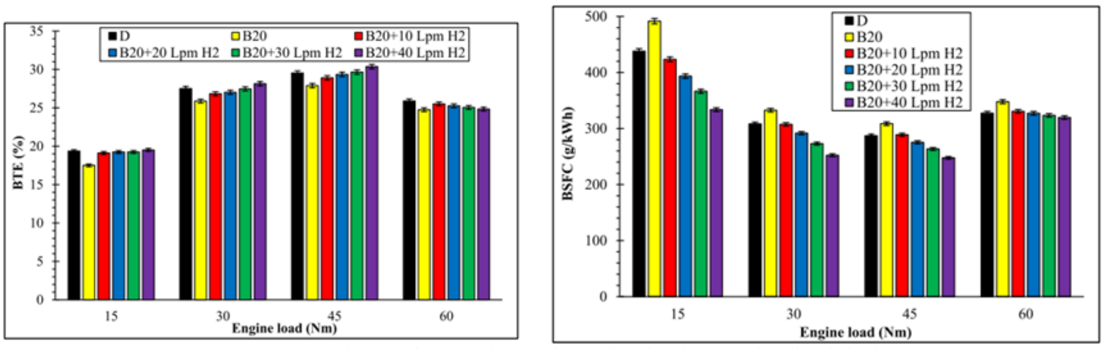

Figure 5. BTE and BSFC for Diesel, Diesel+Biodiesel and Diesel+biodiesel+hydrogen [48]

Brake Power (kW) = (Torque (Nm) * Speed (RPM)) / (60 * 1000) example =5 Nm*2200RPM/(60*1000)=0.5 kW
30 Nm*2200RPM/(60*1000)=1.1 kW
45 Nm*2200RPM/(60*1000)=1.6 kW
60 Nm*2200RPM/(60*1000)=2.2 kW
First, conventional diesel fuel (D) was used to establish a baseline. Then, B20 fuel (a blend of waste cooking oil and 20% diesel by volume) was tested. Finally, four more test fuels were created by adding hydrogen to B20 fuel at different flow rates (10, 20, 30, and 40 L/min). These fuels were named B20 + 10 Lpm H2, B20 + 20 Lpm H2, B20 + 30 Lpm H2, and B20 + 40 Lpm H2, respectively.
From figure 5. The results showed that the BSFC (Brake Specific Fuel Consumption) of B20 fuel increased by

8.78% compared to diesel fuel. However, adding hydrogen to B20 fuel decreased the BSFC value by 8.8%, 13.02%, 17.16%, and 22.12% for B20 + 10 Lpm H2, B20 + 20 Lpm H2,
B20 + 30 Lpm H2, and B20 + 40 Lpm H2, respectively. Hydrogen enrichment also positively impacted BTE (Brake Thermal Efficiency). While BTE dropped by 6.14% in B20 fuel compared to diesel, it increased by 4.51%, 5.05%, 5.62%, and 7.12% in B20 + 10 Lpm H2, B20 + 20 Lpm H2, B20 + 30 Lpm H2, and B20 + 40 Lpm H2 fuels.

2.5.4. Biodiesel-hydrogen dual fuel operation (BH)

Hydrogen gas holds significant potential as a primary fuel for combustion due to its high energy content. It has a lower heating value of 110.1 MJ/kg and a self-ignition temperature between 800°C and 840°C, along with a fast combustion rate. These properties necessitate careful management of hydrogen in the combustion chamber, particularly concerning safety. Because of its high self-ignition temperature, hydrogen typically requires the assistance of other fuels to Require lower ignition temperatures, especially important for CI (combustion internal) engines [29]. Variations in brake thermal efficiency can be seen in Figure 6 Induction hydrogen, Causing an increase in thermal efficiency with engine operation diesel. In the carburizing technique, hydrogen flows continuously into the intake manifold even though the engine does not make an intake stroke, this causes loss of fuel through the intake manifold and also reduced volumetric efficiency because the air is replaced by hydrogen gas fuel [9]. The flow is continuous because the hydrogen is stored at a certain pressure higher and the cylinder valve is open during the entire engine run. Considerable thermal efficiency improvement at high loads of 3000 watts was observed.

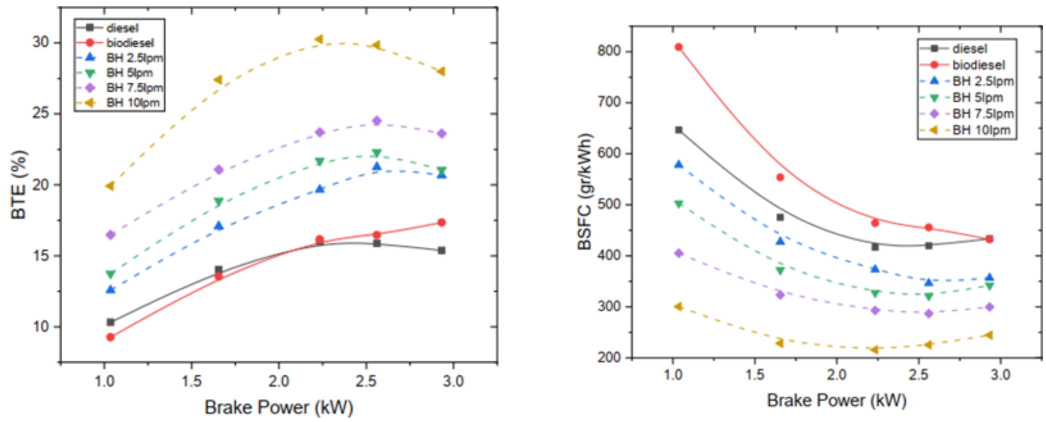

Figure 6. BTE and BSFC for Biodiesel+hydrogen [9]

Increased thermal efficiency by 15.34%, 17.34%, 20.67%, 21.05%, 23.61%, and 27.99% for diesel/diesel, Biodiesel, BH2.5, BH5, BH7.5, and BH10 each. At higher hydrogen flow rates, a large amount of hydrogen gas is present in the combustion chamber. Additionally, the increased amount of pilot fuel injected results in more ignition centers and faster combustion, which can lead to higher thermal efficiency. This increase is due to the rapid combustion causing heat release in a short time, which is not used to generate power but is instead lost to the chamber walls [9].

In general, Figure 6. shows It's clear that SFC decreases as the load increases. This is because a larger engine load requires more fuel for constant motor rotation. After the load is added, the SFC graph tends to decrease up to a load of 3 kW, where the SFC value reaches its minimum. Then, at loads of 3.5 and 4 kW, the SFC value increases. The best SFC is the one with the lowest value. On single fuel diesel/diesel fuel and B100, dual fuel with a hydrogen gas flow rate variation of 2.5 lpm, 5 lpm, 7.5 lpm, and 10 lpm respectively have an SFC value.

In Figure 6. It can be seen that SFC is present in all materials fuel and hydrogen gas flow variations show a concomitant decreasing trend increase in the applied load. The phenomena shown in the conditions. This research is a large mass flow rate of hydrogen gas replacing a number of biodiesel fuel to get the required power. This matter supported by substituted biodiesel data which explains that increasingly Large variations in hydrogen gas flow rate provide substituted biodiesel more and more. Energy content of substituted hydrogen and biodiesel not necessarily capable of producing an effective power of 1 kW. The decline caused by an increase in cylinder temperature which causes fuel that is injected becomes more flammable and is converted into energy generated. So to produce the same amount of energy requires less fuel. On biodiesel fuel B100 without hydrogen gas flow shows the highest compared to fuel Others, this is because no hydrogen mass is used for division in the SFC formula. As the amount of hydrogen gas flow increases making fuel consumption decrease, as seen in the consumption graph lowest fuel at high load at BH10 lpm fuel [9][30], [31].

III. Result and Discussion

3.1. BTE comparison for seceral results

The graph compares the Brake Thermal Efficiency (BTE) for various fuel blends and additives, all tested at a constant brake power of 1 and 1.5 kWh. Biodiesel generally shows a slightly lower BTE compared to diesel. This might be due to factors like the specific properties of the biodiesel used or differences in the combustion process. Blends incorporating different amounts of bio-hydrogen (BH), generally exhibit higher BTEs than diesel or biodiesel. This suggests that the addition of bio- hydrogen can improve fuel efficiency. Within the BDHyd series, BTE tends to increase with higher hydrogen content. This indicates that the addition of more hydrogen can further enhance combustion efficiency. The blends containing ammonia and compressed natural gas (CNG) show varying results. Some combinations lead to higher BTEs, while others have a negligible or even negative impact. This suggests that the interaction between ammonia and CNG with the base fuel can be complex and affect performance differently. Some fuel blends, like BH 7.5, DNH17.5, and especially DBGA, perform significantly better in terms of BTE at lower loads (1 kWh), but their performance drops slightly at higher loads. Blends involving B20 + hydrogen (e.g., B20+H10, B20+H30, and B20+H40) consistently exhibit higher BTE at both engine brake loads, with the BTE generally improving as more hydrogen is added. In general, the hydrogen-blended biodiesel shows the highest efficiency, especially at the 1.5 kWh load, indicating that hydrogen may enhance fuel efficiency when mixed with biodiesel.

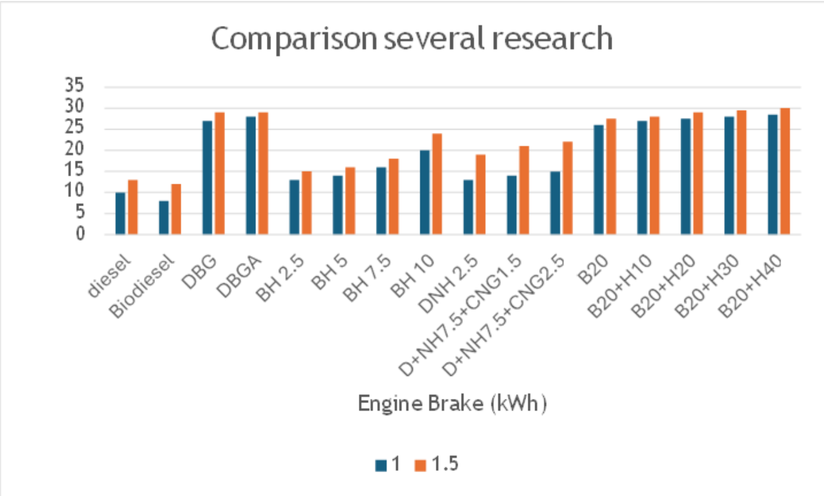

Figure 7. BTE comparison for several research

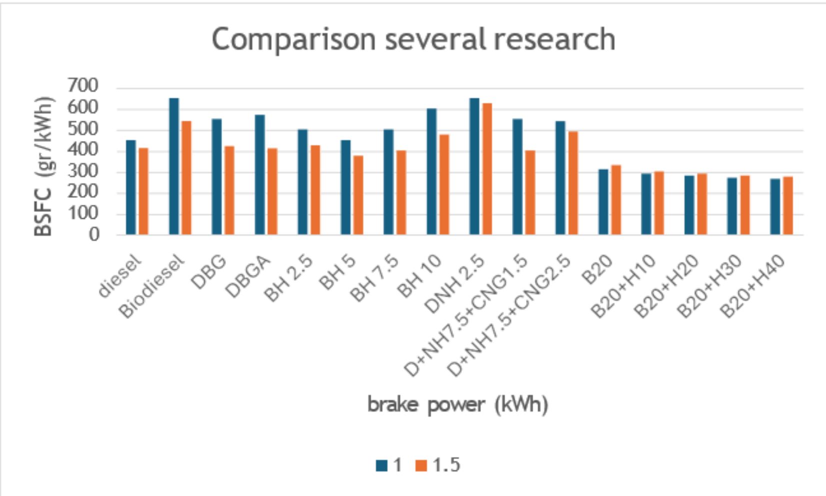

Figure 8. BSFC comparison for several research

Hydrogen as a Fuel Additive: Hydrogen is a clean-burning fuel that can improve combustion efficiency. Adding it to diesel or biodiesel can lead to more complete combustion, resulting in higher BTE. Ammonia as a Fuel Additive: Ammonia can act as a reducing agent, potentially improving combustion and reducing emissions. However, its effectiveness can depend on the specific operating conditions and the presence of other additives. CNG as a Fuel Additive: CNG can provide additional energy content and alter the combustion characteristics of the fuel blend. Its impact on BTE will depend on factors like the ratio of CNG to base fuel and the specific engine design.

3.2. BSFC comparison for several results

The graph compares the Brake Specific Fuel Consumption (BSFC) for various fuel blends and additives, all tested at a constant brake power of 1 and 1.5 kWh. Biodiesel generally exhibits a slightly higher BSFC compared to diesel. This might be due to factors like the specific properties of the biodiesel used or differences in the combustion process. Blends incorporating different amounts of bio-hydrogen (BH), generally show lower BSFC values than diesel or biodiesel. This suggests that the addition of bio-hydrogen can improve fuel efficiency. Within the BDHyd series, BSFC tends to decrease with higher hydrogen content. This indicates that the addition of more hydrogen can further enhance fuel efficiency. The blends containing ammonia and compressed natural gas (CNG) show varying results. Some combinations lead to lower BSFCs, while others have a negligible or even negative impact. This suggests that the interaction between ammonia and CNG with the base fuel can be complex and affect performance differently

Hydrogen as a Fuel Additive: Hydrogen is a clean-burning fuel that can enhance combustion efficiency. Its addition to diesel or biodiesel can lead to more complete combustion, resulting in lower BSFC. Ammonia as a Fuel Additive: Ammonia can act as a reducing agent, potentially improving combustion and reducing emissions. However, its effectiveness can depend on the specific operating conditions and the presence of other additives. CNG as a Fuel Additive: CNG can provide additional energy content and alter the combustion characteristics of the fuel blend. Its impact on BSFC will depend on factors like the ratio of CNG to base fuel and the specific engine design.

IV. Conclusion

Hydrogen as a Fuel Additive: Hydrogen is a clean-burning fuel that can enhance combustion efficiency. Its addition to diesel or biodiesel can lead to more complete combustion, resulting in lower BSFC. The research comparison demonstrates that blending biodiesel with hydrogen significantly improves engine efficiency, particularly at higher power loads. The B20 + H40 blend (20% biodiesel with 40% hydrogen) achieves the highest Brake Thermal Efficiency, making it the most promising alternative to conventional diesel in terms of fuel economy and performance. This highlights the potential of hydrogen-enriched biodiesel as a cleaner and more efficient fuel for future engine technologies. The B20 + hydrogen blends (particularly B20 + H40) show the lowest BSFC values, making them the most fuel-efficient fuel mixtures, especially at higher engine loads. This indicates that blending biodiesel with higher percentages of hydrogen significantly improves fuel consumption efficiency. Conversely, blends like DBGA, DB6, and DNH17.5 exhibit much higher BSFC, indicating poorer fuel efficiency. Traditional diesel shows moderate efficiency but is still outperformed by the best hydrogen-biodiesel blends. Therefore, hydrogen-enriched biodiesel blends offer great potential for improving engine fuel efficiency, particularly under higher loads.

1. Ammonia as a Fuel Additive: Ammonia can act as a reducing agent, potentially improving combustion and reducing emissions. However, its effectiveness can depend on the specific operating conditions and the presence of other additives.
2. CNG as a Fuel Additive: CNG can provide additional energy content and alter the combustion characteristics of the fuel blend. Its impact on BSFC will depend on factors like the ratio of CNG to base fuel and the specific engine design.

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