Applied Energy 215 (2018) 371–383

Contents lists available at ScienceDirect

Applied Energy

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

Exergy analysis of an integrated solid oxide electrolysis cell-methanation reactor for renewable energy storage

Yu Luo[a,b], Xiao-yu Wu[b], Yixiang Shi[a,*], Ahmed F. Ghoniem[b], Ningsheng Cai[a]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China

[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

HIGHLIGHTS

- Compare various electrolysis cells based on the Second Law of Thermodynamics.
- Validated system model for the optimization of power-to-methane route.
- Integrating SOEC and methanation reactor into a single reactor.
- Higher pressure improves the thermal SOEC-methanation performance.

ARTICLE INFO

Keywords:
Solid oxide electrolysis cell
Methanation
Exergy analysis
H_2O/CO_2 co-electrolysis
Intermediate temperature
Pressurizing

ABSTRACT

Renewable power intermittency requires storage for load matching. A system combining a solid oxide electrolysis cell (SOEC) and a methanation reactor (MR) could be an efficient way to convert excess electricity into methane, which can be integrated with the existing natural-gas network. In this paper, a comprehensive exergy analysis is performed for three methane production systems: (i) water electrolysis + Sabatier reactor (SR, CO_2 MR), (ii) H_2O/CO_2 co-electrolysis + MR, and (iii) a single SOEC-MR reactor, is performed. First, we find that in the case of the water electrolysis + SR system, upon replacing the low-temperature electrolysis cell with SOEC, the exergy efficiency is dramatically increased by 11% points of percentage at current densities higher that 8000 A m^{-2}, owing to lower electricity consumption. Second, the type of SOEC, operating mode, and operating conditions are optimized for this system. Results show that H_2O/CO_2 co-electrolysis + MR performs more efficiently than water electrolysis + SR at high current density, especially when using an intermediate-temperature SOEC. The optimal H/C ratio and temperature are found to be 10.54 and 650 °C, respectively. A pressurized intermediate-temperature SOEC enables the system to achieve better thermal integration and improves the exergy efficiency to over 77.43% at 6 bar. Finally, the single SOEC-MR reactor with a spatial temperature gradient has the potential to improve the exergy efficiency to 81.34% while utilizing a compact system.

1. Introduction

Renewable energy, especially wind power, solar power and hydropower, plays an increasingly significant role in the energy roadmap [1,2]. The International Energy Agency (IEA) [3] predicts that renewables will account for nearly 60% of newly installed power generation capacity by 2040, of which wind power and photovoltaics (PV) will make up almost half. The intermittency of renewable energy can lead to the curtailment of large amounts of renewable energy. The curtailment is more serious in China. According to the National Energy Administration of China, 10% of PV power (5.0 TW h) and 15% of wind power (33.9 TW h) were curtailed in 2015 [4,5]. Hydropower curtailment is also serious in China, especially in rainy seasons. Over 25.4 TW h of hydropower was curtailed in two provinces of Southwest China (i.e., Sichuan and Yunnan Provinces) in 2015 [6,7] due to insufficient grid capacity and poor planning [8]. As a result, storage technologies are required. The requirement for future storage capacity has been estimated to be 15–20% of the annual load in order to meet 2–3 months of storage needs [1,9].

Various technologies have been previously studied and developed [1,10–15]. Some are feasible for seasonal storage, such as pumped hydro, compressed air, or fuel storage [11]. Pumped hydro and compressed air storage are both suitable at the large scale, and depend largely on location. Power-to-gas (PtG), using high temperature solid

* Corresponding author.
E-mail address: shyx@tsinghua.edu.cn (Y. Shi).

https://doi.org/10.1016/j.apenergy.2018.02.022
Received 8 November 2017; Received in revised form 24 January 2018; Accepted 5 February 2018
Available online 20 February 2018
0306-2619/

Nomenclature

Abbreviation

AEC	alkaline electrolysis cell
GT	gradient temperature
IEA	international Energy Agency
LSGM	magnesium doped lanthanum gallate
MR	methanation reaction/reactor
NG	natural gas
OCV	open-circuit voltage
PEMEC	proton exchange membrane electrolysis cell
PEN	positive-electrolyte-negative
PtG	power-to-gas
PtM	power-to-methane
SOEC	solid oxide electrolysis cell
SOFC	solid oxide fuel cell
SR	sabatier reaction
TNV	thermal neutral voltage
UT	uniform temperature
WGS	water-gas shift reaction
YSZ	yttria stabilized Zirconia

English letter

A	effective area of mass transfer (m^2)
c	concentration (mol m^{-3})
c_p	specific heat capacity (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2 s^{-1})
E	activation energy for electrochemical reaction (J mol^{-1})
Ex	exergy (W)
ex	exergy per unit mass (W kg^{-1})
$F/\dot{m}$	flow rate (mol s^{-1} m^{-2}) or Faraday constant (96,384 C mol^{-1})
G	transfer function or gas flowrate (m^3 s^{-1})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	enthalpy (J)
i	current density (A m^{-2})
$j_{o,i}$	exchange current density (A m^{-2})
$j_{loc,i}$	local current density (A m^{-2})
J	current (A)
k	pre-exponent factor related to activation resistance
k_f	kinetic constant
K_p	reaction equilibrium constant
L	length (m) or circumference (m)
L_i	thickness (μm)
M_i	molar mass of gas-phase species i (kg mol^{-1})
$\dot{n}$	gas molar flowrate (mol s^{-1})
n	reaction order n relative to activation resistance
N	molar flux (mol m^{-2} s^{-1})
No	number
p	pressure (Pa)
P	power (kW)
Q	heat loss rate (W)
r	radius (m)
R	resistance (Ω m or Ω) or universal gas constant (8.314 J mol^{-1} K^{-1})
R_i	source term of species i for mass balance equation (mol m^{-2} s^{-1})
R_o	O removal rate per active reaction area of electrolysis cells (mol s^{-1} m^{-2})
Rt	reaction rate per area (mol m^{-2} s^{-1})
$S_{a,i}$	specific surface area (m^{-1})
T	temperature (K)
V	volume of flow channel (m^3) or voltage (V)
V_i	diffusion volume of gas-phase species i (m^3)
u	flow velocity (m s^{-1})
U_f	conversion ratio of the reactants
x	molar fraction or distance variable through a battery component (m)

Greek letters

α	total heat transfer area per volume (m^2 m^{-3}) or transfer coefficient for charge transfer
δ	thickness (mm)
δ_t	gap distance of tubes (mm)
ε	porosity
η	exergy efficiency or overpotential (V)
ρ	density (kg m^{-3})
σ	electric conductivity (S m^{-1})
λ	heat conductivity (W m^{-3} K^{-1})
τ	tortuosity
ϕ	electric potential (V)
$\varphi_{s,i}$	active material volume fraction
φ	volumetric fraction
η_i	overpotential (V)
ω	ratio of current related to H_2-H_2O electrochemical reaction
ΔG	change of gibbs free energy (J mol^{-1} K^{-1})

Subscript/ Superscripts

0	environmental state
act	activation polarization
AIT	air injector tube
an	anode
an_surf	anode surface
ca	cathode
ca_surf	cathode surface
cell	solid oxide electrolysis cell
ch	channel
conc	concentration polarization
eff	effective
ex	exergy
el/ca	interface of electrolyte and cathode
el/an	interface of electrolyte and anode
ic	interconnector
in	inlet parameter
inner	inner side of the layer
k	kinetic processes of battery
Kn	Knudsen diffusion
leak	leakage loss
max	maximum exergy efficiency
MR	methanation reaction
OC	open circuit
opt	optimal
ohm	ohmic polarization
out	outlet parameter
outer	outer side of the layer
parallel	in parallel
reac	reaction heat
s	solid
series	in series
tot	total
TPB	triple-phase boundary
WGS	water-gas shift reaction