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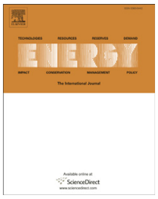

Exergoeconomic analysis of vehicular PEM (proton exchange membrane) fuel cell systems with and without expander

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ABSTRACT

In this paper we perform an exergoeconomic analysis to a PEM (proton exchange membrane) vehicular fuel cell system used in the latest generation of environmentally friendly cars. Two alternative configurations of a fuel cell system are considered (with and without an expander), and two alternative design concepts for each configuration: BoL (Begin of Life) and EoL (End of Life). The system including an expander generates additional power from the exhaust gases leaving the fuel cell stack, which might increase the system efficiency. However the total investment costs for this case are higher than for the other system configuration without an expander, due to the investment costs associated with the expander and its accessories. The fuel cell stack area in the EoL-sized systems is larger than in the BoL-sized systems. A larger stack area on one hand raises the investment costs, but on the other hand decreases the fuel consumption due to a higher cell efficiency. In this paper, exergoeconomic analyses have been implemented to consider a trade-off between positive and negative effects of using an expander in the system and to select the proper design concept. The results from the exergoeconomic analysis show that (a) an EoL-sized system with an expander is the most cost effective system, (b) the compression and humidification of air are very expensive processes, (c) the stack is by far the most important component from the economic viewpoint, and (d) the thermodynamic efficiency of almost all components must be improved to increase the cost effectiveness of the overall system.

1. Introduction

At present, most of the energy in the world is supplied by fossil fuels. During the past decades consumption of fossil fuel resources has been increasing continuously. The problems associated with this development are depletion of resources and higher CO_2 emissions. In this regard, road transport as one of the main sources of CO_2 emissions in Europe (with a share of approximately 15% of the total CO_2 emissions) has led to passing of new regulations in 2007 to oblige the European car manufacturers to produce vehicles with lower CO_2 emissions [1].

For this reason, producing environmentally friendlier cars has become the focus of research activities in the automobile industry. As a result, in addition to some suggested alternative fuels such as *Biofuels*, *Vegetable Oil* and CNG, the concepts of the so-called green cars such as *Electric*, *Hybrid* and *Fuel Cell* cars have been proposed and developed by car manufacturers.

In Ref. [2] biofuels are recommended as an alternative fuel, which can provide 27% of total transport fuel by 2050 and avoid around 2.1 gigatonnes of CO_2 emissions per year when produced sustainably. But meeting such a biofuel demand would need around 100 million hectares space for the feedstock.

Refs. [3,4] show that, if vegetable oils are used as an alternative fuel for diesel, engine performance decreases, CO and HC emissions increase and NO_x emissions decrease accordingly. The most important advantage of vegetable oils is that they are renewable energy sources compared to the limited resources of petroleum.

CNG as another alternative fuel is studied in Ref. [5], in which CO and CO_2 emissions from CNG are reported as 80% and 20% less than gasoline, respectively. The reason is that the hydrogen to carbon ratio (H/C) in gasoline is less than in CNG and it is evident that for higher (H/C) ratios of a fuel, the mentioned emissions are lower. On the other hand, the NO_x emissions for CNG are reported as around 33% more than for gasoline, mostly due to the higher combustion temperature.

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Nomenclature

A	surface area of one fuel cell [cm^2]
c	average cost per unit of exergy [\$/GJ]
$\dot{C}$	cost rate associated with an exergy stream [\$/h]
e	specific exergy [kJ/kg]
$\bar{e}$	standard molar exergy [kJ/kmol]
$\dot{E}$	exergy rate [kW]
F	Faraday constant = 96485 [C/mol]
f	exergoeconomic factor [%]
h	specific enthalpy [kJ/kg]
$\tilde{H}$	molar higher heating value of fuel [kJ/kmol]
i	annual interest rate [%]
i	current density [A/cm^2]
L	plant economic life [years]
m	total number of inlet streams (cost balance) [−]
$\dot{m}$	mass flow rate [kg/h]
MW	molar mass [kg/kmol]
N	number of cells in the stack [−]
n	number of electrons released by one molecule of the fuel (Section 2.3) [−]
n	total number of outlet streams (cost balance) [−]
$\dot{n}$	molar fuel consumption rate [kmol/s]
p	pressure [bar]
$\dot{Q}$	system waste heat [kW]
r	annual escalation rate (economic analysis) [%]
r	relative cost difference (exergoeconomics) [−]
$\bar{R}$	universal ideal gas constant = 8.314 [kJ/kmol.K]
s	specific entropy [kJ/kg.K]
T	temperature [K]
V	voltage of one cell [V]
$\dot{W}$	electric power output of the fuel cell stack [kW]
x	mole fraction [kmol/kmol]
y	exergy destruction ratio [%]
$\dot{Z}$	cost rate associated with capital investment and operating & maintenance expenses [\$/h]

Greek symbols

Δ	difference [−]
η	energetic (thermal) efficiency [%]
ε	exergetic efficiency [%]
τ	system annual full-load operating hours [h]

Subscripts

0	(restricted) dead state
0	current time (economic analysis)
e	electron
F	fuel (exergy)
FL	full load
HC	hill climb
i,j	subscript for exergy and cost streams
k	component
L	losses (exergy)
L	levelized (economic analysis)
P	product (exergy)
tot	overall system
dif	subscript for a fictitious cost rate associated with the use of dissipative components
eff	effective (interest rate)
in	inlet (stream)
out	outlet (stream)
sys	system
W	stream of work

Superscripts

CH	chemical (exergy)
PH	physical (exergy)
OM	operating and maintenance
CI	superscript associated with carrying charges (economic)

Abbreviations

AF	air filter
CC	carrying charges
CELF	constant escalation levelization factor
CM	compressor
CRF	capital recovery factor
CV	control valve
DC	dissipative components
EJ	ejector
EXP	expander
FC	fuel cell
FC	fuel cost (economic analysis)
HX	heat exchanger
M	mixing unit
MHX	mixer-heat exchanger
OMC	operating and maintenance costs
PEC	purchased equipment costs
PEM	proton exchange membrane
S	splitting unit
SEP	vapor–liquid separator
TRR	total revenue requirement
TV	throttling valve
PFD	process flow diagram

Electric and hybrid cars are being also considered by car manufacturers as alternative options of environmentally friendlier cars. The disadvantages of electric cars are associated with high cost, low power, low traveling range and high recharging time. Although hybrid cars consume less fuel in comparison to diesel engine cars, they still use internal combustion engines, which convert the chemical energy of a fuel to shaft power with a relatively low efficiency [6].

Fuel cell systems have been developed and implemented in the newest generation of cars. The idea is to convert the chemical energy of a fuel directly into electricity while producing none of the undesired typical byproducts of combustion processes. Furthermore, quiet operation without vibration and noise is another advantage of fuel cell systems.

Recent research emphasized the importance of the thermodynamic modeling and analysis of fuel cell systems (in terms of energy and exergy) besides economic evaluation to improve the performance of the PEM (proton exchange membrane) fuel cell systems.

In Ref. [7] system modeling and analysis for the main types of fuel cells, either as standalone or as a part of a larger system, are studied. Fuel cells in this reference are presented as an energy conversion system which will play a significant role in meeting both the resource and environmental issues in this century.

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