Proceedings of Combustion Institute - Canadian Section
Spring Technical Meeting
The University of Alberta
May 15-18, 2023

Performance and Emission Investigation of Hydrogen Diesel Dual Fuel Combustion

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Abstract

Due to the carbon dioxide reduction potential, hydrogen is gaining popularity in the transportation sector as a motor fuel. Combining hydrogen and diesel operation (dual-fuel) has many advantages, including flexibility in fuel supply logistics. In this study, up to an 88% reduction in CO_2 emissions was achieved at part engine load. The effects of port-injected hydrogen energy replacement on the steady-state combustion properties and emissions of a production diesel engine at various loads from 4.5 bar to 12.5 bar gross indicated mean effective pressure at 1500 RPM. CO_2, NO_x and particulate emissions are investigated. Hydrogen addition caused a CO_2 reduction that scaled with diesel replacement at all operating points, and caused NO_x emissions to increase for most operating conditions. Combustion timing (CA_{50}) was seen to advance at all loads and particulate emissions were seen to decrease with increasing hydrogen fraction. Higher hydrogen additions allowed the engine to meet Tier 4 Offroad particulate emissions standards (20 mg/kWh) without aftertreatment.

1 Introduction

The usage of hydrogen as an engine fuel has been explored since the De Rivaz engine in 1806 [1], and holds promise in reducing carbon dioxide emissions [2]. Additionally, when burned under fuel-lean conditions, hydrogen can have very low NO_x emissions [2, 3]. However, hydrogen combustion dynamics are very different than conventional hydrocarbon fuels [4], including a thermo-diffusive instability where hydrogen molecules diffuse faster than heat at engine-relevant conditions. This means that new operating points and conditions are required for hydrogen use in diesel dual-fuel combustion.

Many methods of using hydrogen in engines have been studied. The oldest is spark ignition of a pre-mixed charge [1] and this is still studied today [5]. Hydrogen can be injected directly into the combustion chamber as a gas [6] or cryogenic liquid [7]. When directly injected into the combustion chamber, it can burn as either premixed or stratified charge ignited by a diesel pilot [6], or as a jet which can be ignited by pilot fuel [8] or hot surface igniter [9]. HCCI combustion has also been studied [10]. In this study, hydrogen is injected into the intake port and combustion is initiated by, and occurs alongside, conventional diesel combustion.

Dual-fuel conversions of existing engines are attractive for several reasons. The ability to run on hydrogen when available, and switch to conventional or bio-diesel when not, may be critical logistically. Additionally, if the local cost of hydrogen varies significantly, it is possible for operators to temporarily increase the usage of conventional fuels to cost-optimize their operations.

Hydrogen-diesel dual fuel has been explored extensively in literature for both port and direct injection. Both strategies show significant reductions in CO_2 output, and increased NO_x production at higher engine loads. For load conditions of 6 bar BMEP and higher, Suzuki and Tsujimura reported an increase in NO_x emissions scaling with load and hydrogen replacement ratio [11, 12]. High exhaust gas recirculation (EGR) concentrations were able to decrease NO_x output to be comparable to pure diesel operation with a particulate formation penalty. Engine efficiency was also found to decrease at low loads and power outputs due to increasing hydrogen slip. A

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similar impact of EGR on NO_x trends, where increasing EGR rates allowed for a 35% decrease in NO_x emissions versus zero EGR flow [13].

The hydrogen combustion efficiency (and overall engine efficiency) of hydrogen at low load falls significantly. Running at an engine load of 2.1 bar BMEP in a heavy duty engine, approximately 80% hydrogen combustion efficiency was reported due to failure to support a vigorous premixed flame [14]. Combustion efficiency was improved dramatically at higher engine loads. EGR has been used to increase the combustion efficiency of the premixed hydrogen. A sensitivity analysis at 3 bar BMEP engine load found a strong correlation between increased EGR rate and improved hydrogen combustion efficiency [15], at a cost of increased particulate generation. A similar improvement in efficiency with increased EGR rate at 6 bar BMEP load was also reported, but with a lower magnitude of improvement [16].

Port fuel hydrogen substitution is usually limited by maximum pressure rise rate and end-gas knock [17]. Direct injection allows for the extension of knock limits and to allow stratification of the hydrogen mixture. 90% energy replacement of hydrogen using direct injection with a peak 57.2% indicated efficiency [6], at a cost of high NO_x emissions.

This paper explores the effects of adding hydrogen port hydrogen injection to a production common rail DI diesel engine. –

2 Experimental Methods

This study was performed on cylinder 1 of a Cummins QSB 4.5 4-cylinder (EPA Offroad Tier 3 certified) engine. Hydrogen was injected into cylinder 1 via a port injector mounted in the intake runner as shown in Fig. 1. For all tests, the engine was run at 1500 RPM. Cylinders 2 to 4 were run with diesel combustion only, with parameters approximating the stock controller. The intake manifold pressure was boosted using building compressed air. The goal of the testing was to keep the engine as close as possible to the production diesel engine. The combustion chamber is not optimized for premixed combustion and uses production valve timings and has no EGR system.

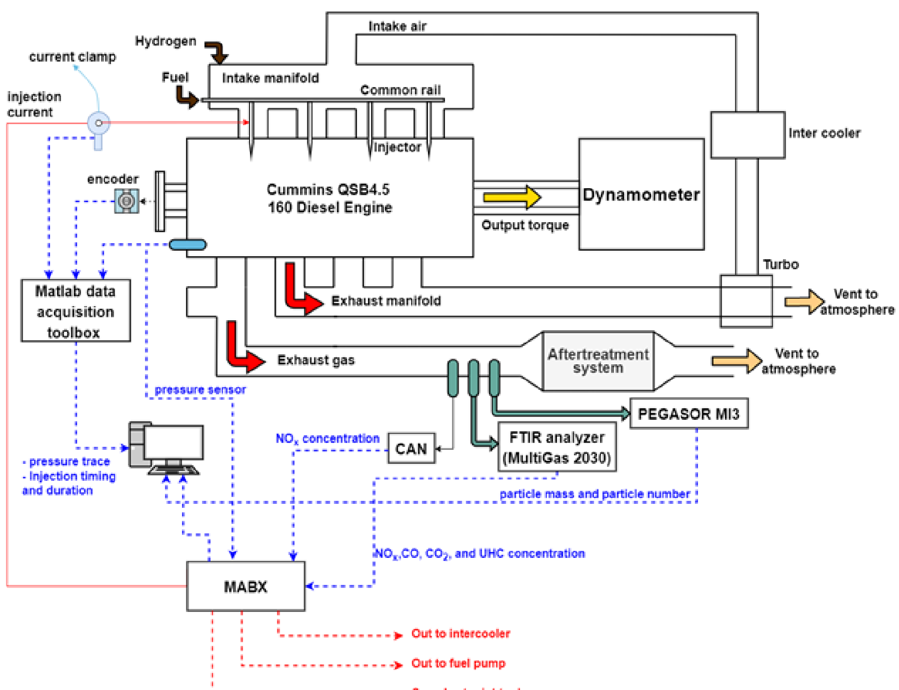

Fig. 1: Schematic of engine testcell showing measurement setup.

The production engine control unit (ECU) has been replaced with a dSPACE 1401 Micro Autobox II prototyping ECU with a dSPACE 1514 FPGA daughter board, providing real-time in-cylinder maximum pressure rise rate (MPRR), maximum cylinder pressure and indicated mean effective pressure (IMEP), similar to [18]. A dSPACE

RapidPro Power unit is used to provided the required high current switching for driving both the diesel and Hydrogen injectors.

The injection strategy used for the experiment is shown in Fig. 2. A short fixed-duration pilot injection was used with a larger variable-duration main injection to limit the MPRR and maximum cylinder pressure during combustion. The Main Start of Injection (MSOI) was held constant at 0 deg ATDC for all trials, and the pilot to main timing (P2M) timing was varied. The pilot injection duration was held constant at 0.23 ms. Diesel fuel rail pressure was held at 1000 bar. At high hydrogen replacement values, the main injection duration was reduced to zero to further reduce diesel consumption. To prevent ensure all hydrogen is drawn into the cylinder and to prevent backfires, the port injection window of hydrogen into the intake runner was limited to a 90 degree span during the intake stroke.

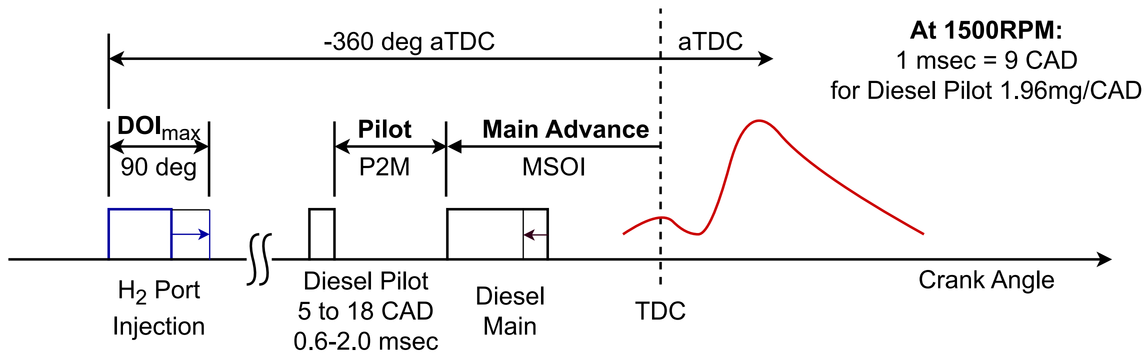

Fig. 2: Hydrogen diesel dual fuel injection strategy schematic.

Four load setpoints were selected, 4.5, 7.5, 10.5, and 12.5 bar gross IMEP ($IMEP_g$). This represents up to 69% of the rated engine load (18 bar $IMEP_g$). Gross IMEP was calculated between -180 to 180 crank angle degrees after top dead center (CAD aTDC) to limit the effect of Intake manifold pressure (MAP) on IMEP. The pilot injection advance was varied from 600-2000 μs in steps of 200 μs. Hydrogen injection was stepped in 450 J/cycle increments from 0 (pure diesel) to a maximum value that could be achieved without a MPRR greater than 7 bar/CAD. Two MAP setpoints were tested for each load point where the main diesel injection duration was adjusted until the target load was achieved, and the engine was measured under steady-state operation for 600 cycles.

3 Results

The influence of hydrogen replacement at a constant load of 10.5 bar IMEP and a P2M of 1000 μs can be seen in Fig. 3. Two values of MAP are run, 1.5 bar and 2.0 bar. The injection timing is held constant to isolate how increasing hydrogen fraction effects the outputs of the engine. The pure diesel trials are presented at 0% hydrogen fraction. CO_2 and particulate emissions can be seen to fall with increasing hydrogen fraction as the carbon containing diesel is replaced by the zero carbon hydrogen. The combustion phasing (CA_{50}) advances with increasing hydrogen fraction, however, their is a discontinuity in the slope of CA_{50} at approximately 20% to 40% hydrogen energy fraction. This discontinuity occurs at a higher hydrogen fraction for the 2.0 bar MAP trial, as the extra charge pressure causes a leaner mixture. This point is likely associated with the hydrogen lambda entering a sufficient range to support vigorous premixed combustion as seen in [14].

NO_x can be seen to behave in two modes depending on the intake pressure. For the 1.5 bar MAP case, a rapid increase can be seen where the NO_x output continually rises with increasing hydrogen. This is attributed to the higher peak cylinder pressures and temperatures. For the 2.0 bar MAP case, a asymptotic-like trend can be seen as the hydrogen replacement value increases with the leaner mixture.

Evidence of a diesel-like particulate-NO_x tradeoff can be seen for the 1.5 bar MAP case, especially for the $\approx$ 50% hydrogen energy fraction case, where a large increase in NO_x production is accompanied by a large fall in particulate emissions.

In Fig. 4, the whole dataset is analyzed. The trials with the highest H2 replacement value (and highest

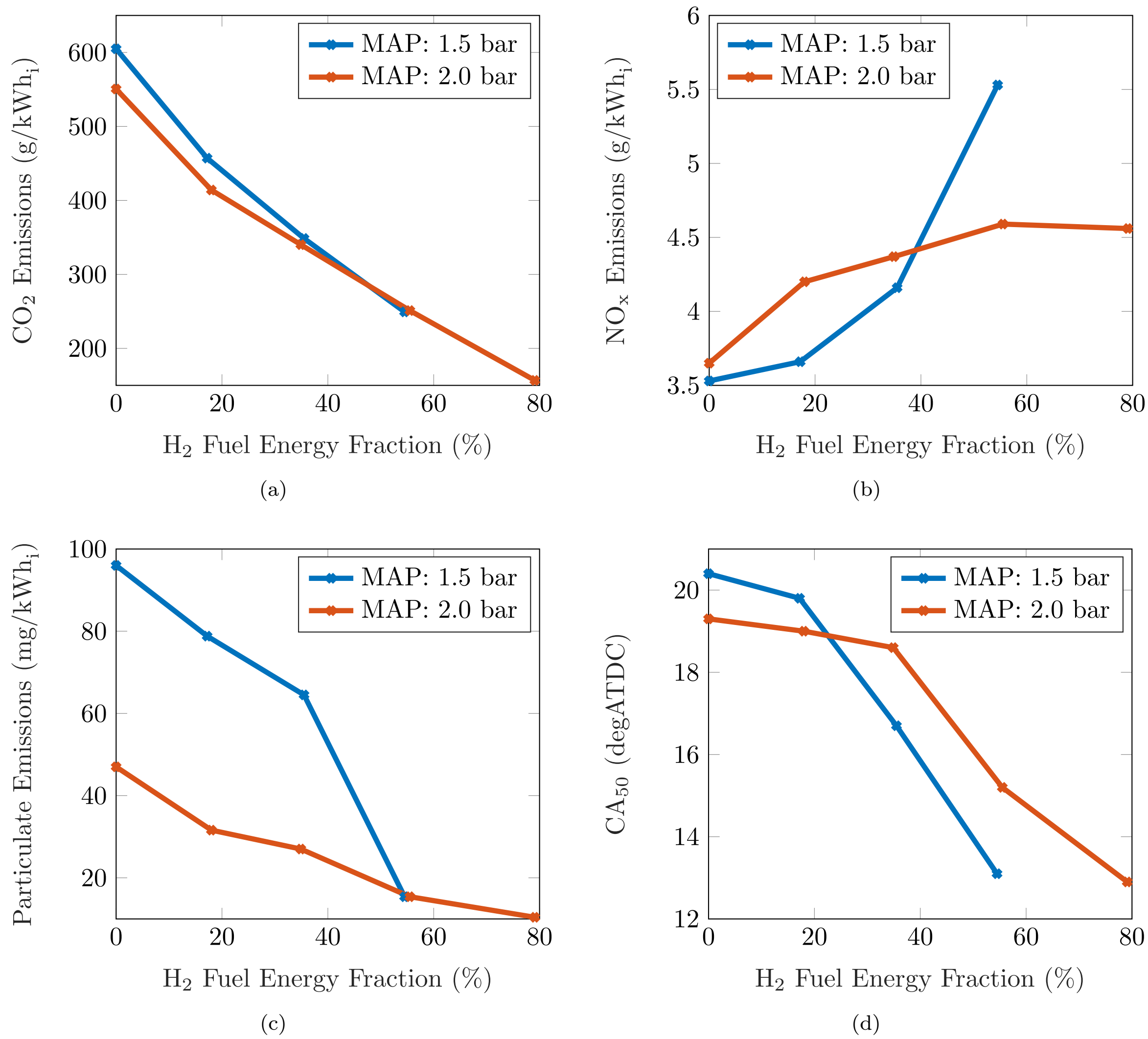

Fig. 3: Engine-out emissions at varying H2 energy fractions. 10.5 bar $IMEP_g$ load at a P2M advance of 1.0 ms at two boost pressures. (a) CO_2, (b) NO_x, (c) Particulate, (d) CA_{50}

CO_2 reduction) are presented. A carbon dioxide reduction of up to 88 percent was achieved at 7.5 bar $IMEP_g$, demonstrating dual fuel's potential in meeting CO_2 reduction targets. The decrease in CO_2 emissions is coupled with the hydrogen energy fraction, which is limited by knock, high pressure rise rates and preignition within the cylinder at higher loads. As such, control strategies or engine design changes to mitigate the maximum pressure rise rate are of great importance to further reduce high load CO_2 emissions.

NO_x emissions were found to be higher under dual-fuel combustion as shown in Fig. 4a. A possible reason for this is the higher in-cylinder pressures and temperatures caused by the rapid hydrogen combustion, which would promote increased NO_x production compared to pure diesel combustion.

Hydrogen addition was effective in reducing low-load particulate emissions, with over 90 percent reduction at 4.5 bar IMEP. Notably, the particulate reduction is greater than the hydrogen replacement fraction at all points (the particulate reduction is of a greater magnitude than the removed diesel), suggesting either higher cylinder temperatures or a chemical reaction between hydrogen and particulate.

Maximum load was limited by preignition and the resulting maximum cylinder pressure. Often this preignition occurred with no or acceptable ringing (< 5 MW/m^2 [19]) and without violating the maximum pressure rise rate limit constraint. At higher loads ($\geq$10.5 bar) and higher hydrogen replacement fractions preignition became

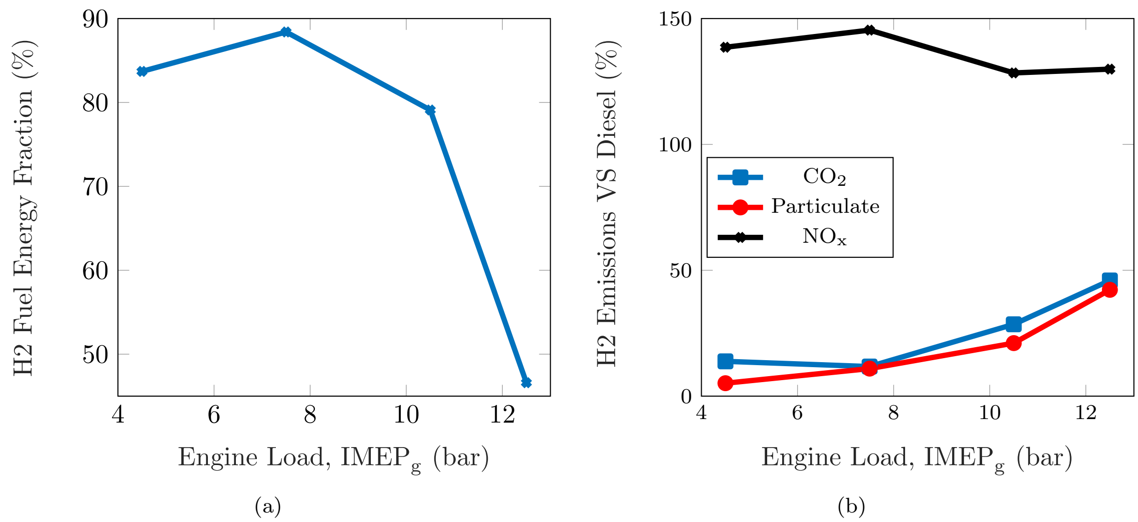

Fig. 4: Load variation for best-case dual fuel operation compared to best-case diesel baseline. (a) H2 energy fraction, (b) Engine-out emissions reduction compared to diesel operation

more common. At these high loads, the preignition was also noted to cause preignition leading to severe knock. This can be attributed to cylinder hot-spots. Parameters such as intake temperature, coolant temperature and residual gas fraction will likely have a significant effect on the probability of preignition. As such, precise control over the premixed air-fuel ratio and optimization of the cylinder head to reduce hot-spotting are of the utmost importance for stable combustion, along with knock-based feedback control.

4 Conclusion

Premixed (port injection) hydrogen addition to an unmodified commercial diesel engine was tested at 4.5-12.5 bar IMEP load and 1.5-2.0 bar MAP. Increasing hydrogen fraction caused CA_{50} to advance at all loads and was significantly increased at higher hydrogen fractions supporting fast premixed combustion. Evidence of a NO_x-particulate tradeoff was seen, with hydrogen addition causing increased NO_x and large decrease in particulate emissions. The CO_2 reduction was roughly linear with hydrogen fuel percentage, with a peak CO_2 reduction of 88% at 7.5 bar load.

Acknowledgments

Funding from CFREF Future Energy program at University of Alberta and NSERC Grant RGPIN-2022-03411 is gratefully acknowledged.

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