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# Effect of hydrogen supplementation on engine performance and emissions

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ABSTRACT

Vehicular Pollution and environmental degradation are on the rise with increasing vehicles and to stop this strict regulation have been put on vehicular emissions. Also, the depleting fossil fuels are of great concern for energy security. This has motivated the researchers to invest considerable resources in finding cleaner burning, sustainable and renewable fuels. However renewable fuels independently are not sufficient to deal with the problem at hand due to supply constraints. Hence, advanced combustion technologies such as homogeneous charge compression ignition (HCCI), low-temperature combustion (LTC), and dual fuel engines are extensively researched upon. In this context, this work investigates dual fuel mode combustion using a constant speed diesel engine, operated using hydrogen and diesel. The engine is operated at 25, 50 and 75% loads and substitution of diesel energy with hydrogen energy is done as 0, 5, 10 and 20%. The effect of hydrogen energy share (HES) enhancement on engine performance and emissions is investigated. In the tested range, slightly detrimental effect of HES on brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) is observed. Comparision of NO and $NO_2$ emissions is done to understand the non-thermal influence of $H_2$ on the $NO_x$ emissions. Hence, HES is found beneficial in reducing harmful emissions at low and mid loads.



## Introduction

Diesel engines, attributed to their superior fuel economy, higher low-end torque and durability are much celebrated in long-distance transportation, heavy hauling and power generation [1]. However, transportation sector alone produces nearly 30% of the world's greenhouse gases [2]. Amongst the transportation sector, diesel engines produce nearly 50% of the urban $NO_x$ emissions leading to acid rain, smog and the ground-level ozone layer. The rise in such anthropogenic greenhouse gas (GHG) emissions has led to increasing global warming, resulting in climate change [3]. Also, the heterogeneous nature of combustion in such engines makes them a significant source of particulate matters (PM) [4]. These air-suspended PM are composed of hazardous substances such as organic carbon, trace elements and inorganic ions, which threaten the ecosystem and human health. Moreover, these GHG emissions along with other harmful emissions have led to rising air pollution and vitiated the air [3]. Thus, regulation around the globe for environmental protection focuses on reducing the PM and $NO_x$ emissions from diesel-powered vehicles [5]. Implied by these regulations, researchers are trying to find solutions to mitigate the harmful emissions from the diesel engines. Recent studies report that use of sustainable alternative fuels such as natural gas, hydrogen gas, biodiesel, and green diesel is efficient in reduction of PM and $NO_x$ emissions [6]. Meanwhile, the dwindling fossil fuel reserves

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**Nomenclature and abbreviations**

| | |
|---|---|
| ATDC | After top dead centre, degrees |
| BTDC | Before top dead centre, degrees |
| CA | Crank angle, degrees |
| CI | Compression ignition |
| CN | Cetane number |
| CO | Carbon monoxide, ppm |
| CR | Compression ratio |
| DDF | Diesel dual fuel |
| DI | Direct injection |
| EVC | Exhaust valve close |
| EVO | Exhaust valve open |
| H2 | Hydrogen gas |
| HC | Hydrocarbon (unburnt), ppm |
| HCCI | Homogeneous charge compression ignition |
| HES | Hydrogen energy share, % |
| IVC | Intake valve close |
| IVO | Intake valve open |
| kJ | Kilo Joules |
| LTC | Low-temperature combustion |
| MPa | Mega Pascal |
| ms | Millisecond |
| NOx | Nitrogen Oxide, ppm |
| $O_2$ | Oxygen gas |
| TDC | Top dead centre |
| $\theta$ | Degree crank angle |

pose a problem of energy scarcity as there are rapid motorisation and industrialisation to carter the growing comfort seeking population. Moreover, the exigency of these fossil oil products is such that global economies are contingent on the prices of these products [7]. Thus, the need to discover alternative fuel sources is pressing, to reduce the economic dependency and achieve sustainable growth.

Therefore, the current research in the field of internal combustion engines is primarily focused on the reduction of engine emissions and search for cheap, sustainable fuels. Hydrogen amongst the alternative fuels particularly stands out due to its multiple renewable energy based production routes and clean burning characteristics. These features make it pivotal in energy scarcity elevation and pollution reduction. Application of hydrogen in internal combustion engines is considered since as early as 1806 in De Rivaz Engine [8]. Table 1 Important properties of diesel and hydrogen. Table 1 compares some of the combustion relevant properties of hydrogen to that of diesel. The comparison highlights the advantages and disadvantages hydrogen when used as fuel in internal combustion engine [9–11]. The high auto-ignition temperature and high diffusivity of hydrogen make it more suitable for compression ratio (CI) engine compared to spark ignition (SI) engine application as high auto-ignition temperature allow the engine to operate at high compression ratio and high diffusivity leads to homogeneous charge formation [12]. However, long ignition delay and high-pressure rise rate adversely affect the prospect of neat hydrogen application in CI engines. Researchers have purposed various technologies such as LTC, HCCI and Dual fuel to exploit the superior combustion characteristics of hydrogen. Ibrahim et al. ran a single cylinder CI engine in $H_2$-HCCI mode by heating the intake air and also tried charge dilution using $CO_2$ to control/phase the HCCI combustion process [13]. However, many of these combustion technologies require specialised engines or significant modifications to the engines. Therefore, the numerical studies on hydrogen HCCI engines are more frequent compared to experimental studies [14–16]. Where else, Dual fuel is rather easy to implement for the in-service engines as it requires minimal modifications to the fuel supply system. In this mode, the hydrogen is premixed with the air during the suction stroke and is called secondary fuel. While, diesel is the pilot fuel, which is injected later in the cycle during compression stroke before TDC. Diesel spray initiates the combustion, and hydrogen contributes to improving combustion by making the charge homogenous. Moreover, these dual-fuel engines can be operated on single fuel also, and hydrogen addition is reported to be effective in emission reduction [17]. Varde et al. spearheaded some of the work on hydrogen enrichment in modern diesel engine during 1983 [18]. Thus, considerable IC engine research in last decade focuses on studying the impact of $H_2$ addition on diesel engines performance and emission [17].

Yilmaz et al. studies 20% and 40% hydrogen energy share (HES) at 50, 75 and 100% engine loads and found improvement in brake thermal efficiency (BTE) and reduction in brake specific fuel consumption (BSFC) [19]. Similarly, Bose et al. also studied the effect of engine load in hydrogen diesel dual fuel engine at compression ratio (CR) of 17.5 [20]. The hydrogen supplied was kept constant at 0.15 kg/h at all loads. They observed an increase in brake thermal efficiency (BTE) by 3.9% with hydrogen compared to regular diesel at 80% engine load. The increase in BTE is lesser for dual fuel engines at lower loads in their experiments. Masood et al. experimented in similar settings at different compression ratios and concluded that the improvement in BTE is favoured by higher compression ratios under similar HES levels [21]. Hydrogen DDF engine with EGR showed excessive knocking along with decrease in BSFC beyond 70% load in a study by Yadav et al. [22]. Suggesting that excess hydrogen can too adversely affect the BTE of the engine. However, in a study by Karagöz et al., the BTE decreases and BSFC increased by 8.4% and 9.4% respectively [23]. They studied the effects of engine load on the performance of $H_2$ enriched diesel engine at 40, 60, 75 and 100% engine load levels with 0 and 30% hydrogen energy content. Christodoulou et al. also report deterioration in engine performance at low speed due to a decrease in hydrogen combustion efficiency [24]. Both the researchers attributed the reduction of engine performance to the dilution of charge as

**Table 1 – Important properties of diesel and hydrogen.**

| Properties | Diesel | Hydrogen |
|---|---|---|
| Lower Heating Values (MJ/kg) | 43 | 120 |
| Stoichiometric air fuel ratio | 14.5 | 34.2 |
| Energy Density at 15 °C and 100 kPa, MJ/$m^3$ | 35.8 | 10.3 |
| Autoignition temperature, K | 530 | 858 |
| Laminar burning velocity, m/s | 0.3 | 2.65–3.25 |
| Flammability limits (% volume in air) | 0.7 to 5 | 4 to 75 |
| Density at 15 °C and 100 kPa, kg/$m^3$ | 848 | 0.0083 |
| Diffusivity in air, $cm^2$/s | 0.038 | 0.63 |

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