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Performance and emissions characteristics in the combustion of co-fuel diesel-hydrogen in a heavy duty engine

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HIGHLIGHTS

- The combustion of diesel-hydrogen in a heavy duty engine at full load is simulated.
- Replacement and adding hydrogen to diesel from 0% to 70% are examined.
- In the best condition, emissions of NO_X, UHC, soot, CO and CO_2 are reduced.
- When 54% and 70% hydrogen is added to diesel, knocking phenomenon takes place.

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ABSTRACT

Owing to the adverse environmental impacts of fossil fuel consumption, a lot of research has been conducted to select alternative sustainable fuel sources with lower emissions. Hydrogen is one of the promising alternative fuels; it is because of its similarity of combustion characteristics to fossil fuels and the fact that it is clean and located in the renewable fuels category. In this paper, the combustion of co-fuel diesel-hydrogen in a heavy duty engine at full load and at speeds of 1600 rpm is simulated. All parameters such as engine speed, spray angle, injection time and input energy have been presumed constant, and variable parameters are the ratio of hydrogen to diesel per mass or energy. In the case of replacement and addition of hydrogen, hydrogen energy is changed from 0% (pure diesel) to 70% in comparison to the input energy of diesel. In the case of replacement of hydrogen instead of input diesel energy fraction, the simulation results indicate that in its best case, emissions of NO_X, unburned hydrocarbons, soot, CO and CO_2 are reduced by 8%, 54%, 14%, 70%, 2.8% and 14%, respectively. Meanwhile, concerning addition of hydrogen as a fuel excess, the emission of unburned hydrocarbons, soot, CO and CO_2 in the best case diminish at a rate of 69%, 9.5%, 17% and 8%, respectively; while NO_X emissions and indicator power increase as 2% and 8%, respectively. It is revealed that replacement and addition of hydrogen to the combustion chamber results in a delay in the ignition, growth in the rate of pressure rise and an increase of heat releasing. It should be noted that this pressure rise will not cause knocking in the hydrogen replacement case; however, when 54% and 70% hydrogen is added to diesel, knocking phenomenon takes place in the engine.

1. Introduction

Nowadays, control and reduction of air pollution are one of the biggest problems in industrialized and developing countries. In the metropolises around the world, the polluting vehicles are one of the main sources of environmental crisis and human diseases. To overcome these adverse effects, in addition to efforts in combustion optimization, the sources of pollutant emissions must decrease from their origin. Blending some of clean or commercial fuels such as natural gas-diesel [1–6], biodiesel-diesel [7], kerosene-diesel [8], reformer gas-diesel [2], hydrogen-natural gas [2,9], hydrogen-diesel [4,10–21], and diesel/gasoline/n-butanol [22] were used by many researchers to improve combustion and emission characteristics. In this regards, employment of clean fuel such as hydrogen can be one of the promising solutions in reducing adverse effects of vehicle pollution. Hydrogen combustion will produce only NO_X pollutant, and there is no footprint of unburned hydrocarbons, soot, CO and CO_2 emissions. Since the characteristics of the hydrogen combustion resembles fossil fuels, hydrogen can be a suitable alternative to fossil fuels if it is obtained from clean upstream resources [23]. More importantly, since 70% of the surface earth is covered by water, hydrogen is classified under the clean renewable fuels category. Today, although 95% of hydrogen is produced from

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Nomenclature

A_0	fluid flow constant
C_n	maximum nucleation rate (1/m³s)
D	diffusion coefficient (m²/s)
f	mixture fraction (of fuel)
f_n	mixture fraction for maximum nucleation rate
F	rate of momentum gain per unit volume
g	specific body force, assumed constant (m/s²)
I	specific internal energy (J/kg)
k	k turbulent kinetic energy (J)
K	Kelvin
m	mass
P	pressure (Pa)
P_{O_2}	partial pressure of oxygen
$\dot{Q}^c$	source term due to chemistry (W/m³)
$\dot{Q}^s$	source term owing to spray (W/m³)
R	Universal Gas Constant
$S_{\varnothing_s}$	source term of the conservation equation
S_n	nucleation source
S_{O_2}	oxidation source
T	temperature
u	velocity (m/s)
V	volume
W	work
Y	mass fraction

Subscripts

f	fuel
m	number of species in chemical kinetics mechanism

Superscripts

c	chemistry source
s	number of species in chemical kinetics mechanism

Greek symbol

δ_{ml}	Dirac delta function
ε	dissipation rate of turbulence (J/kg·s)
η	efficiency
ρ	density (kg/m³)
$\dot{\rho}^s$	density change rate owing to Spray (kg/m³·s)
$\dot{\rho}^c_m$	density change rate due to chemistry (kg/m³·s)
σ_n	predefined f_n variance
φ	fuel-air equivalence ratio
$\dot{\omega}_m$	molar production rate (kmol/m³·s)
Δh^0_f	the standard heat of formation of species m (kJ/kmol)

Abbreviations

ATDC	After Top Dead Center
BTDC	Before Top Dead Center
C.A.	Crank Angle
CDC	Conventional Diesel Combustion
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EGR	Exhaust Gas Recirculation
EVO	Exhaust Valve Opening
GIE	Gross Indicated Efficiency
HHV	High Heat Value
HICE	Hydrogen Internal Combustion Engine
HRR	Heat Release Rate
IVC	Intake Valve Closing
LHV	Low Heat Value
LTHR/HTHR	Low/High Temperature Heat Release
NO_x	Nitrogen Oxide
PRR	Pressure Raise Rate
RI	Ring Intensity
RPM	Revolution Per Minute
SCOTE	Single Cylinder Oil Test Engine
SFC	Specific Fuel consumption
SUB	Substitution
TDC	Top Dead Center

natural gas reforming and only 5% of hydrogen is obtained by electrolysis of water, due to the increased installation and use of renewable energy sources, it can be expected that hydrogen can be obtained from clean energy [24,25]. Hydrogen can also be produced by converting power to gas from the surplus of power plant electricity during low load period [26].

Table 1 demonstrates the details of the hydrogen fuel specifications in comparison to diesel fuel. Because of hydrogen storage difficulties, the high cost of extraction and low required ignition energy (the high tendency of knocking phenomenon) this fuel is not considered as a commercially common fuel except in fuel cells right now. However, small amounts of hydrogen are used as a secondary or additive fuel in some investigations, recently. In Table 2 a comprehensive overview of the studies performed on diesel-hydrogen combustion is demonstrated. Some of them are considered in more detail in the following.

In a work performed by Osama [27], the effect of air–fuel ratio, engine speed and the concentration of hydrogen on the power output are addressed. His simulation using Lotus code shows that for the air–fuel ratio (AFR) < 15 adding 5–10% hydrogen improves engine performance, and for AFR > 15 adding 30% hydrogen leads to enhanced engine performance. This power enhancement is about 14% higher than pure diesel mode. He has also shown that the highest thermal efficiency at full load without the occurrence of a knock takes place when $(5-10)$ percent hydrogen is added and AFR is increased up to 20. In Massoud et al's study [13], the effect of types of hydrogen injection on engine performance is studied. It is reported that because of the better mixture of hydrogen and air, adding hydrogen into the

Table 1
Comparison of diesel fuel and hydrogen characteristics.

Properties	Diesel	Hydrogen
Formula	n-C_7H_{16}	H_2
Autoignition temperature (K)	530	858
Minimum ignition energy (MJ)	–	0.02
Flammability limits (volume % in Air)	0.7–5	4–75
Stoichiometric air–fuel ratio on mass basis	14.5	34.3
Molecular weight ($\frac{g}{mole}$)	100	2
Limits of flammability	–	0.1–7.1
Density at 160 C and 1.01 bar $\frac{kg}{m^3}$	833–881	0.0838
Net heating value (Lower) ($\frac{MJ}{kg}$)	42.5	119.93
Flame velocity $\left(\frac{cm}{s}\right)$	30	265–325
Quenching gap in NTP Air (cm)	–	0.064
Diffusivity in Air $\left(\frac{cm^2}{s}\right)$	–	0.63
Octane number	30	130
Cetane number	40–55	–
Boiling point (K)	436–672	20–27
Viscosity at 15.5 °C, centipoise	2.6–4.1	–
Specific gravity	0.83	0.091