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RESEARCH ARTICLE

Experimental Study on the Effect of Hydrogen Enrichment in Diesel–Biodiesel Fueled RCCI Operation of a CRDI CI Engine

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ABSTRACT
In this present study, a CRDI (Common Rail Direct Injection) CI (Compression Ignition) engine operating in RCCI (reactivity Controlled compression ignition) mode was experimentally investigated to evaluate the effect of varying hydrogen share (HS) on engine performance and emission characteristics. The engine is tested under part load settings of 2.7 kW with fixed Fuel Induce timing (FIT) of 20˚bTDC while HS changed from 15% to 75% in increments of 15%. According to the experimental findings, varying HS increases the combustion's homogeneity and stability, leading to an improved engine power output. Brake thermal efficiency (BTE) likewise rises by 3.1% under diesel-hydrogen strategy than biodiesel-hydrogen at HS 60%. The results indicate that at 75% hydrogen share, HC and CO emissions were reduced by 22.58% and 11.51%, respectively. This study also demonstrates the possibility of using hydrogen to run the engine with a very lean combustion.

Keywords: *RCCI, Hydrocarbon (HC), Nitrogen oxide (NOX), Carbon monoxide (CO), Hydrogen ratio.*

INTRODUCTION
In today's world, the diesel engine has become a necessity. Diesel engines are effectively used to produce power almost every sector of economy, including transportation, agricultural, construction, and many more [1]. This is because of their inherently durable design, dependability, and reduced fuel consumption. Diesel engines are excellent for a country's economic growth and well-being. They are providing the foundation for the world economy [2]. However, because of the rising cost of crude oil, the depletion of fossil fuel sources and the high import duty levies, diesel has almost become unaffordable. Additionally, because of their unchecked emissions of particulate matter (PM), nitrogen oxides (NOx), and hydrocarbons (HC), which represent a serious risk safety for both the environment and human health, diesel engines are frequently penalized. To address this, a number of agencies have implemented strict emission regulations (Bharat stage in India-year-2000, BS-I to BS-VI) on vehicles. Modern engine designers meet the severe emission regulations of the modern era with better fuel efficiency and greater engine operational stability, a variety of engine add-ons, complex control systems and knowledge are required.

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As a result, an unprecedented amount of money and resources must be given up. A state-of-the-art technology has yet to reach the infrastructure, market penetration, and reliability required to replace diesel power trains. However, a minimum change to the current engine layout using a number of tried-and-true technologies (such as Advanced processes of combustion, dual-fuel operation based on alternative energy sources, and blends) seem more feasible, affordable, and capable of maintaining the advantages of diesel [3,4].

The development of a sustainable energy system and reduction of global emissions footprints are driving the replacement of traditional fossil fuels with renewable energy sources [5]. Hydrogen has gained a great deal of significance as a desired alternative fuel that can replace fossil fuels and ensure long-term energy security. Utilizing hydrogen can help to mitigate some of the serious negative effects of excessive fossil fuel use on the environment and society (including climate alteration and the quality of air index) [6]. The transportation sector must switch from traditional energy sources to an alternative fuel-based energy (hydrogen) system in order to achieve an ecological future because it is the biggest energy consumers on the globe. [7]. The higher performance obtained from hydrogen-based IC engine ensured by the greater ignition temperature of hydrogen than gasoline, NG and other fuel [8]. Additionally, hydrogen's stronger air diffusivity ensures a more uniform mixture formation. For use in transportation, a number of government policies have been put out [9]. Hydrogen becomes advantageous fuel for CI engines in view of its greater LHV. Generally speaking, a number of strategies based on LTC, including partially 0 compression ignition (PPCI), 0 charge compression ignition (PCCI), and reactivity-controlled compression ignition (RCCI), have demonstrated their viability in CI engines [10]. Moreover, different LTC strategies preferred with little change in the existing engine configuration by varying high reactivity fuel (HRF) injection phasing. Additionally, the injection phasing sequence can do away with numerous intricate control schemes needed to switch

from various advanced combustion regimes. Overall, the significance of hydrogen as a potentially viable fuel for lowering pollution imprints, enhancing engine capability and stability, and transitioning between diverse regimes, as well as the effective injection phasing tactics.

Based on the study, it is understood that diesel, biodiesel may have specific operational difficulties, but it can be mitigated with utilize along with gaseous fuel (Hydrogen). Moreover, the effect of maximum hydrogen share needs to be investigated as it may lead to a better quality of combustion in RCCI approach. Hence the extant work examines the impact of higher Hydrogen share in attaining fuel-lean combustion in a Hydrogen RCCI mode. The primary task of the extant work is to study the RCCI engine performance and emission variables fueled with diesel-hydrogen and biodiesel-hydrogen under maximum possible load conditions. No research has been found utilizing hydrogen injection in 0 ratio under RCCI strategy. Diesel-hydrogen and biodiesel-hydrogen fuels are therefore innovative works in RCCI combustion rather than gasoline, alcohol, etc.

2. Experimental methodology

The test engine is run with diesel and biodiesel with no load condition. The engine is then gradually loaded up to full load conditions and maintained there for a predetermined amount of time to achieve stability. The fuel is injected at a minimum pressure and then steadily raised to 300 bar and maintained there. The decision to run the engine at full load was made primarily to refute the findings of an earlier literature review [11]. The current task is carried out under (2.7 kW) conditions in order to finish the entire testing experiment. The fuel addition profile is termed as the pilot and main in two separate phases. The pilot fuel injection angle is set to 20˚bTDC while the main fuel injection angle is kept at 10˚bTDC after the engine attains stability at the given load and pressure. The CRDI was integrated into the already-existing diesel engine fuel line pipe to enable diesel-hydrogen and biodiesel-hydrogen setup. The hydrogen share varies from 15% to 75% in steps of 15%. Beyond 70% unnecessary engine vibration and knock was observed, which prevented any additional increment beyond 75%. In addition, some critical parameters of the tested fuel are measured and shown in Table

1. while Table 2 lists the technical characteristics.

Table 1 Physical properties of test fuels used for this study [12]ergy share.

Property	ASTM standard	Diesel	Biodiesel
Heating value (kJ/kg)	D-240	45,448	40,630
Density (kg/m^3)	D-4052	0.831	0.881
Specific gravity at 15.56˚C	D-1298	0.8421	0.883
Latent heat of vaporization(kJ/kg)	-	250	320

Table 2 Specificationof the DI engine test bed

Make/Model	Kirloskar/AV 1
Engine Type	VCR CRDI engine
No. of cylinder	1
Bore/Stroke (mm)	80/110

Swept Volume	553 cc
Injection angle	17^{o}bTDC
Injection Pressure range	280 Bar

3. Results and Discussion

3.1 Performance Analysis

3.1.1 Brake Thermal Efficiency

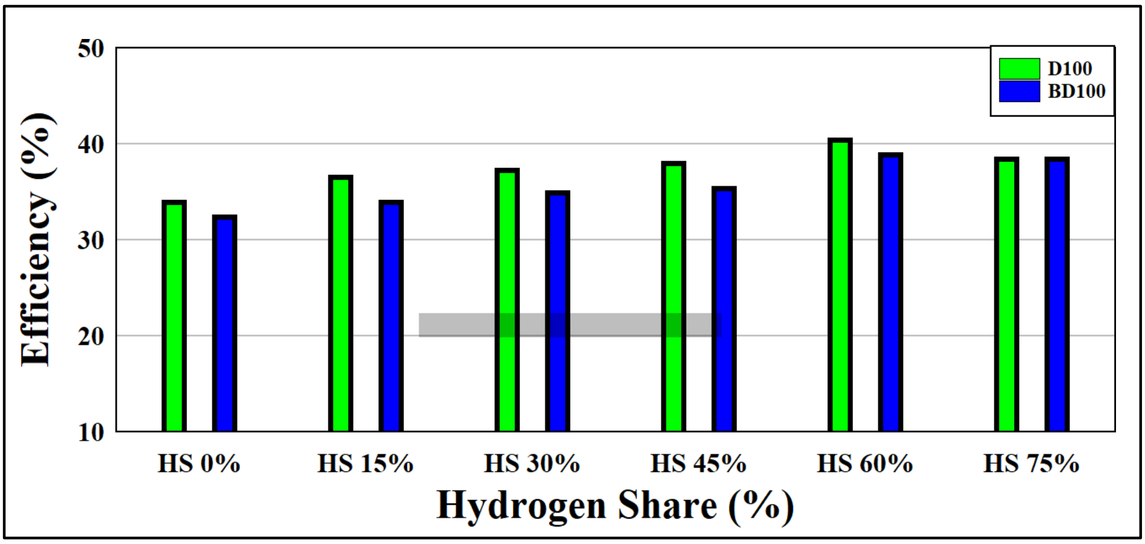

Fig.1. Effects on BTE with varying energy share.

The BTE is tested for different ratios of Hydrogen in RCCI mode is depicted in Fig.1. The highest BTE is obtained with diesel-hydrogen strategy at HS 60%. This is caused by the proper utilization of LRF which enhances the charge quality and hence BTE increases. The graph delineate that the efficiency increased with hydrogen addition than conventional diesel/biodiesel mode [13]. This is in view of the increased homogeneous nature of the combustion process due to the participation of hydrogen [14]. From Fig.1, it is noted that the maximum BTE of 40.01% is observed for HS 60% at 2.7kW, while 38.98% is observed with biodiesel-hydrogen strategy at the same load. Hydrogen induction during the intake stroke suitable for creation of homogeneous mixture, when ignited with the pilot fuel provides better quality of combustion [15]. Moreover, another significant factor for the rise in BTE with diesel-hydrogen RCCI mode running with increased calorific value. However, The

BTE of the engine drops marginally with 75% for higher load conditions. This decrease may be caused by increased intake air replacement caused by higher participation of LRF.

3.2 Emission Analysis

3.2.1 NOX Emissions

Figure 2 depicts the trend of NOX emissions for different strategies in RCCI mode at different HS ratio. The temperature, oxygen, and nitrogen existing in the combustion chamber exposure at high temperatures contribute to NOX emissions [16,17]. The graph describes the NOX emissions are higher under base biodiesel operation than base diesel. The probable reason for rising NOx emissions with biodiesel, especially in contrast to diesel, might be the shorter ignition delay and premature early stages of combustion attributed to their maximum of cetane value and oxygen presence. Using pilot diesel and biodiesel in dual fuel RCCI operation, NOX emissions increase with increasing Hydrogen share. The NOX emissions increased with growing ratios up to a 75% HS. This indicates higher chamber temperature generation produced by the fast burning of hydrogen [18].

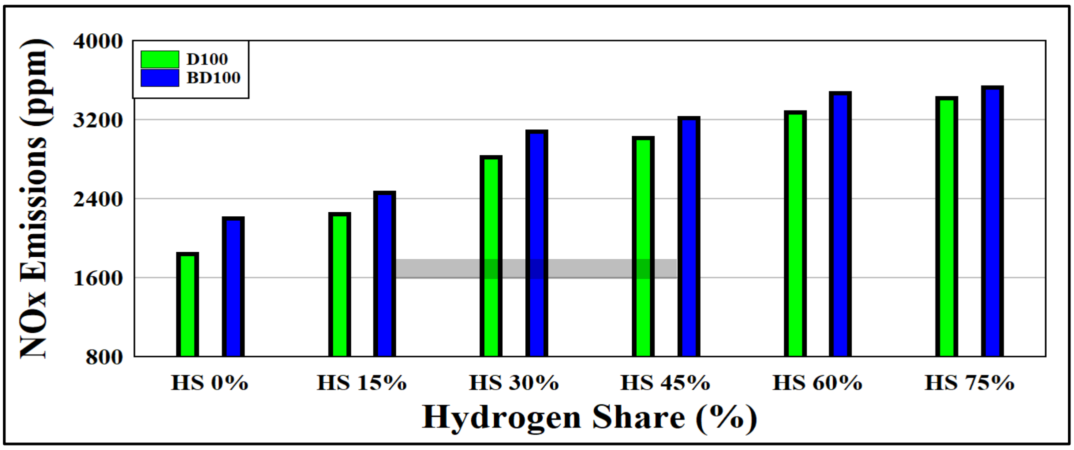

Fig.2. Effects on **NOX** emissions with varying energy share.

3.2.2 HC Emission

Figure 3 depicts the engine's hydrocarbon emissions for different strategies in RCCI mode at different ratio. HC emission formation is lieu of fuel accumulation on wall of the combustion chamber resulted in the deficient combustion. A perfect combustion process produces less HC, as maximum of the HC disassociates to discharge their chemical form of energy into heat energy. The graph demonstrates biodiesel single fuel approach produces HC slightly higher in contrast to conventional diesel mode.

It might be caused by the charge's deteriorated combustibility due to the larger droplet size of biodiesel, which can retard the burning rate. However, reductions in HC emissions are more prominent in increasing Hydrogen ratios. This is explained by adding hydrogen, which lowers the fuel's hydrocarbon composition. Additionally, the higher burn rate and smaller quenching distance of hydrogen improve the fuel combustibility, resulting in lower HC emission.

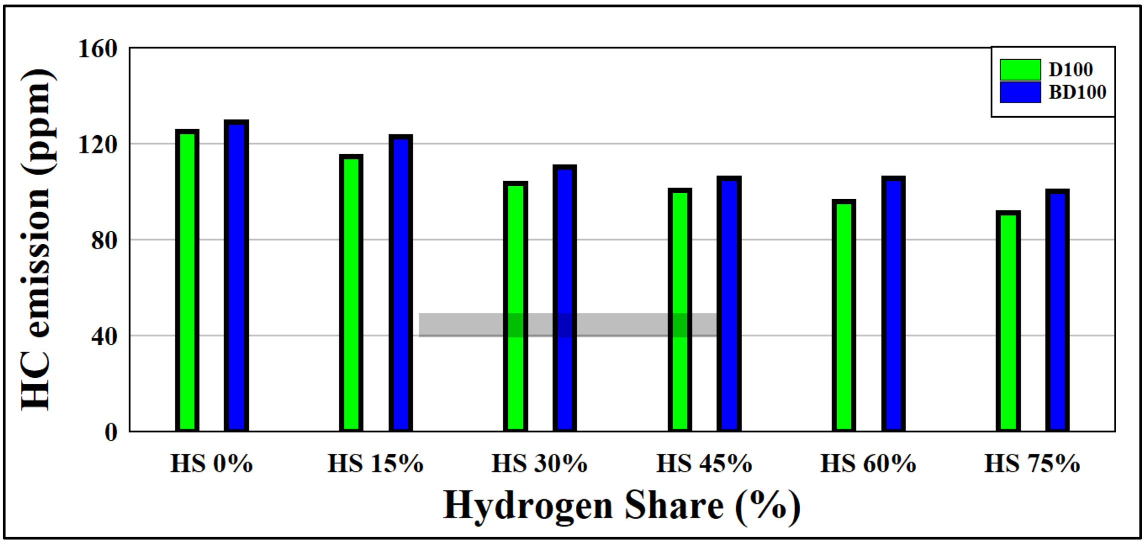

Fig.3. Effects on HC emission with varying energy share.

3.2.3 CO Emission

Figure 4 encapsulates the CO variations of different strategies in RCCI mode at different HS. The figure delineates that jatropha biodiesel creates higher CO emissions among all the test settings. This is due to the incompleteness of the combustion process due to the larger droplet size caused by the greater kinematic viscosity and slower burning rate of biodiesel that promotes extra CO emission. The utilization of hydrogen in RCCI mode noticeably lessened the CO emission for all test settings. The reason is hydrogen incorporation diminishes the accumulative carbon contented of the fuel. This is also because hydrogen burns more quickly than other fuels which makes it possible for hydrocarbons to split into carbon particles and ultimately carbon dioxide. Additionally, the engine may run on leaner equivalency ratios due to the increased HS, which enhances charge burning. Thus, as HS rise, the charge's homogeneity rises as well, promoting better combustion and lowering CO emissions.

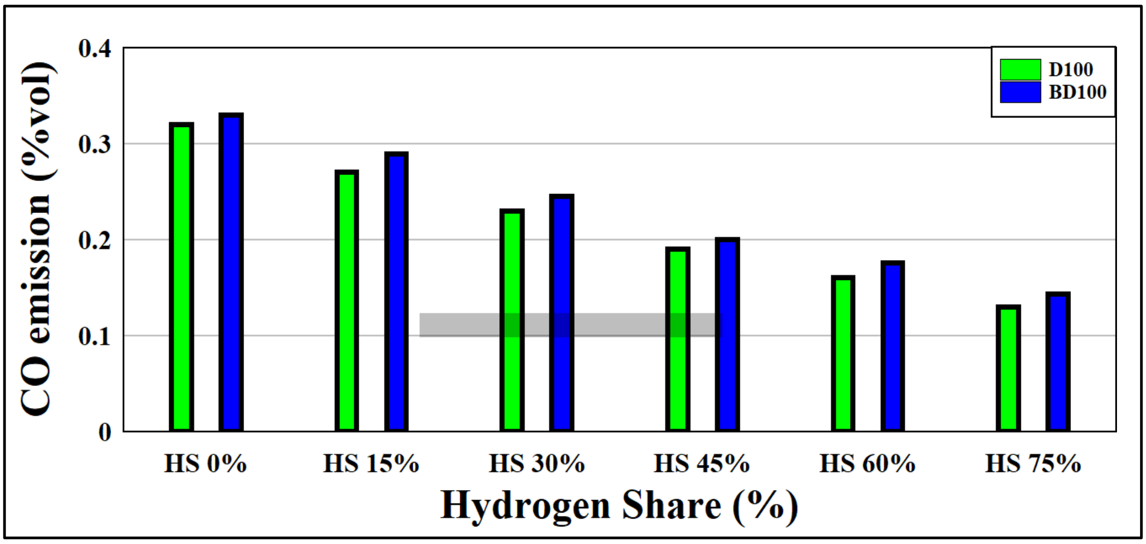

Fig.4. Effects on CO emission with varying energy share.

4. Conclusion

The current experimental work examines the influence of dual fuel combinations on the emission and performance variables in a CI engine under RCCI mode. Hydrogen induction into the entree manifold by means of an electronic injection system, while base fuel is added straight into the engine chamber. With precise control of the gaseous and liquid fuel flow rates, the HS ratios are varied from 15%-75% in step of 15%. Based on the outcomes of the experiment, the generalizations tha follow, which are listed below:

- The inclusion of hydrogen to diesel and biodiesel ameliorates the BTE of the engine under RCCI mode when compared to pure diesel and biodiesel under all experimental test settings. The 60% of HS resulted in an increase in BTE by 4.1% compared to biodiesel-hydrogen operation at 2.7kW BP.
- The engine emission is mostly reduced with increasing Hydrogen participation. The HC and CO emissions for the HS 60% strategy are reduced by 22.58% and 11.51% respectively with respect to baseline diesel.

From the above, it is deduced that the inclusion of hydrogen up to 60% can enhance the engine efficiency, and smoother engine operation. Moreover, the operational envelop for the dual fuel RCCI mode is effective only up to 60%. However, the emissions reduced at HS 75%. Hence, higher participation of Hydrogen may be tried by altering the operating parameters and propertied of the pilot fuel.

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