Energy Conversion and Management 105 (2015) 798–809

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance evaluation of an open-cathode PEM fuel cell stack under ambient conditions: Case study of United Arab Emirates

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ARTICLE INFO

Article history:
Received 11 June 2015
Accepted 30 July 2015

Keywords:
Ambient conditions
Humidity
Fuel cell
Open-cathode
UAE

ABSTRACT

The open-cathode polymer electrolyte membrane (PEM) fuel cell stack has been a promising candidate as a sustainable energy conversion system for replacing fossil fuel-based energy conversion devices in portable and automotive applications. As the ambient air is directly used to provide both oxidant and cooling, the complex cooling loop can be avoided which reduces the complexity and cost. However, the stack performance is highly affected by ambient conditions, i.e., ambient temperature and humidity. In this study, the effect of monthly ambient air conditions (temperature and humidity) is evaluated with respect to the stack's power production performance as well as thermal, water and gas management by employing a validated three-dimensional open-cathode PEM fuel cell stack model. The annual climate data from the hot and arid environment of Abu Dhabi, United Arab Emirates (UAE) are used as a case study. The objective is to develop a better fundamental understanding of the interactions of physical phenomena in a fuel cell stack, which can assist in improving the performance and operation of an open-cathode PEM fuel cell-powered vehicle. The results indicate that the stack performance can vary significantly (up to 40%) from winter to summer, especially at high operating currents, with significant changes in the stack temperature and the water content at the membrane. Moreover, the anode humidification results in a significant improvement in the stack performance (up to 40%) in hot and dry conditions. However, a careful balance has to be struck between the humidifier parasitic load and the stack power.

1. Introduction

Due to escalation of the economics, infrastructure development and population growth supported by abundant oil and gas resources, the United Arab Emirates (UAE) is considered to have one of the highest energy consumptions per capita in the world [1]. UAE's emission per capita has also been reported to be very high in comparison to that of many developed countries. The average emission for the UAE in the past 23 year period is about 10.5 tones carbon equivalent (TCE) per capita as compared to only about 1.1 TCE per capita for the world's annual average emission [2]. A major contribution to the UAE's emissions comes from the transportation sector since the demand for personal vehicles has been increasing rapidly (annual growth rate of 6%) since past 15 years [3].

In tandem, the UAE government plans to diversify its fossil fuel-based energy portfolio by adding cleaner new and renewable energy sources. The establishment of Masdar City in 2009 – the world's pioneer carbon neutral city – is a major realization and implementation of the government's efforts for cleaner alternatives. Kazim [1] proposed a strategy for the UAE sustainable development through a hydrogen energy program where, fuel cell vehicles, especially the proton exchange membrane (PEM) fuel cell vehicles, were introduced in the UAE transportation sector.

PEM fuel cell vehicles are gaining significant interest all over the world because of the general awareness of reducing air pollution and carbon dioxide (greenhouse gas) emissions as well as the need of reducing dependence on fossil fuels. Much progress has been made in the research and development of fuel cell technology in the last decade. Several leading automotive companies have also successfully demonstrated their fuel cell vehicles, such as Honda FCX Clarity and Mercedes-Benz F-cell [4]. In the UAE, the BMW group optimistically projected a scenario that up to 30% of fuel cell vehicles would be used in the country by 2020–2030 [3].

Despite the promising achievements and plausible prospects for fuel cell vehicles, there are several major challenges that need to be

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http://dx.doi.org/10.1016/j.enconman.2015.07.082
0196-8904/

Nomenclature

a	water activity
$c_i^{(g)}$	molar concentration of species i, mol m^{-3}
$c_{i,ref}^{(g)}$	reference molar concentration of species i, mol m^{-3}
$c_p^{(g)}$	specific heat capacity of gas mixture, J kg^{-1} K^{-1}
$c_{p,i}^{(g)}$	specific heat capacity of species i, J kg^{-1} K^{-1}
c_r	condensation/evaporation rate constant, s^{-1}
c_1, c_2, c_3, c_4	constants for the saturation pressure of water; –, K^{-1}, K^{-2}, K^{-3}
$C_1, C_2, C_3, C_4, C_5, C_6, C_7, C_8$	polynomial constant for fan model, Pa s^6 m^{-6}, Pa s^5 m^{-5}, Pa s^4 m^{-4}, Pa s^3 m^{-3}, Pa s^2 m^{-2}, Pa s m^{-1}, Pa
$D^{(c)}$	capillary diffusion, m^2 s^{-1}
$D_i^{(g)}, D_{i,eff}^{(g)}$	diffusivity and effective diffusivity of species i, m^2 s^{-1}
$D_{H_2O}^{(m)}$	diffusivity of water in the membrane, m^2 s^{-1}
$D_{O_2}^{(l)}, D_{O_2}^{(p)}$	diffusion coefficient of oxygen in liquid water and in polymer film, m^2 s^{-1}
$\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$	coordinate vectors
E_{cell}, E_{stack}	cell and stack voltage, V
E_a	activation energy, J mol^{-1}
E_{rev}	reversible cell potential, V
F	Faraday constant, C mol^{-1}
h_j	height of layer j, m
H_{vap}	heat of vaporization, J kg^{-1}
H	relative humidity,%
i, $\mathbf{i}$	current density, A m^{-2}
$j_{a,c}^{ref}$	anode and cathode volumetric reference exchange current density, A m^{-3}
J	volumetric current density, A m^{-3}
$\mathcal{J}$	Leverett function
k	thermal conductivity, W m^{-1} K^{-1}
L	length of channel, m
$\dot{m}_{H_2O}$	interphase mass transfer due to condensation/evaporation of water, kg m^{-3} s^{-1}
$M^{(g)}$	mean molecular mass of the gas phase, kg mol^{-1}
M_i	molecular mass of species i, kg mol^{-1}
$M^{(m)}$	equivalent weight of the dry membrane, kg mol^{-1}
n_d	electroosmotic drag coefficient
$\mathbf{n}_i^{(g)}, \mathbf{n}_{H_2O}^{(m)}$	mass flux of species i and water in the membrane, kg m^{-2} s^{-1}
$p^{(c)}, p^{(g)}$	capillary and gas pressure, Pa
P	power W
$p_{H_2O}^{sat}$	saturation pressure of water, Pa
R	gas constant, J mol^{-1} K^{-1}
s	liquid saturation
S	source term
T_0, T_1, T_2	constant, K
T	temperature, K
$\mathbf{u}, u, v, U$	velocities, m s^{-1}
V	volume, m^3
$x_i^{(g)}$	molar fraction of species i
x, y, z	coordinates, m

Greek

α	transfer coefficient
$\beta^{(m)}$	membrane modification coefficient
ε	porosity
η	overpotential, V
θ	wetting angle
κ	permeability, m^2
λ	membrane water content
μ	dynamic viscosity, kg m^{-1} s^{-1}
ξ	stoichiometry
ξ_1, ξ_2, ξ_3	correction factors for agglomerate model
ρ	density, kg m^{-3}
τ	surface tension, Pa
$\boldsymbol{\sigma}$	total stress tensor, Pa
σ	conductivity S m^{-1}
ϕ	potential, V

Superscripts

(c)	capillary
(C)	carbon
(g)	gas phase
in	inlet
(l)	liquid phase
(m)	membrane
ox	oxidation
(p)	polymer phase
rd	reduction
ref	reference
(s)	solid
sat	saturation
set	setting

Subscripts

α, β	index for species
a	anode
ave	average
c	cathode
cc	current collector
cl	catalyst layer
co	coolant channel
cool	coolant
eff	effective
ff	flowfield
fin	fins
gdl	gas diffusion layer
H_2	hydrogen
H_2O	water
i	species i
j	functional layer j
m	membrane
mass	mass
N_2	nitrogen
O_2	oxygen
pot	potential
ref	reference
sp	separator plate
temp	temperature

addressed before the fuel cell can be considered as a viable alternative to the established internal combustion engine technology [5]. Hydrogen supply-chain and infrastructures, fuel cell performance, fuel cell durability and cost are amongst the major challenges [6]. In addition, the successful operation of fuel cell vehicles depends on several factors related to technological, economic, political and environmental aspects. From the technological point of view, the complexity of the fuel cell system can be reduced significantly by introducing an open-cathode fuel cell concept, for which the ambient air is used directly to feed-in oxygen to the cathode as well as to dissipate the heat generated by electrochemical reactions. Thus, cooling loop, compressor, radiator, humidifier