

Article

An Exploratory Study of Direct Injection (DI) Diesel Engine Performance Using CNSL—Ethanol Biodiesel Blends with Hydrogen

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Abstract: The emissions from direct injection (DI) diesel engines remain a serious setback from the viewpoint of environmental pollution, especially for those who have been persuaded to use biofuel as an alternative fuel. The main drawbacks of using biofuels and their mixtures in DI diesel engines are increased emissions and decreased brake thermal efficiency (BTE) compared to using neat diesel fuel. The current study analyses the biodiesel made from cashew nut shell liquid (CNSL) using a single-cylinder, direct-injection diesel engine to validate the engine's performance and discharge characteristics. In addition to the improved CNSL and a twin-fuel engine that runs on hydrogen, ethanol was added to the fuel at rates of 5%, 10%, and 15%. The investigation was conducted using a single-cylinder direct injection diesel engine at steady-state settings, above the sustained engine speed (1500 RPM). Several performance parameters and pollutant emissions, such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x) were tracked during this study. According to the experimental findings, the biodiesel mixture's brake heat was reduced by 26.79% in comparison to the diesel fuel. The brake-specific fuel consumption (BSFC) declined with the addition of hydrogen to the CNSL mixture. An increase in the BTE with increasing concentrations of hydrogen in the CNSL fuel blend was observed. The best blends of ethanol and CNSL–hydrogen perceptibly increased the exhaust gas temperature and NO_x emissions, while also producing the fewest HC and CO emissions. The current research acts as a novel paradigm that makes it possible to comprehend the exergy related to mass or energy exchanges as a by-product of thermodynamic quality and quantity.



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Keywords: CNSL oil; hydrogen; biodiesel; ethanol

1. Introduction

The demand for fossil fuels has increased worldwide due to industrialization and modernization across the globe, especially in developing nations. Currently, a variety of alternative fuels can be used in cars to reduce engine exhaust emissions or increase their thermal efficiency [1,2]. The extensive usage of traditional fossil fuels to fulfill most global energy needs has had a detrimental effect on the environment. Airborne pollutants have been recorded at distressingly high levels. Given this background, the finite nature of fossil fuel sources has sparked researchers' interest in alternative fuel sources [3]. As a result, various effective alternative fuels, which should be considered alternatives to hydrocarbon-based fuel, have been developed to support energy conservation, energy efficiency, and sustainable development [4,5]. Conventional petroleum-based fuels can be

backed by substitute energies, including LNG, LPG, CNG, H₂, vegetable oils, biogas, and producer gas. Among these alternative fuels, H₂ has become a prominent fuel due to its unique characteristics, such as durability and sustainability, and it is contaminant-free.

In addition, H₂ is odorless, harmless, and exerts no adverse effects on the environment. When it is completely burned, H₂ provides the uncontaminated energy required to run IC engines, or be mixed with other hydrocarbon fuels [6]. Due to these characteristics, hydrogen has received special attention from researchers as a replacement fuel to be used in internal combustion engines (ICEs), and regarding expanding the use of energy particles in engines [7,8]. For instance, hydrogen can be used as a unique fuel in spark ignition (SI) engines, either via carburetion or through a direct injection process [9–11]. The cost of hydrogen-powered internal combustion engine (ICE) vehicles manufactured using current technology remains higher than that of vehicles powered using methanol or coal [12]. The finest alternative sources of diesel oil are oils derived from eco-friendly plants. In 1920, Rudolf Diesel first tested his engine using peanut oil; it was not the source of any engine-related issues at the time [13,14]. In biofuel production processes, various types of pyrolysis, catalytic cracking, and transesterification processes have been reported, which have the potential to contaminate the energy produced [15,16]. Based on the literature, it can be inferred that most experiments focused on preheating vegetable oil, the transesterification of vegetable oil, hydrogen induction, and the application of alcohols as viable options to illuminate the performance and emanations of a vegetable oil-operated CI engine [17].

Emissions from the energy supply industry are causing much concern and difficulty for the global environment, as fossil fuel is continuously depleted. On the other hand, efficiency is a debated subject. In general, the concept of energy serves as a foundation for discussions regarding efficiency. As per the basic rule of thermodynamics, energy cannot be destroyed or created, it can only be changed from one form to another [18]. In this scenario, only the losses that occur within the confines of a system under examination affect energy efficiency. As per the second law of thermodynamics, it is an established fact that not all types of energy can be fully converted into the expected types. Lord Kelvin asserted that heat could not be totally converted into work during the cycle, without causing other consequences [19]. Thanigaivelan and Loganathan tested a diesel engine with TC-CNSL (thermal-cracked cashew nut shell oil) blended with diesel. Ethanol was added with an optimum hydrogen flow rate and a CNSL mixture. Their study noted that the addition of ethanol to biodiesel results in a decrement in particulate emissions [20]. The effects of biodiesel on single-cylinder diesel engine combustion and emission characteristics were examined using three fuel blends, including biodiesel/n-butanol, biodiesel/ethanol, and biodiesel/2,5-dimethylfuran. The findings inferred that pure biodiesel and the three different fuel mixtures achieved lesser indicated thermal efficiency (ITE) than diesel fuel at low loads did. With an increase in the load, especially at a high load with high exhaust gas recirculation (EGR) rates, pure biodiesel and the three fuel mixtures achieved the maximum ITE compared to diesel fuel. In general, biodiesel is produced in different forms, such as E20 (20% ethanol and 80% diesel), DMF20 (20% dimethylfuran and 80% diesel), and Bu20 (20% butanol and 80% diesel). E20 generates lower NO_x emissions than diesel and pure biodiesel, and Bu20 and DMF20 produce higher NO_x emissions than diesel. It was found that the three fuel mixtures produced more HC and CO emissions than diesel at low load conditions. However, in the case of high load conditions, HC and CO emissions were lower than those of diesel fuel were. Therefore, it is feasible to improve thermal efficiency and reduce the smoke at high loads by increasing the blending proportion of high-octane number oxygenated fuels. The soot reductions for Bu50 and DMF50, at a 50% EGR rate, were 79% and 99.4%, respectively, when compared with diesel fuel [21,22].

Soybean oil can be used as biodiesel after the application of a few procedures and additives such as diethyl ether, ethanol, methanol, and n-butanol. Similarly, cashew nut shell oil (CNSL) is manufactured using the additives mentioned above from the waste shells of cashew nuts. Diesel fuel was combined with both biofuels at rates of 10%, 20%, 30%, and 40% to investigate characteristics such as fire point, viscosity, and calorific value. In the case

of CNSL, the viscosity was high on both dynamic as well as kinematic levels, but changed slightly when the temperature increased. In comparison with CNSL blends, soybean oil blends have a low calorific value and the lower viscosity. It has been observed that CNSL is more reactive than soybean oil and maintains its viscosity at high temperatures [23–25].

2. Materials and Methods

2.1. Liquid Biofuel from Thermal-Cracked Cashew Nut Shells

The primary phase of treating CNSL, as shown in Figure 1, involved cleaning the thermal-cracked CNSL (TC-CNSL). The TC-CNSL contained 3% polymeric material and 78% cardanol in addition to the ingredients that remained in the capability base.



Figure 1. Cashew nut shell liquid thermally and technically distilled (TC-CNSL).

Maintaining TC-CNSL temperature between 180 °C and 380 °C under decreased atmospheric pressure resulted in the production of cardanol. The temperature level was continuously varied from 180 °C to 380 °C in the step of 50 °C. The maximum level of biofuel generation from cashew nut shell was observed at 330 °C. The cost-effective and readily available coal ash (50 g, 100 g, 150 g, and 200 g in quantity) was used as a catalyst in the cracking process. The study outcomes indicated that 150 g of coal ash produced the maximum quantity of biofuel [26].

A descriptive and comprehensive diagram of the system designed to retrieve the TC-CNSL during processing is shown in Figure 2. The CNSL biofuel (B100) configuration was examined using a gas chromatography-mass spectrum (GCMS) analyzer, with pier parameters offset at 220 °C effective temperature, 3 °C/min slope level, 4 L/min stream level, and 70:1 splitting proportion. The GC spectra of the CNSL biofuel (B100) are shown in Figure 3. An extensive analysis was conducted on the CNSL biofuel, and its composition was found to have unsaturated hydrocarbons equal to the earlier biofuels. This might be attributed to lengthy hydrocarbon chains and built-in oxygen content.

2.2. Gas Chromatography–Mass Spectrum (GCMS) Examination

The purpose of GCMS analysis was to establish a system within a realistic range, although in practice, it is frequently required to have a solid understanding of the system in a questionable way. Chromatography refers to a technique that divides the body into two halves while maintaining a particle's mobility and agility. The process comprises gas absorption from the outside, functional gas parting with the lasting gases, and composites with low boiling points. A standardized technique should be used to establish the system's limitations, so that multiple systems can be appropriately compared with one another. This scenario indicates that the selection of the system's limits may exert a heavy influence on the outcomes, even if the definition of the system's limits must adhere to a set of principles that remain the same for all systems under consideration. Energy efficiency is one of the most frequently used thermodynamic assessment parameters. The conclusion of the energy conversion or transfer process was taken into consideration as indicated in the

literature [26]. Energy efficiency does not account for internal irreversibility; as a result, this definition was insufficient. The main drawback of the energy-based thermodynamic analysis was its inability to quantify a process-irreversibility, although it could detect a process -energy loss [27].

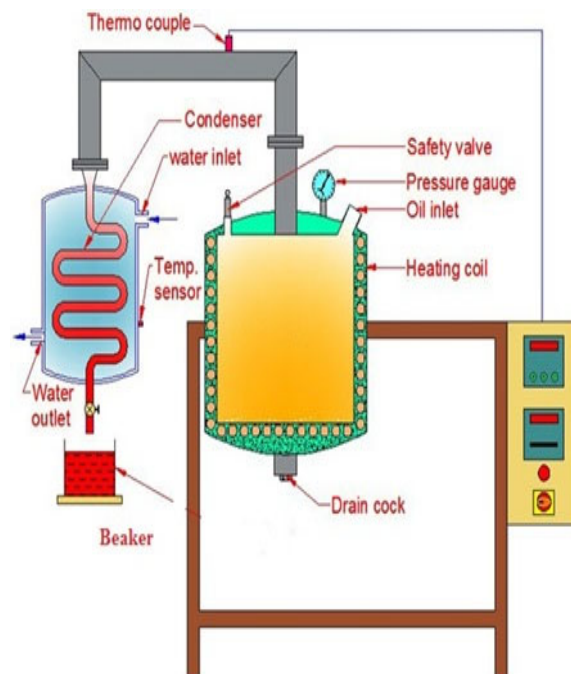


Figure 2. Schematic view of the thermal cracking reactor.

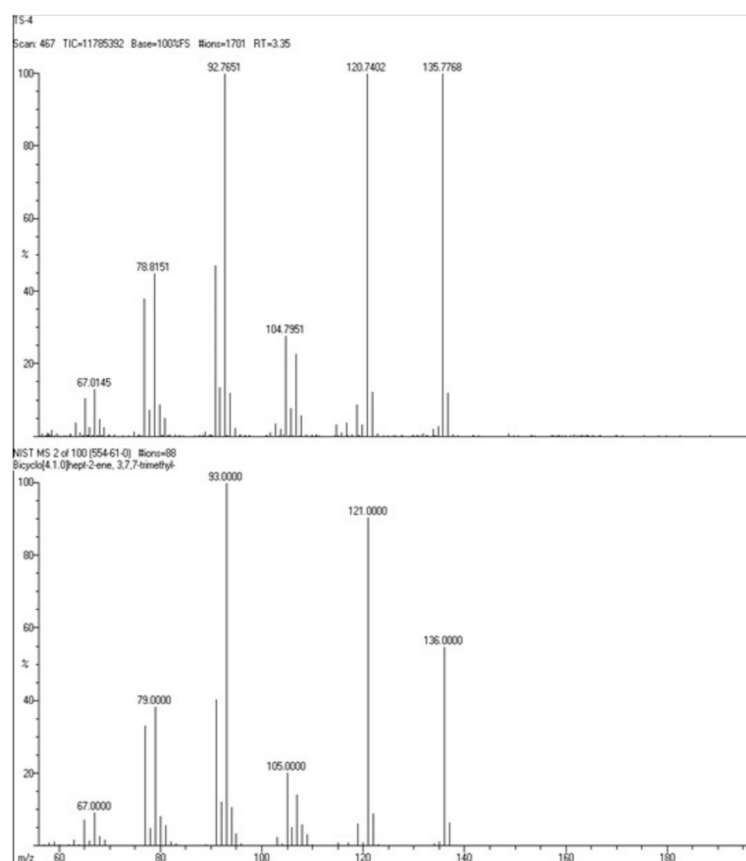


Figure 3. GC spectrum of the CNSL biofuel (B100).

2.3. Examination of the Updraft-Cracked CNSL

The integrated analytical system at IIT-MADRAS, Chennai, was used to conduct the gas chromatography analysis, Fourier transform infrared (FTIR) analysis, and other necessary procedures to examine the TC-CNSL sample. The overall properties of every thermally fractured CNSL, including the diesel fuel, are listed in Table 1. The kinematic viscosity of the liquid cashew nut shell oil was found to be dramatically reduced due to the thermal cracking process. With the help of the method outlined above, similar improvements were made to other parameters, such as the flash point, fire point, and calorific value. In tests conducted using the gasoline components, the TC-CNSL displayed a piled kinematic viscosity of 17.5 cP at 32 °C, an improved thickness of 0.9336 g/cc, and a heaped flash point of more than 197 °C. The FTIR study provided a vibrational examination of the particle data. As shown in Figure 4, transmittance (% T) and infrared frequency range may be used to illustrate the notable analysis conducted on the molarity of the substances and their corresponding bandwidth (cm^{-1}). The FTIR spectrum of the diesel fuel is shown in Figure 4, illustrates the significant groups that represent methylene and carbonyl sets in the ranges of 2931 and 2843 cm^{-1} , respectively. The first heap was related to the elongation of the olefins group shakings with terminal CH_2 . The second heap showed a decline in the paraffin groups with C-H and CH_2 bonds. These bands show similarities between diesel fossil fuel and CNSL biofuel [28,29].

Table 1. Properties of B20 CNSL biodiesel and neat diesel.

Properties	Measurement Standards	Diesel	TC-CNSL (Cardanol)	TC-CNSL
Density 25 °C (g/cc)	ASTM D1298	0.8/0.84	0.9326	0.821
Flash point (°C)	ASTM D93	80	198	<28
Calculated cetane index	ASTM D976	52	28	45
Boiling point (°C)	ASTM D1160	180–340	225	180–380
Kinetic viscosity at 30 °C (cP)	ASTM D445	2.0 to 4.5	17.2	4.43
Calorific value (kJ/kg)	ASTM D240	44,000	39,600	41,780

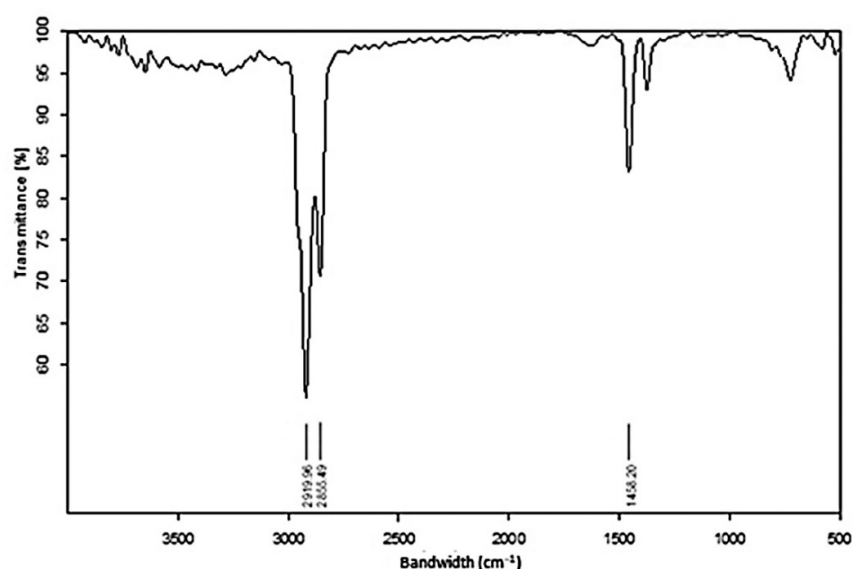


Figure 4. FTIR spectrum image of diesel fuel.

3. Results and Discussion

This section discusses various investigative arranging mechanisms. Figures 5 and 6 depict the schematic view and the photographic view of the single-cylinder, four-stroke, vertical, water-cooled, DI diesel engine, respectively, with clear perspectives of the experimental structure. The experimental setup was inclusive of an engine, an air intake system,

a fuel amalgamation system, and measurement equipment. This system provided the necessary tools, techniques, and system guidance to determine various operating constraints during the investigation, such as the fuel stream, air drift, cylinder force, exhaust-gas temperature (EGT), and drain discharge.

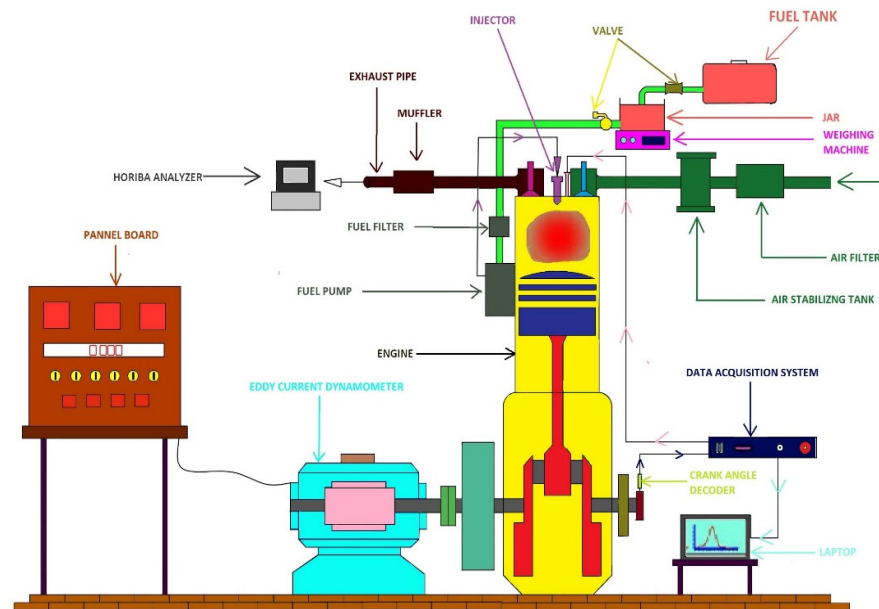


Figure 5. Schematic view of the experimental setup.



Figure 6. Photographic view of the experimental setup.

The engine was allowed to reach a constant speed of 1500 rpm, and then readings were taken. Initially, the measurement was recorded using neat diesel, followed by ethanol and CNSL mixtures (with equal proportions) of biodiesel blends. The direct fuel induction technique was used to inject the hydrogen in parallel to the liquid fuel. Each load's airflow, EGT, fuel flow, CO, HC, and NO_x emissions were recorded and interpreted. Data regarding the cylinder pressure with respect to the crank angle were also recorded. The average change in cylinder pressure was measured based on these values.

3.1. Experimental Characteristics of CNSL- Ethanol Biodiesel Blend with the Hydrogen Addition

3.1.1. Brake-Specific Fuel Consumption

Variations in brake-specific fuel consumption (BSFC) under the impact of braking using different biodiesel blends with hydrogen are depicted in Figure 7. The biodiesel fuel blend engine operation attains the higher BSFC in comparison with the neat diesel engine operation [30]. When the hydrogen flow rate was increased to 8 LPM, BSFC decreased. The lowest BSFC was achieved using a 4 LPM hydrogen flow rate associated with the diesel fuel. This was because the hydrogen fuel, which is highly diffusible and constantly exchanges with the air after improved incineration, was premixed with the air. The BSFC decrease rate was experimentally maintained at 12% between the diesel and hydrogen flow of 4 LPM.

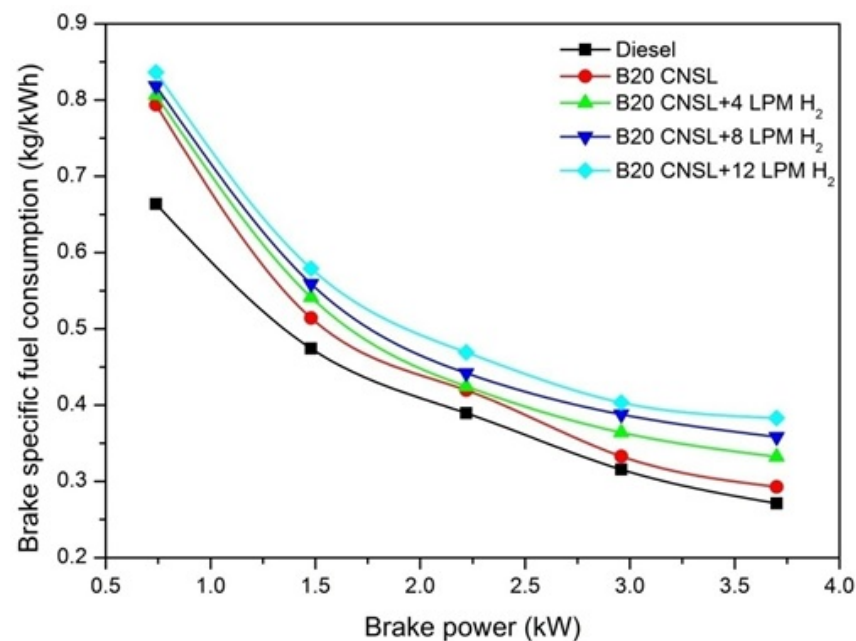


Figure 7. BFSC against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.2. Brake Thermal Efficiency

The disparity in brake thermal efficiency (BTE) values with various hydrogen stream charges are shown in Figure 8. The highest brake thermal competence (37.5%) was observed at an 8 LPM hydrogen flow rate in comparison with B20 CNSL at full capacity. The increase in BTE was attributed to the high calorific rate of the hydrogen and improved airflow in addition to its rapid flame characteristics [31]. It was evident that the hydrogen buildup in the intake air yielded an improved performance compared to the regular clean diesel method.

3.1.3. Exhaust Gas Temperature

Figure 9 illustrates the negative effects of exhaust gas temperature (EGT) on brake power when using hydrogen combined with CNSL and diesel mixtures. When using the CNSL mix with hydrogen, an increment was observed in exhaust gas temperature [32–34], which was attributed to the fact that the increased rate of hydrogen combustion increased the EGT.

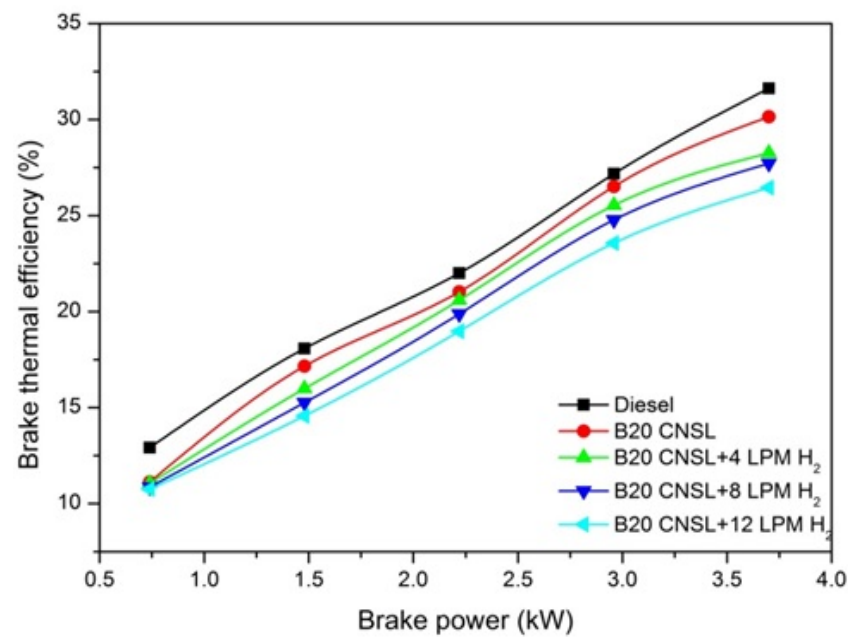


Figure 8. BTE against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

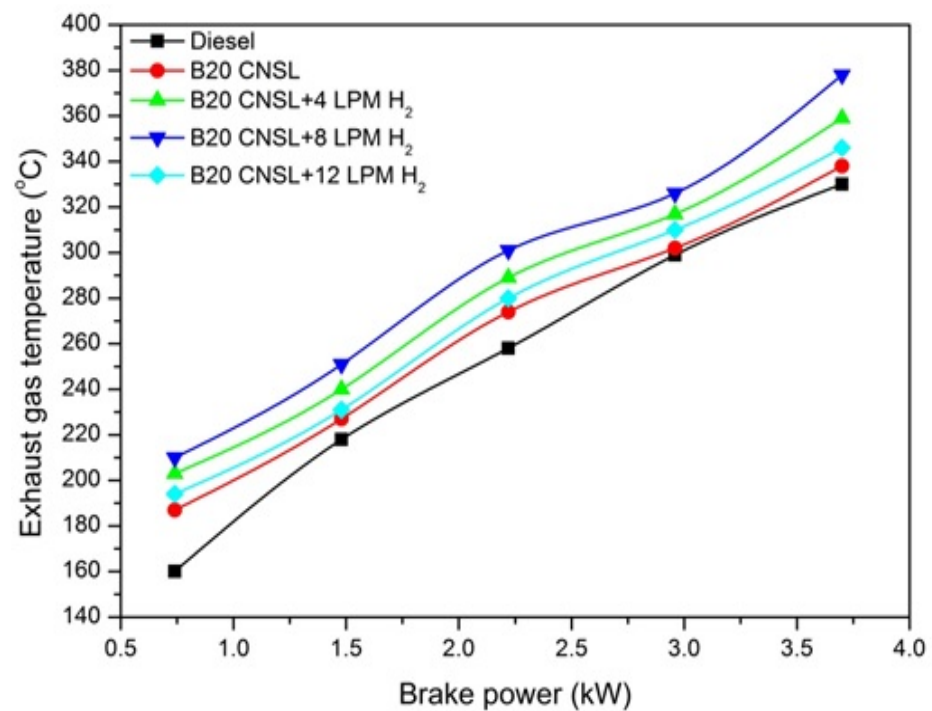


Figure 9. EGT against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.4. NO_x Emissions

Figure 10 depicts variations in NO_x emissions with brake power. NO_x operated at the highest incineration temperature at more oxygen uptake. In relation to neat diesel, B20, and the additional stream degrees of hydrogen, NO_x formation was advanced at a rate of 8 LPM. With an increase in hydrogen content, the flame speed, and subsequently the incineration ability, also increased [35]. A maximum of 34% NO_x was observed for B20 CNSL+8 LPM H₂ in comparison with the pure diesel at a higher BP capacity.

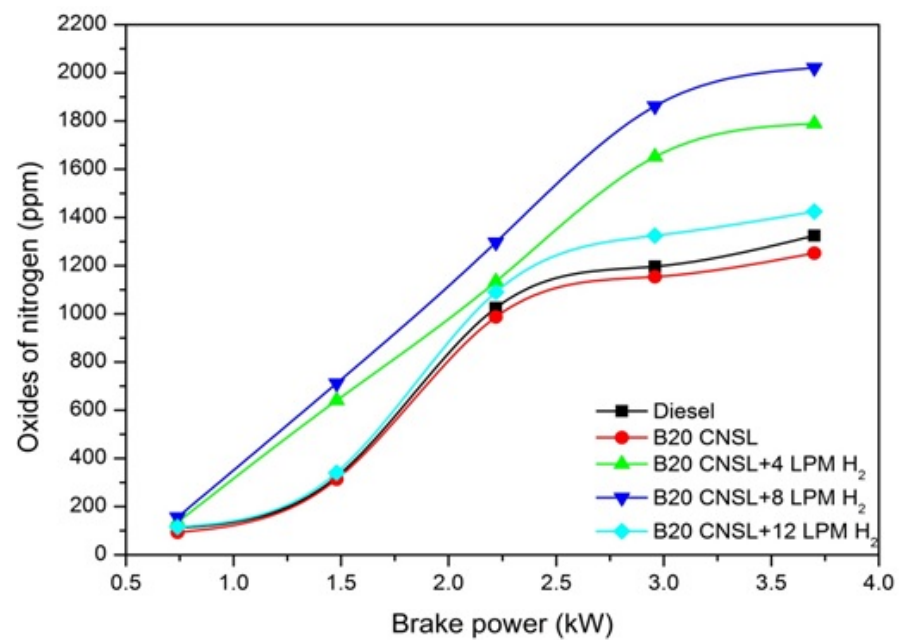


Figure 10. NOx emissions against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.5. HC Emissions

Figure 11 illustrates variations in HC emissions under different fuel blend operations. The amount of unburned hydrocarbon was substantially reduced during hydrogen-blended fuel operation due to the absence of carbon in the hydrogen fuel. HC emissions at 4 LPM, 8 LPM, and 12 LPM of hydrogen flow, using a blend of B20 CNSL fuel, were 216 ppm, 199 ppm, and 203 ppm, respectively. The high percentage of hydrogen used with the fuel blend enhanced the burning of hydrocarbon fuel, reducing HC emissions.

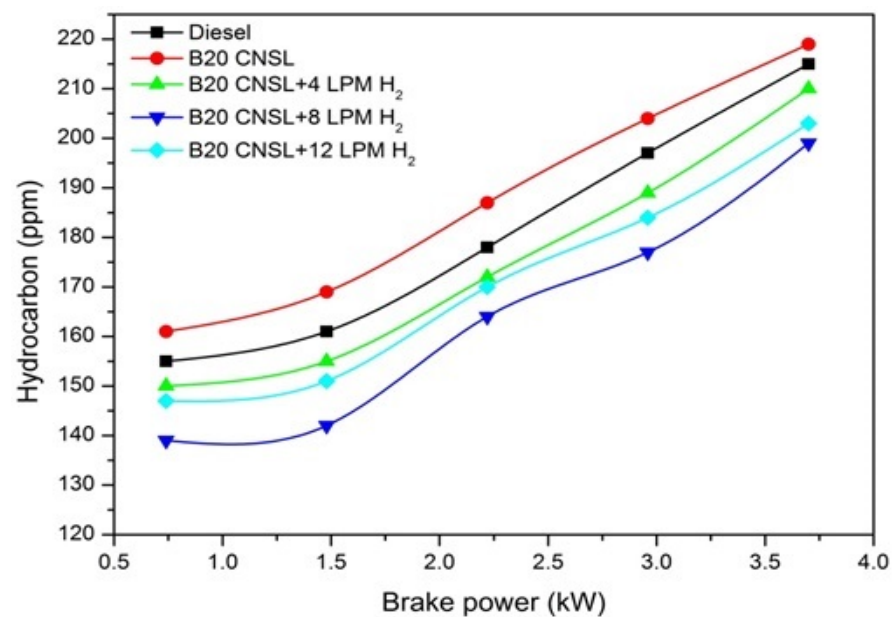


Figure 11. HC emissions against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.6. CO Emissions

Figure 12 illustrates variations in carbon monoxide emissions with brake power. In comparison with operations using all fuel blends, the fewest CO emissions were observed at 8 LPM hydrogen flow at a rate of 0.05%. However, the oxygen was deliberately decreased because of a short response time, which in turn caused a notable increase in the CO level; the entire CO amount increased at full capacity, in relation to the diesel fuel.

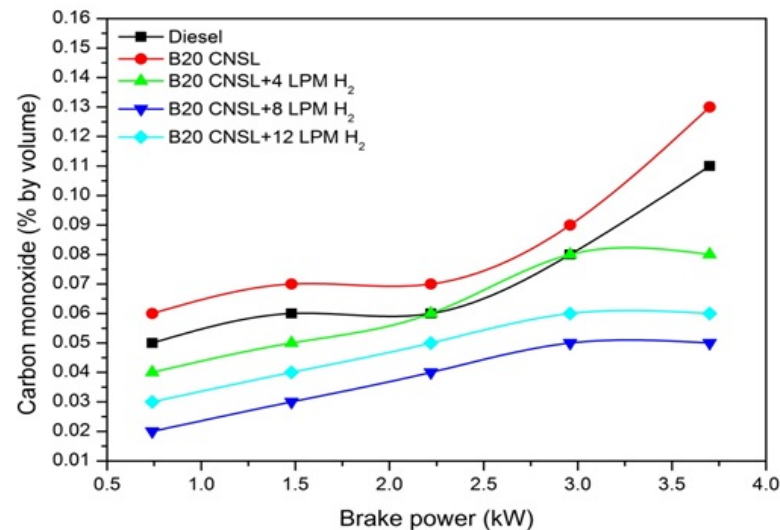


Figure 12. CO emissions against brake power using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.7. Variations in the Combustion In-Cylinder Pressure with the Crank Angle

Figure 13 illustrates the relationship between the combustion pressure in the cylinder and the crank angle. According to the results, biofuel (B20 CNSL) and hydrogen (12 LPM) fuel modes provided the highest peak pressure at full load compared with regular fossil diesel-based operation. For neat diesel engine operation, the maximum pressure in the cylinder was 55 bar, whereas the maximum pressure for a blend of hydrogen fuel (12 LPM) and biofuel (B20) was 61 bar. The diesel operation produced a smaller increase in the cylinder pressure than the hydrogen enhancement did, because of the low combustion rate of the diesel fuel.

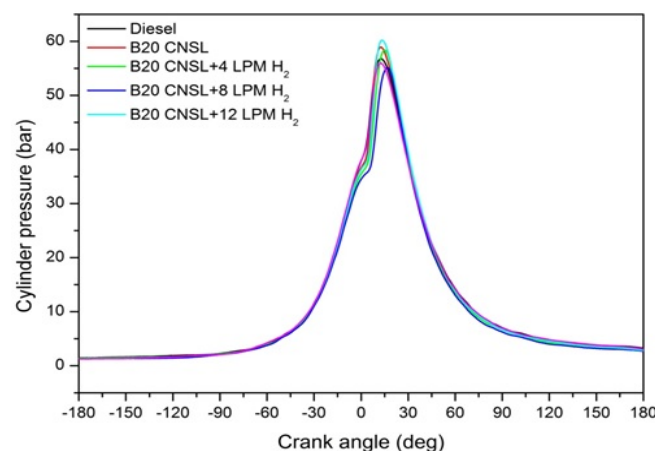


Figure 13. In-cylinder pressure against crank angle using CNSL- ethanol biodiesel with the hydrogen addition.

3.1.8. Variations in the Heat-Release Rate with the Crank Angle

Figure 14 shows variations in the in-cylinder heat-release rate for the neat diesel and the CNSL biofuel mix with hydrogen engine operations at full load conditions. In comparison with the clean fossil diesel, which had a heat release rate of $54 \text{ J}/^\circ\text{CA}$, 12 LPM hydrogen fortification achieved the maximum heat release rate of $70 \text{ J}/^\circ\text{CA}$. The CNSL biofuel with hydrogen fuel released heat from the cylinder more quickly than the diesel fuel combustion did. This was due to the instantaneous combustion that occurred when CNSL biofuel was combined with hydrogen. The pre-mixed fuel ignited quickly and released a significant amount of heat at a well-timed rate [19]. The highest peak pressure for heat released during premixed combustion was achieved using B20 CNSL with 12 LPM H_2 .

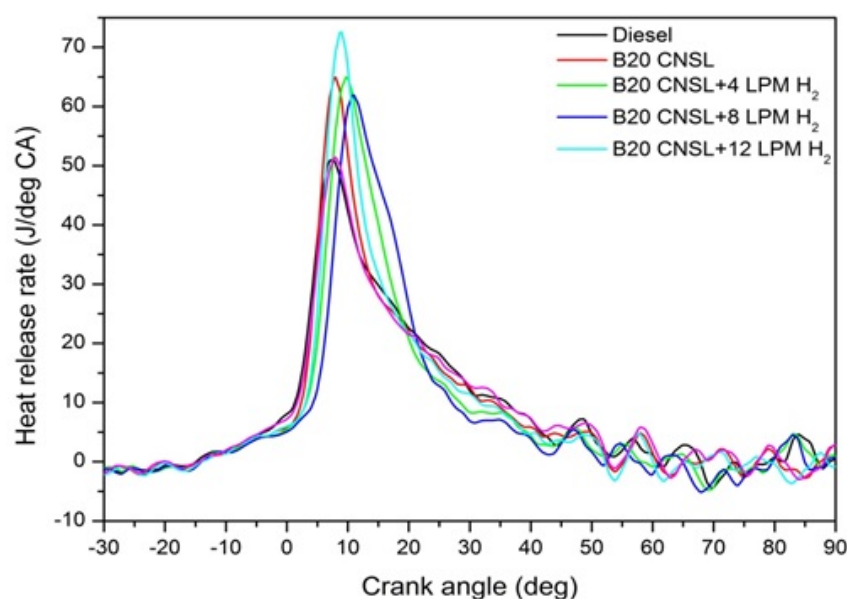


Figure 14. In-cylinder heat release rate against crank angle using CNSL- ethanol biodiesel with the hydrogen addition.

4. Conclusions

To test engine performance and emission characteristics, various combinations of CNSL, hydrogen, and ethanol (at 5%, 10%, and 15% supplements) were tested in a single-cylinder direct-injection diesel engine. The emission parameters of pollutants, such as the fuel consumption rate, hydrocarbons, carbon monoxide, NO_x , and cylinder pressure, were determined. The highest brake thermal efficiency (37.5%) was observed at an 8 LPM hydrogen flow rate in comparison with diesel and B20 CNSL without H_2 . CO and HC emissions were drastically reduced using the B20 CNSL with 8 LPM H_2 compared to other fuel blend engine operations. As biodiesel has a high viscosity and density, it possesses the most optimal properties for the reduction of NO_x emissions. The results confirmed that hydrogen-boosted biodiesel engines could operate successfully and emit less pollution than diesel-fueled engines. Moving forward, diesel may be replaced by hydrogen augmentation in CI engines as an environmentally benign fuel. It is advised that future studies should focus on the usage of CNSL and hydrogen with ethanol and diesel mixtures. It is possible to use hot pyrolysis CNSL to enhance engine combustion outcomes. Further, cetane needs to be optimized to produce low-viscosity biofuel.

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