Energy Conversion and Management 151 (2017) 764–777

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

A comparative exergetic performance and emission analysis of pilot diesel dual-fuel engine with biogas, CNG and hydrogen as main fuels

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ARTICLE INFO

Keywords:
Exergy
Dual fuel
Hydrogen
CNG
Biogas
Irreversibility

ABSTRACT

In this experimental study coupled with exergy analysis, a small compression ignition engine is modified to operate in dual fuel (DF) mode with biogas, CNG and hydrogen as main fuels, and diesel as pilot fuel. Injection timing (IT) advance is studied as a strategy to improve the low load performance and emission characteristics of DF engine. Experiments were performed at ITs of 20, 23, 26, 29 and 32 degree crank angles before top dead center (°BTDC) for two engine loading conditions of low and full loads at the operating points corresponding to maximum diesel substitutions. It was found that maximum diesel substitution was considerably affected by the type of main fuel and engine load, however, relatively less affected by IT advance. Highest maximum diesel substitution was observed with CNG, and lowest with hydrogen as main fuels in DF mode. It was also found that IT that gave highest performance or lowest emission varied with both the type of gaseous main fuels and engine loads. At low load, ITs of 32, 29 and 26 °BTDC showed highest exergy efficiencies of 8.5%, 11.1% and 11.9% for biogas, CNG and hydrogen DF operations respectively, compared to 12.6% for diesel only operation. At these operating conditions, exergy destructions of 73.67%, 64.86% and 60.96% (% of total input exergy) were found for DF operations compared to 62.98% for diesel only operation. At full load condition, hydrogen DF operation exceeded exergy efficiency by 2% compared to that with the diesel only operation. On the emissions side, HC, CO and smoke emissions were found to be reduced with advanced ITs; however, NO_x emissions were significantly increased.

1. Introduction

Rapid rise in energy demand and uncontrolled exploitation of limited fossil fuel reserves have led to twin problems of energy security and environmental degradation. An immediate and economically viable solution to this situation lies in the technological developments for utilization of relatively clean burning gaseous alternative fuels, such as biogas (BG), methane (CH_4) and hydrogen (H_2) in existing internal combustion engines (ICEs). Utilization of these fuels in both the configurations of ICEs, i.e. spark ignition (SI) and compression ignition (CI) is a well-studied research area and has revealed specific advantages and challenges at the same time. Gaseous alternative fuels can be utilized in a CI engine in dual fuel (DF) mode, where, gaseous fuels are main fuels and a pilot fuel is required in small quantities to ignite the combustible gas-air mixture. This brings in great flexibility to DF engines that they can be switched to conventional single fuel (diesel only) operation, when the availability of alternative fuel is not sufficient. In addition to that, DF engines also offer other potential benefits in the terms of both performance and emission characteristics. The current and potential applications of gaseous alternative fuel based DF engines range from stationary power generators to transportation sectors. DF engines have been commonly used in liquefied natural gas (LNG) transporting marine engines by utilizing boil-off gases [1,2]. It has also been used in many industries, where CH_4 or other high calorific value (CV) gases are associated with various processes. Furthermore, research projects are being carried out to demonstrate the feasibility of diesel-hydrogen DF engines in public and private transports [3]. Abundant natural resources and established infrastructure make natural gas (NG) the strongest candidate in the context of mass dissemination of gaseous DF technology in the short term. It has been reported that natural gas DF engines show improved thermal efficiency, particularly at high engine loads [4–6]. Simultaneously, it is also possible to reduce carbon dioxide (CO_2), NO_x and smoke emissions, however, carbon monoxide (CO) and hydrocarbon (HC) emissions are found to be significantly higher compared to conventional diesel engine operations [6–8]. Biogas is another prominent alternative from the prospects of its renewable nature and tremendous potential in developing countries [9]. Biogas is produced from anaerobic digestion of biomass, and therefore, it has also been an

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http://dx.doi.org/10.1016/j.enconman.2017.09.035
Received 29 June 2017; Received in revised form 9 September 2017; Accepted 11 September 2017

Nomenclature

Abbreviations

BDC	bottom dead center
BG	biogas
BMEP	brake mean effective pressure
BP	brake power
CH_4	methane/natural gas
CI	compression ignition
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DF	dual fuel
DS	diesel substitution
ED	exergy destruction
EGE	exhaust gas exergy
EGR	exhaust gas recirculation
EGT	exhaust gas temperature
EPC	exergetic performance coefficient
H_2	hydrogen
HC	hydrocarbon
HTE	heat transfer exergy
ICE	internal combustion engines
ID	ignition delay
IT	injection timing
N_2	nitrogen
NO_x	oxides of nitrogen
O_2	oxygen
SI	spark ignition
TDC	top dead center
WTE	work transfer exergy

Symbols

Cp	specific heat at constant pressure, J/kg K
$\dot{I}$	irreversibility, J/s
$\dot{m}$	mass flow rate, kg/s
P	absolute pressure, Pa
Q	heat, J
R	characteristic gas constant, J/kg K
$\bar{R}$	universal gas constant J/mole K
S	entropy, J/K
s	specific entropy, J/kg K
T	absolute temperature, K
t	time, s
X	exergy or Availability, J
x	specific exergy, J/kg; Mole fraction

Subscripts

II	second-law
BG	biogas
ch	chemical
CNG	compressed natural gas
comb	combustion
D	diesel fuel/Diesel mode
DF	duel fuel mode
des	destruction
ex	exhaust
fri	friction
g	in-cylinder gas
gas	gaseous fuels
gen	generation
H_2	Hydrogen
in	incoming
i, j	arbitrary number/species
m, mix	mixture
out	outgoing
p	products
Q	heat transfer
r	reactants
sys	system
W	work
w	wall
un	unaccounted

Superscripts

0	reference state

Greek symbols

θ	crank angle
η	efficiency

attractive option for rural energy supplementation [9,10]. However, it has been found that BG-DF engine is less efficient compared to natural gas DF engine because of low calorific value and high CO_2 content of biogas, which reduce in-cylinder flame propagation speed resulting in incomplete combustion [11,12]. Duc and Wattanavichien [13] found that at low to medium loads, the DF engine operations produced higher unburned HC. This effect was also found to be more pronounced at lower loads, however, at higher loads, efficiency deterioration was reduced, and at the full load, an efficiency similar to that with the conventional diesel engine was achieved. In this category, utilization of H_2 as gaseous alternative fuel in DF mode has many inherent advantages over both natural gas and biogas. Based on a computational study, Yousefi et al. [14] found that the performance of hydrogen DF engine was superior to that of natural gas DF engine at the lean operating conditions. In DF mode, hydrogen improves the overall H/C ratio of combustible mixture causing lesser carbon based emissions [15,16]. Furthermore, high diffusivity and high flame speed of hydrogen allow for better homogeneity in fuel distribution, and therefore, quicker and completer combustion of air-fuel mixture. This results in increased thermal efficiency and reduced emissions (smoke, particulate matters, CO and HC) from H_2-DF engines [16,17]. Nevertheless, high NO_x emissions, backfire and engine knock are some phenomena, which constrain the amount of H_2 that can be utilized in DF mode [16,18,19]. Lata et al. [19] found that maximum amount of substitution by hydrogen was limited to 50% due to knocking problem. Chintala and Subramanian [20] reported significantly high NO_x emissions with increase in hydrogen energy share in DF mode as compared to that with the baseline diesel mode.

In spite of above advantages, DF operation has drawbacks of lower thermal efficiency at low loads, and high HC and CO emissions throughout the engine load spectrum. Lata et al. [18] found that the lean gaseous fuel-air mixture and low pilot fuel quantity at low loads led to slower combustion rates and consequently, the lower thermal efficiency. Similarly, Nirendra et al. [8] found significantly high brake specific fuel consumptions at low load with diesel-natural gas DF operations. Furthermore, on the emission side, both HC and CO emissions were considerably higher compared to the diesel operation. The performance of a DF engine is affected by many operating parameters such as engine load, type of gaseous fuel and injection timing (IT) of the pilot fuel. It has been reported that advancing the pilot ITs shows significant