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Effect of hydrogen addition on criteria and greenhouse gas emissions for a marine diesel engine

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ABSTRACT

Hydrogen remains an attractive alternative fuel to petroleum and a number of investigators claim that adding hydrogen to the air intake manifold of a diesel engine will reduce criteria emissions and diesel fuel consumption. Such claims are appealing when trying to simultaneously reduce petroleum consumption, greenhouse gases and criteria pollutants. The goal of this research was to measure the change in criteria emissions (CO, NO_x, and $PM_{2.5}$) and greenhouse gases such as carbon dioxide (CO_2), using standard test methods for a wide range of hydrogen addition rates. A two-stroke Detroit Diesel Corporation 12V-71TI marine diesel engine was mounted on an engine dynamometer and tested at three out of the four loads specified in the ISO 8178-4 E3 emission test cycle and at idle. The engine operated on CARB ultra-low sulfur #2 diesel with hydrogen added at flow rates of 0, 22 and 220 SLPM.

As compared with the base case without hydrogen, measurements showed that hydrogen injection at 22 and 220 SLPM had negligible influence on the overall carbon dioxide specific emission, EF_{CO_2}. However, in examining data at each load the data revealed that at idle EF_{CO_2} was reduced by 21% at 22 SLPM (6.9% of the added fuel energy was from hydrogen) and 37.3% at 220 SLPM (103.1% of the added fuel energy was from hydrogen). At all other loads, the influence of added hydrogen was insignificant. Specific emissions for nitrogen oxides, EF_{NO_x}, and fine particulate matters, $EF_{PM_{2.5}}$, showed a trade-off relationship at idle. At idle, EF_{NO_x} was reduced by 28% and 41% with increasing hydrogen flow rates, whilst $EF_{PM_{2.5}}$ increased by 41% and 86% respectively. For other engine loads, EF_{NO_x} and $EF_{PM_{2.5}}$ did not change significantly with varying hydrogen flow rates. One of the main reasons for the greater impact of hydrogen at idle is that the contribution of hydrogen to

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the total fuel energy is much higher at idle as compared to the other loads. The final examination in this paper was the system energy balance when hydrogen is produced by an on-board electrolysis unit. An analysis at 75% engine load showed that hydrogen production increased the overall equivalent fuel consumption by 2.6% at 22 SLPM and 17.7% at 220 SLPM.

Nomenclature

A/F ratio	air/fuel ratio
BSFC	brake specific fuel consumption, g/kW-h
BSU	Bosch Smoke Unit, BSU
CARB	California Air Resources Board
CO	carbon monoxide
CO_2	carbon dioxide
DAF	dilution air filter
DT	dilution tunnel
EF	specific emission, g/kW-h
EGA	exhaust gas analyzer
EPA	Environmental Protection Agency
g/kW-h	grams per kilowatt-hour
ICEs	internal combustion engines
ISO	International Organization for Standardization
kg/m^3	kilograms per cubic-meter
kW	kilowatt
LHV	lower heating value, kJ/kmol
min	minutes
NO_x	oxides of nitrogen
OC	organic carbon
PM	particulate matter
PTFE	polytetrafluoroethylene or teflon filter
ppm	parts per million
RGA	residual gas analyzer
RPM	revolutions per minute
SLPM	standard liter per minute
TDI	turbocharged direct injection
THC	total hydrocarbons
UCR	University of California, Riverside
VN	Venturi
v%	volume %

Introduction

Hydrogen is considered as an alternative source of energy for a sustainable system and improved air quality. Hydrogen has some unique features compared to hydrocarbons, such as high mass and thermal diffusivity, wide range of flammability limits, low minimum ignition energy, and high stoichiometric air-to-fuel ratio. With these properties, hydrogen is an ideal fuel to combine with other fuels or solely used to potentially improve combustion and emission response [1]. Rakopoulos et al. [2] pointed out that hydrogen's potential for increased second-law efficiency is possibly one of the most significant advantages. The application of hydrogen injection control technology in internal combustion engines (ICEs) was proposed in the 1970's. Since then, there have been numerous hydrogen engine-powered vehicles ranging from two-wheelers to passenger cars, pickup trucks and buses that have been designed, built and tested. Many studies have implemented the use of hydrogen as a fuel in spark ignition (SI) engines [3]. However, these studies showed that using hydrogen in SI engines would lead to substantial drop in power output as well as the occurrence of backfire and knocking problems at high loads due to the spontaneous combustion of hydrogen [4]. Thus, the use of hydrogen in SI engines is limited to a certain range of operating conditions [5].

Due to the relatively high self-ignition temperature of hydrogen and the inability of compression to reach that limit, previous studies looked into technologies that supplied hydrogen into diesel fuel ICEs (dual fuel mode) with the purpose of reducing criteria air pollutants and greenhouse gases simultaneously. Varde and Frame [6] carried out an experimental study on a single cylinder, four-stroke direct injection diesel engine. It was reported that at full load, the brake thermal efficiency increased from 30.5% to 33.7% with approximately 12.5% of the energy supplied by hydrogen. The improved thermal efficiency was attributed to the increased combustion efficiency. Bika et al. [7] tested a 1999 Volkswagen 4 cylinder, 1.9 L TDI diesel engine. Results showed that when 10% and 40% of the energy were supplied by hydrogen, PM emissions reduced by 10% and 50% respectively. Kumar et al. [8] investigated the addition of hydrogen into a vegetable oil fueled compression ignition engine. Results indicated that the brake thermal efficiency increased from 27.3% to a maximum of 29.3% at 7% of hydrogen mass share at maximum power output. Smoke was reduced by 16% of Bosch Smoke Unit (BSU) at the best efficiency point. HC and CO emissions decreased by 23% and 35% by volume respectively at maximum power output. NO level increased by 16% at full output due to higher combustion temperature. Tsolakis et al. [9] conducted experiments that showed that diesel engine exhaust particulate emissions can be reduced by the use of hydrogen-rich gas that is produced by the catalytic reaction of diesel fuel and exhaust gas. There is also evidence