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Evaluation and optimization of the alkaline water electrolysis ohmic polarization: Exergy study

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ABSTRACT

A model is created in order to investigate the effect of different material parameters on the ohmic overpotential of the alkaline water electrolysis for hydrogen production, which influences the exergy efficiency of the water electrolysis. In this research, it was demonstrated that the electrode material parameters and electrolyte conditions of the water electrolysis components such as electrode and membrane resistivity, distance between the electrodes, oxygen and hydrogen bubbles that covers the electrode surface, electrolyte concentration, electrolyte ionic conductivity, and temperature have various effects on the ohmic overpotential, which consequently affect the exergy efficiency of the alkaline water electrolysis. The results of our model has illustrated that the highest exergy loss is due to hydrogen bubbles followed by the electrolyte ionic resistance and oxygen bubbles resistance, respectively. The model has also provided a strong direction for how to optimize the exergy efficiency by reducing the ohmic overpotential, which is affected by various material parameters and operating conditions.

Introduction

The environmental pollution and the diminution of fossil fuel have increased the interest of the research and development of renewable energy technologies. Hydrogen is the most abundant element in the universe, is considered to be environmentally friendly and to have high energy density. On planets such as Earth, hydrogen is found as part of the molecules of water, organic material, and natural gas. Hydrogen is expected to play an important role in the near future especially as an energy carrier for sustainable research and development. Water electrolysis is a well-known process and is currently adopted in many applications in order to produce hydrogen with high purity [1,2]. Water electrolysis is particularly suitable for use in combination with photovoltaics (PVs) because hydrogen production by electrolysis of water is a mature and efficient technology. Various technologies are available to produce hydrogen via water electrolysis.

The most common water electrolysis is alkaline water electrolysis, polymer exchange membranes (PEM), and solid oxides. The concept is the same for most technologies, which

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Nomenclature

A	Area, cm^2
C	Coulomb, C
c	The Concentration of dissolved gas, mol m^{-3}
D_v	diffusion coefficient, cm^2 s^{-1}
d	Bubble diameter, cm
E	electrode potential, V
E_{act}	activation overpotential, V
E_{rev}	ohmic overpotential, V
F_o	Fourier number
F	Faraday's constant, C mol^{-1}
f	volume fraction
f_G	gas evolution efficiency
G	Gibbs free energy, kJ
i	current density, mA cm^{-2}
i_o	exchange current density, mA cm^{-2}
H	enthalpy, kJ
K_d	the apparent conductivity, S cm^{-1}
k_{water}	the specific conductivity, S cm^{-1}
L	length, cm
m	the hydraulic radius, cm
M	molecular weight, g mol^{-1}
n	number of moles of electrons

Greek symbol

α	transfer coefficient
α_{act}	the activation transfer coefficient
θ	gas bubble surface coverage percentage, %
ε_b	efficiency
η	overpotential, V
η_{ohm}	ohmic polarization, V

Subscript

ele	electrolyte
m	membrane
Ohm	ohmic
w	water
p	partial pressure, kPa
P	pressure, kPa
Q	electrical charge, C
Q_j	the heat loss, kJ
R_g	universal gas constant 8.314 J mol^{-1} K^{-1}
R_e	Reynolds number
R	electrical resistance, Ω
R_{ions}	ionic resistances, Ω
R_1	the electrical circuit resistance (External), Ω
R'_1	wiring and connections electrical resistance, Ω
$R_{bubble;O2}$	oxygen bubbles resistance, Ω
$R_{membrane}$	membrane resistance, Ω
R_{anode}	anode resistance, Ω
R_b	Bubble radius, cm
S_{gen}	the entropy generation, kJ
r	production rate, m^3 h^{-1}
T_{amb}	the ambient temperature, K
t	time, s
U	electrical voltage, V
V_r	bubble volume, cm^3
V_G	volume rate of evolved gas, cm^3 s^{-1}
η_{act}	activation polarization, V
ρ_j	the resistivity of component j, Ω cm
σ_o	the interface conductivity, S cm^{-1}
σ_{el}	electronic conductivity, S cm^{-1}
σ_{io}	ionic conductivity, S cm^{-1}

Superscript

rev	reversible
t,n	thermoneutral
act	activation

is two electrodes and an electrolyte that allows the transport of ions. The alkaline water electrolysis usually operates with electrolyte concentrated with NaOH or KOH. The operating temperature for alkaline water electrolysis and PEM water electrolysis is between 60 and 90 °C, while the solid oxide is between 600 and 900 °C. The alkaline water electrolysis has been widely used in industrial application and for a large number of built units already in operation, while the PEMs water electrolysis still have limited application in terms of production capacity because of the limited lifetime and corrosion of the cells [3,4]. Hydrogen can be produced using a number of different processes such as water electrolysis, thermochemical process, and direct solar water splitting process [5]. Currently, hydrogen is mostly being produced from fossil fuels such as natural gas, coal and oil, using the following thermochemical process: steam reforming, gasification, and partial oxidation. The most frequently used process is the catalytic steam reforming of natural gas and coal gasification.

The water electrolysis process carries significantly higher costs than hydrogen production from fossil fuels [6]. Hydrogen production via water electrolysis process represents less than 5% of world hydrogen production [7], which is used for small scale hydrogen production whereas large-scale hydrogen production is prohibitively expensive or impossible to implement with usages such as spacecraft. The alkaline water electrolysis has many generous advantages such as flexibility, availability, and high purity compared to the thermochemical processes (steam reforming or coal gasification) [8]. While possessing these advantages, hydrogen production via water electrolysis still required improvement in the efficiency and cost of the material and installations, and for this reason we are performing our study on the effect of the materials' parameters and water electrolysis geometry and conditions on the alkaline water electrolysis exergy efficiency.

The alkaline water electrolysis has two types of losses [9]: ohmic overpotential and activation overpotential. The ohmic polarization is caused by the electrodes' resistance, electrolyte resistance, membrane resistance, internal connection wire resistance, and hydrogen and oxygen bubbles resistance. The most critical factors governing the ohmic losses in alkaline water electrolysis are the electrode and membrane material resistivity, electrolyte conductivity and concentration, and electrode and electrolyte geometry. Activation polarization is the voltage overpotential required to overcome the activation energies of the electrochemical reactions on