

Emissions Effects of Hydrogen as a Supplemental Fuel with Diesel and Biodiesel

Anil Singh Bika, Luke M. Franklin and David B. Kittelson

University of Minnesota

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ABSTRACT

A 1.9 liter Volkswagen TDI engine has been modified to accommodate the addition of hydrogen into the intake manifold via timed port fuel injection. Engine out particulate matter and the emissions of oxides of nitrogen were investigated. Two fuels, low sulfur diesel fuel (BP50) and soy methyl ester (SME) biodiesel (B99), were tested with supplemental hydrogen fueling.

Three test conditions were selected to represent a range of engine operating modes. The tests were executed at 20, 40, and 60 % rated load with a constant engine speed of 1700 RPM. At each test condition the percentage of power from hydrogen energy was varied from 0 to 40 %. This corresponds to hydrogen flow rates ranging from 7 to 85 liters per minute. Particulate matter (PM) emissions were measured using a scanning mobility particle sizer (SMPS) and a two stage micro dilution system. Oxides of nitrogen were also monitored.

For most conditions of both diesel and biodiesel testing a reduction in total mass and number PM emissions is observed with increasing amounts of hydrogen energy input. A small reduction of NO_x emissions is observed with 5% hydrogen energy input at all load conditions. At all other conditions NO_x emissions show little change with hydrogen energy input. At all conditions tested there is a significant increase in the ratio of NO₂ to NO_x in the engine out emissions with increasing amounts of hydrogen. The most notable changes occur with less than 10% hydrogen energy added. This phenomenon is seen with both diesel and biodiesel.

INTRODUCTION

The use of alternative fuels has been the significant focus of engine research in recent years. The escalating interest is due both to the increase in energy use in the world, which is causing a depletion of fossil fuels, and the impact of combustion emissions on the environment. The Environmental Protection Agency (EPA) regulates

PM, NO_x, CO, and HC emissions from diesel engines and these regulations are becoming increasingly stringent [1]. Diesel engines, with their high thermal efficiency and excess oxygen combustion environment, still suffer from high PM and NO_x emissions. To combat these emissions, engine manufacturers are implementing after-treatment devices on diesel vehicles, but other methods, such as a dual fueling with hydrogen, may provide a solution.

There has been much interest in the use of hydrogen as a fuel for the transportation sector. Work has been done with both hydrogen engines and hydrogen fuel cells. Fuel cell technology, however, is still in a developmental stage and may be many years away. Hydrogen as a fuel in internal combustion engines may serve as a possible bridge between the current hydrocarbon fuels the world relies so heavily upon, and future fuel cell vehicles. Hydrogen is appealing as a fuel, because of its clean burning properties and the hope of being able to produce it from renewable resources. Hydrogen can be produced from various methods such as conversion of fossil fuels and biomass, electrolysis, and direct solar conversion by thermo-chemical means [2]. Major impediments to the use of hydrogen in transportation are the lack of a suitable distribution and fueling infrastructure and difficulties with onboard storage. However, on-board reforming of portable liquid fuels may allow at least partial fueling with hydrogen in dual fuel systems [3-5].

Much work has been devoted to hydrogen use in spark ignition engines [9]. However, fewer researchers have achieved successful combustion of neat hydrogen via compression ignition [10-11]. In contrast to neat hydrogen fueled compression ignition engines, dual fuel applications have been researched by many investigators with widespread success [6,7,12-17]. The dual fuel engine has the advantage of operating on a variety of fuels and can be simply retrofitted to existing diesel engines. Detailed emissions from diesel engines with hydrogen addition have been investigated by few researchers.

Tsolakis, et al. investigated PM emissions using an Electrical Low Pressure Impactor (ELPI) and found that the shapes of the number and mass size distributions were not significantly affected, but the total mass and total number concentrations were decreased. A technique of feeding the engine with simulated reformed EGR, which consisted of a mixture of gases with 24% hydrogen by volume, was used. It was concluded that the PM emissions are reduced because of an increased premixed combustion phase and the displacement of diesel fuel.

Chae, et al. investigated PM emissions by means of gravimetric filter measurements and found the PM concentration to decrease at light loads with increasing hydrogen energy input, however an increase in PM was seen at high loads with large amounts of hydrogen energy input. Decreases in NO_x emissions were also seen at the light load (<50%) conditions. This was explained by a decrease in both fuel NO_x and intake manifold O₂ concentration, with increasing hydrogen energy input. At higher loads the NO_x values were increased, due to enhanced thermal NO_x formation with increasing hydrogen energy input.

Varde, et al. found that 10% of the total energy supplied from hydrogen significantly reduced the smoke emissions at part loads, while at high loads this reduction was limited. The NO_x emissions were found to increase with increasing amount of hydrogen energy input. These changes were attributed to the increased rate of heat release which elevated peak cycle temperatures.

Kumar, et al., used vegetable oil and diesel fuel with hydrogen supplementation and found that the smoke levels were decreased with increasing hydrogen fuel mass share in both fuels. The NO emissions were reported to increase with increasing amounts of hydrogen mass share, with the cause cited as increased combustion rate in both diesel and vegetable oil.

Tomita, et al. found that NO_x levels can increase or decrease depending on the engine conditions and injection timings. The NO_x emissions can also be brought to near-zero levels with extremely advanced diesel injection timing in which the hydrogen/diesel/air mixture is well mixed and the initial combustion is mild. Engine operation, however, was found to be unstable, approaching HCCI.

The purpose of this work is to conduct a detailed investigation into the effects of timed port fuel injected hydrogen on particulate and gaseous emissions in a dual fuel engine. Tests were conducted using hydrogen as a supplemental fuel with diesel and biodiesel as the main energy sources in a multi-cylinder production engine.

EXPERIMENTAL SETUP

ENGINE TEST STAND - A 1999 1.9 liter Volkswagen turbocharged direct injection (TDI) diesel engine was

used for this study. The engine compression ratio was 19.5 :1 with a peak power of 66 kW at 3750 RPM and a peak torque of 210 Nm at 1900 RPM. A 55 kW eddy current dynamometer was used to load the engine. Apart from EGR and turbocharger control, diesel engine operation was maintained in the factory configuration.

High purity hydrogen was introduced into the intake manifold via a timed port fuel injection system using four Quantum PQ2-3200 gaseous fuel injectors. Hydrogen flowrates were varied by changing injector duration and supply pressure. Duration was varied via a controller developed in-house, with supply pressures ranging from 5-30 psig. Hydrogen was injected into the intake manifold exclusively when the cylinder intake valve was open to prevent a buildup of hydrogen-air mixture in the intake manifold and to minimize stratification of the intake charge. Hydrogen flow rates were monitored using an Alicat M series mass flow meter. A PRX8491-F flame arrestor was used to prevent any flashback of the hydrogen-air mixture and safety guidelines [18-19] were followed where applicable.

A Micro-oval flow meter and Merriam laminar flow element, model 50MC2-4, were used for diesel and air flow rate measurements, respectively. Temperature measurements were made using type-K Omega thermocouples. The intake manifold, exhaust manifold, and exhaust after-turbocharger pressure were monitored with Omega PX481AD series pressure transducers. LAB-view 6.1 was used for data acquisition. The engine test stand schematic can be seen in Figure 1.

EMISSIONS EQUIPMENT – A scanning mobility particle sizer (SMPS), manufactured by TSI inc., was used for particulate measurements. The SMPS was comprised of a 3071A electrostatic classifier with long differential mobility analyzer (DMA) and a model 3010 condensation particle counter (CPC). The SMPS was operated with a 10 lpm sheath flow rate and a 1 lpm aerosol flow rate giving a size range from 7 nm to 300 nm.

A two-stage micro-dilution tunnel was used to dilute the engine out exhaust sample, which is described in detail by [20]. The dilution system is designed to simulate particle formation and growth that occurs as vehicle exhaust dilutes and cools under on-road driving conditions and to provide particle concentrations that are in a suitable range for the instruments. The first-stage dilution ratio was maintained at 15:1 and the secondary ranged from 10 to 13:1. These ratios were measured using the nitric oxide (NO) concentrations in the engine out exhaust and after each dilution stage.

The NO and NO₂ were measured using a California Analytical Instruments model 600 HCCD for concentrations above 10 ppm. NO₂ was not measured directly but was taken as the difference between NO_x and NO. A Monitor Labs High Sensitivity NO_x Analyzer model 8840 was used for secondary stage NO dilution

measurements where concentrations were below 10 ppm.

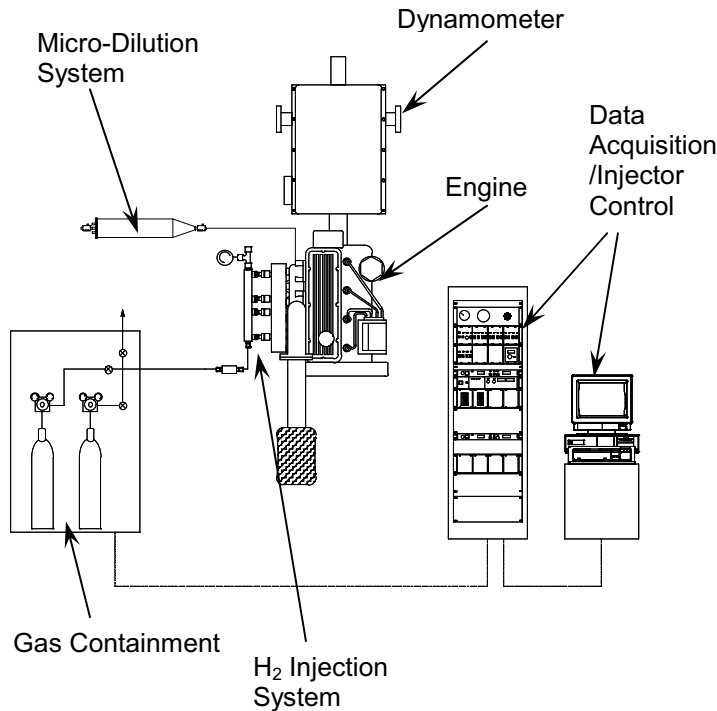


Figure 1: 1.9L VW TDI Engine Test Stand

TESTING PROCEDURE – Two fuels were tested with supplemental high-purity gaseous hydrogen fueling. The first fuel was a low sulfur diesel fuel with 50 ppm sulfur content (BP50). The other fuel tested was a soy based biodiesel (B99) comprised of 99% soy methyl-ester and 1% low sulfur diesel fuel. Table 1 shows properties of hydrogen and typical properties of diesel and SME biodiesel [6-8].

Property	Diesel	Biodiesel	H ₂
LHV (MJ/kg)	42.3	37	120
Flame Speed (m/s)	0.3	-	2.92
Auto-Ignition Temp (K)	525	-	845.1
Flamm. Limits (%Vol)	.6–6.5	-	4-74
Density @ STP (kg/m ³)	~830	860-885	.081
Distillation Range (K)	453-613	588-623	-

Table 1: Fuel Properties

Exhaust gas recirculation (EGR) was disabled during testing. The engine ECU was overridden for the turbocharger boost control by removing the variable vane waste-gate vacuum line and instead supplying a constant vacuum of 10 in-hg via an external pump. Thus, boost pressure was different for the various engine load conditions, but was maintained constant for

diesel/biodiesel comparison with hydrogen addition. Table 2 shows the test conditions which were tested.

Test Fuel	Engine Load (Nm)	Engine Speed (RPM)	Hydrogen Energy Input (% Load)
BP50 & B99	40	1700	0
	40	1700	5
	40	1700	10
	40	1700	20
	40	1700	40
	80	1700	0
	80	1700	5
	80	1700	10
	80	1700	20
	80	1700	40
	120	1700	0
	120	1700	5
	120	1700	10
	120	1700	20

Table 2: Experimental Test Matrix

Hydrogen energy input is defined as the ratio of the energy supplied by hydrogen to the total energy supplied by the diesel and hydrogen fuel at a given engine load and speed condition [17].

The engine was initially brought to a coolant operating temperature of 84 – 88 C. Preceding each test condition, the engine was run at a high speed, high load condition of 2000 RPM and 120 Nm for 5 minutes. This was done to allow any volatile materials left within the dilution tunnel to be burned off. Then, the test condition was set and given 10 minutes to stabilize, after which the dilution ratio was recorded and the data gathered.

PM emissions were collected using an SMPS. The SMPS was operated with a sheath flow of 10 lpm and an aerosol flow of 1 lpm. A total scan time of 120 seconds was used with a 90 second up-scan and a 30 second down-scan. This corresponds to the time allowed for the voltage on the DMA column to move from 0 to 10,000 V (up-scan) and 10,000 to 0 V (down-scan). Three to five SMPS scans were performed at each condition. A minimum of 30 seconds was given between scans to ensure the aerosol path was completely purged between scans.

The temperature in the dilution tunnel was maintained at 47 C using a PID controller. This was accomplished by heating the clean compressed air used in the primary diluter.