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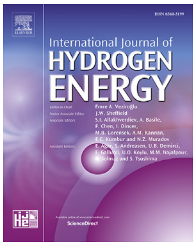

# Hydrogen-diesel fuel co-combustion strategies in light duty and heavy duty CI engines

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ABSTRACT

The co-combustion of diesel fuel with $H_2$ presents a promising route to reduce the adverse effects of diesel engine exhaust pollutants on the environment and human health. This paper presents the results of $H_2$-diesel co-combustion experiments carried out on two different research facilities, a light duty and a heavy duty diesel engine. For both engines, $H_2$ was supplied to the engine intake manifold and aspirated with the intake air. $H_2$ concentrations of up to 20% vol/vol and 8% vol/vol were tested in the light duty and heavy duty engines respectively. Exhaust gas circulation (EGR) was also utilised for some of the tests to control exhaust $NO_x$ emissions.

The results showed $NO_x$ emissions increase with increasing $H_2$ in the case of the light duty engine, however, in contrast, for the heavy duty engine $NO_x$ emissions were stable/reduced slightly with $H_2$, attributable to lower in-cylinder gas temperatures during diffusion-controlled combustion. CO and particulate emissions were observed to reduce as the intake $H_2$ was increased. For the light duty, $H_2$ was observed to auto-ignite intermittently before diesel fuel injection had started, when the intake $H_2$ concentration was 20% vol/vol. A similar effect was observed in the heavy duty engine at just over 8% $H_2$ concentration.

## Introduction

Policy makers and the general public alike are increasingly aware of, and concerned by, the negative impacts of IC engine exhaust gas species on urban air quality and human health [1]. Recent attention has focused on levels of both nitrogen oxides (NOx) and particulate matter (PM) emitted by diesel engine powered vehicles, with higher mortality rates being attributed to PM emissions alone in urban cities. Cities across the world are now moving to establish ultra-low emission zones, and four major cities worldwide have announced plans to ban diesel powered vehicles from 2025 [2]. Future fuel and combustion strategies for IC engines must therefore be designed such that the necessary reductions in pollutant emissions can be met, while also addressing the need to reduce net greenhouse gas emissions [3–5].

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Mitigating the adverse impacts of exhaust pollutants from light and heavy duty diesel engines alike is challenging; both in the context of the range of diesel powered vehicle applications and the inherent complications that arise from after-treatment of compression ignition exhaust relative to that from spark ignition combustion. Large vans, trucks and lorries are required to operate both in urban and extra-urban environments and utilise diesel engines of various sizes, the replacement of which with electric and hybrid power units is less imminent than in the case of SI engine powered passenger vehicles [6–9]. Meanwhile, the often locally rich but globally lean stoichiometry of diesel combustion [10] results in elevated levels of PM and excess oxygen in engine exhaust gases that necessitate the use of several after-treatment systems in series for effective reduction of pollutant emissions. One possibility for the reduction of PM formation during combustion [11], and to lower the burden on after-treatment devices, is the use of alternative fuels other than fossil diesel. The use of biofuels is a potential opportunity for the reduction of PM emissions by this approach (in addition to the possibility of reducing GHG emissions from the transport sector) as they often contain oxygen, the presence of which within a fuel molecule can reduce the availability of fuel carbon for soot formation [12], and do not typically contain high sooting tendency aromatic molecules [13]. Fatty acid esters derived from vegetable oils (and commonly referred to as biodiesel) have been widely considered for the displacement of fossil diesel fuel [14]. While the use of biodiesels, either in blends with fossil diesel or unblended, has often resulted in reduced particulate emissions relative to straight fossil diesel, in many studies concurrent increased NOx emissions have also been observed [15,16]. However, studies utilising potential biofuels containing a higher proportion of oxygen than long chain fatty acid esters, for example ethers and short chain alcohols, in blends with fossil diesel and biodiesel have reported simultaneous reductions in both PM and NOx [17,18]. In addition to oxygen bearing fuels, a further approach that has been considered for the reduction of PM in particular has been the partial displacement of fossil diesel or biodiesel with fuels of lower carbon content, for example with co-combustion of natural gas [19] or hydrogen [20–22].

Several $H_2$-diesel fuel co-combustion studies have been conducted in literature with the hydrogen introduced in the intake manifold, and thus aspirated into the combustion chamber with the intake air [23–27]. Co-combustion studies undertaken on naturally aspirated engines have reported reductions in exhaust emissions of NOx and particulates at low $H_2$ substitution levels, however, at higher $H_2$ substitution levels, an increase in both exhaust NOx and particulate emissions has been observed [26–28]. NOx emissions were speculated to increase due to higher in-cylinder gas temperatures resulting from $H_2$ combustion, while particulate emissions increased due to displacement of intake $O_2$ by $H_2$. Some researchers have attempted to mitigate these effects by utilising exhaust gas recirculation (EGR) and intake air boost with $H_2$-diesel co-combustion [29–32]. Miyamoto et al. [29] studied the effect of EGR with $H_2$-diesel co-combustion, and was able to achieve simultaneous reductions in smoke and $NO_x$ emissions. Roy et al. [31] managed to achieve a 90% energy substitution of diesel by $H_2$ in a supercharged engine, with $N_2$ utilised as simulated EGR to dilute the intake air. The authors were able to operate the engine at 42% brake thermal efficiency, with negligible levels of $NO_x$ and smoke emitted. More recently, Wu et al. [33] investigated the effect of elevated intake air temperature on an engine operating on $H_2$ and diesel fuel. Although a considerable reduction in exhaust emissions was achieved (41% $NO_x$ and 30% smoke emissions reduction), no significant impact of intake air temperature on engine performance and emissions was observed by the authors.

More recently, Pana et al. [34] investigated the effect of $H_2$ fuelling on the efficiency and emissions parameters of a truck diesel engine. The authors reported a 10% reduction in break specific energy consumption (BSEC), a 5.5% reduction in $NO_x$ emissions and considerable reduction smoke and soot emissions, with the engine operating on 3.9% energy substitution by $H_2$ relative to diesel only engine operation. This in contrast to the work of Liu et al. [35] who, in aspirating $H_2$ to the intake of a heavy duty diesel engine, observed a reduction in brake thermal efficiency (BTE) and increase in $NO_2$ emissions arising from poor $H_2$ combustion efficiency and significant $H_2$ slip to the exhaust, with the presence of unburnt $H_2$ suggested to have enhanced the conversion of NO to $NO_2$. Liew et al. [36] also observed low $H_2$ combustion efficiency when aspirated into the intake of a heavy duty diesel engine, and at high loads for the addition of $H_2$ to result in significant increases in peak heat release rates during diffusion controlled combustion. Morgan et al. [37] observed a relatively minor reduction in BTE (~1%) when undertaking $H_2$-diesel co-combustion in a heavy duty engine, attributed to higher diesel fuel direct injection pressures (of up 3000 bar) that enhanced mixing of diesel fuel with the air-$H_2$ mixture and resulted in higher levels of $H_2$ combustion efficiency.

However, $H_2$ combustion in diesel engines can lead to issues such as uncontrolled ignition, surface ignition and backfiring, and high rates of heat release leading to knock. Tsujimura and Suzuki (2017) recently conducted a detailed study on the phenomenon of abnormal combustion (auto-ignition of $H_2$) in a hydrogen-fuelled diesel engine. At low engine loads, the authors did not observe any apparent evidence of $H_2$ combustion in the heat release rate. However, at higher loads and higher $H_2$ fractions, the start of combustion was observed to advance. Abnormal combustion of $H_2$ was observed when the $H_2$ fraction was above 50% under high load engine operation. At these conditions, the cylinder head temperature was also observed by the authors to be strongly dependent on $H_2$ fraction, probably due to increased flame propagation speeds of $H_2$ with increasing $H_2$ fraction.

Hydrogen has also been utilised as a fuel for homogenous charge compression ignition combustion (HCCI), where controlled autoignition of the intake aspirated $H_2$ close to engine TDC is required [38–40]. This was achieved, for example, by Ibrahim and Ramesh [41] in a single cylinder CI engine where $H_2$ was aspirated into preheated air at 120 °C to 130 °C. As the fraction of $H_2$ aspirated into the intake, and thus the equivalence ratio, was increased an advance in the start of combustion (SOC) and higher peak heat release rates were observed, until an engine load of 2.2 bar BMEP (brake mean effective pressure), after which knocking (uncontrolled $H_2$ ignition) occurred.

The above review of literature shows that while a variety of work has been conducted in $H_2$-diesel co-combustion, there is

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