Applied Energy 219 (2018) 226–239

Contents lists available at ScienceDirect

Applied Energy

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

Development and assessment of a new hybrid vehicle with ammonia and hydrogen

M.F Ezzat[a,b,*], I. Dincer[a]

[a] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada
[b] Automotive and Tractor Engineering Department, Faculty of Engineering, Minia University, Egypt

HIGHLIGHTS

- A novel carbon-free fuel integrated system is proposed for vehicle applications.
- Comprehensive energy, exergy and dynamic analyses are carried out to evaluate the proposed system performance.
- Energy and exergy efficiencies of the proposed integrated systems are determined.
- Hydrogen is produced onboard and used as a promoter in the integrated system.

ARTICLE INFO

Keywords:
Ammonia
Hydrogen
Electrolyzer
Energy
Exergy
Efficiency
Thermoelectric generator
Internal combustion engine

ABSTRACT

In the current study, a new carbon-free ammonia-hydrogen internal combustion engine is integrated with thermoelectric generator and ammonia electrolyte cell and proposed for green vehicles. This integrated system aims to produce hydrogen onboard to enhance the combustion characteristics of the ammonia fuel and enhance internal combustion engine performance. The proposed system is analyzed both energetically and exergetically. Also, a dynamic analysis is provided to investigate the dynamic performance of the proposed system during vehicle operation. The overall energy and exergy efficiencies of the integrated system are found to be 31.1% and 28.94% respectively. The highest exergy destruction rates are found for the internal combustion engine followed by the thermoelectric generator system and ammonia electrolyte cell. Furthermore, hydrogen produced from ammonia electrolyte cell was sufficient to provide the internal combustion engine with the required hydrogen for better combustion and engine performance.

1. Introduction

The utilization of fossil fuels has a significant effect on releasing the greenhouse gas (GHG) emissions, particularly the release of carbon dioxide, which is believed to cause global warming [1,2]. Transportation sector is responsible for the utilization of around 29% of the global final energy consumption, and it also emits around 23% of the global carbon dioxide emissions due to fuel combustion [1,3]. Thus, utilizing alternative clean fuels in the transportation sector should be promoted and applied [4].

Ammonia has the potential to replace fossil fuels in vehicle applications due to the following reasons; ammonia can be easily stored in liquid form at 20 °C, and 8.7 bar, ammonia distribution infrastructure is available [5]. Furthermore, ammonia can be combusted in an environmentally benign way, any ammonia leakage can be noticed by smelling in concentrations as low as 5 ppm, and the ammonia-specific energetic cost is around 13.3$ for every GJ which way less than other fossil fuels such as gasoline and compressed natural gas, which have the specific energetic cost of 29.1$/GJ and 38.3$/GJ respectively [5]. Ammonia can be categorized as a sustainable fuel, and it can be easily manufactured utilizing the process of Haber-Bosh [6]. Implementation of ammonia as a fuel in internal combustion engines (ICE) took place in Belgium during World War II because of the scarcity of fossil fuels supplies [7]. Since then there has been increasing interest in using ammonia as a potential fuel in vehicle applications and the research in this area has been flourished. Grannell et al. [8] concluded that utilizing ammonia as a sole fuel in spark ignition (SI) ICE will result in a deterioration in engine performance. However, blending ammonia with combustion promoter such as gasoline with specific percentages leads to a substantial enhancement in the SI engine performance. Reiter and Kong [9] blended ammonia and diesel in compression ignition (CI) engine to study the combustion mechanism and emissions. The results

* Corresponding author at: Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada.
E-mail addresses: muhammad.ezzat@uoit.ca (M.F. Ezzat), ibrahim.dincer@uoit.ca (I. Dincer).

https://doi.org/10.1016/j.apenergy.2018.03.012
Received 11 December 2017; Received in revised form 28 February 2018; Accepted 14 March 2018
0306-2619/

Nomenclature

A	Area, m^2
C_d	drag coefficient
D^{eff}	diffusion coefficient, m^2/s
E	cell voltage, V
Er	reversible cell voltage, V
$\dot{Ex}$	exergy rate, kW
ex	specific exergy, kJ/kmol
F	Faraday constant, C/mol
h	specific enthalpy, kJ/kmol
J	current density, A/cm^2
J_L	limiting current density, A/cm^2
$J_{o,an}$	anode exchange current density, A/cm^2
$J_{o,ca}$	cathode exchange current density, A/cm^2
J_0	exchange current density, A/cm^2
$\dot{N}$	molar flow rate, mole/min
N_e	engine speed per second, rev/s
N_r	number of revolution per cycle
n	number of moles
P	pressure, bar
PEl	electrolysis power, kW
$\dot{Q}$	heat rate, kW
Q_{HV}	fuel heating value, MJ/kg
R	gas constant, kJ/kmolK
T	temperature, °C *or* K
Tor	torque, N m
u	speed, m/s
V	voltage, V
$\dot{W}$	power, kW
Y	molar fraction

Greek letters

α	road gradient angle, deg
β	reduction ratio
δ	element thickness, m
η	energy efficiency
μ	rolling resistance coefficient
ρ	material resistivity, Ω m
φ	road friction coefficient
ψ	exergy efficiency
ω	engine speed

Subscripts

0	ambient conditions
1,2,…*i*	state points and numbers
Act	activation
a	air
an	anode
c	cold
ca	cathode
Ch	chemical
Conc	concentration
cool	cooling
d	differential
dis	displacement
dr	drag
e	electrolyte
f	frontal
h	hot
Ke	kinetic
lub	lubrication
m	maximum
MEP	mean effective pressure
n	semiconductor "n" type
ohm	ohmic
p	semiconductor "p" type
Pe	potential
Ph	physical
sys	system
v	volumetric

Acronyms

AEC	ammonia electrolyte cell
BSEC	brake specific energy consumption
BTDC	before top dead center
CI	compression ignition
DSU	dissociation separation unit
ICE	internal combustion engine
Pr	pressure regulator
SHE	standard hydrogen electrode
SI	spark ignition
TEG	thermoelectric generator
UNEC	united nations economic commission for Europe
WLTP	worldwide harmonized light vehicle test procedure

demonstrated that, for the same engine power output, the engine with blended ammonia and diesel recorded higher carbon monoxide and hydrocarbon emissions compared to the engine operating with diesel fuel. Moreover, they observed that increasing the ammonia ratio in the fuel blend resulted in a higher ignition delay and causes a deterioration in the peak pressure of combustion. Ryu et al. [10] developed a direct gaseous ammonia injection system into SI engine and compared the performance of SI engine running on a blended ammonia-gasoline fuel with gasoline SI engine. Their experimental evaluation was conducted to identify the best injection time and duration. They found that the most suitable injection timing for gaseous ammonia varies from 320 BTDC at low loads to around 370 BTDC at high loads. Furthermore, the slow speed and temperature of ammonia flames resulted in mitigation in the cylinder peak pressure and overall combustion temperatures in the Ammonia-gasoline blended SI engine. Nevertheless, the brake specific energy consumptions (BSEC) from the two engines were relatively close. Ryu et al. [11] studied both combustion and emissions characteristics of a compression-ignition engine that utilizes different blended mixtures of ammonia (NH_3) and dimethyl ether (DME). Their results showed that the engine performance declined with increasing the ammonia concentration in the fuel mixture, also they found that utilizing a mixture of 40 DME–60%NH_3 yielded higher CO and HC emissions.

Hydrogen is a promising fuel that can be used in many applications in the near future, predominantly, if renewable energy sources are used to produce it [12]. Hydrogen has very high energy density per mass. Its energy density ranges between 120 MJ/kg (as the lower heating value) and 142 MJ/kg (as the higher heating value). Hydrogen is carbon-free fuel and can be combusted in a clean way producing only water vapor. Thus it can be used as fuel in the ICE, and can also be used to power fuel cell vehicles [13–15]. Nevertheless, hydrogen storage is a crucial issue, and further improvement needs to be carried out in this field. Hydrogen can efficiently function as a combustion promoter in ammonia ICEs, even a small amount of hydrogen (around 1% hydrogen to ammonia ratio by mass and nearly 10% by volume) blended with ammonia can achieve satisfactory combustion speed and better engine performance [16–18]. Frigo and Gentili [16] utilized hydrogen as combustion promoter in an ammonia ICE. They found that adding hydrogen to the