Journal of Power Sources 239 (2013) 584–595

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

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

Model-based behaviour of a high temperature electrolyser system operated at various loads

Floriane Petipas [a,b,*], Annabelle Brisse [a], Chakib Bouallou [b]

[a] European Institute For Energy Research (EIFER), Emmy-Noether-Strasse 11, 76131 Karlsruhe, Germany
[b] MINES ParisTech, Centre for Energy efficiency of Systems (CES), 60 Boulevard Saint Michel, 75006 Paris, France

HIGHLIGHTS

► Dynamic model of an SOEC system operated at different loads.
► Stable system efficiency of 91% vs. HHV considering no external heat source.
► System power 80% dedicated to electrolysis and 15% dedicated to electrical heating.
► System power load ranged from 60% to 100%.
► Necessity of complementary control strategies to enlarge the load range.

ARTICLE INFO

Article history:
Received 18 October 2012
Received in revised form
1 March 2013
Accepted 6 March 2013
Available online 19 March 2013

Keywords:
High temperature electrolysis
Dynamic model
System integration
Variable operation
Hydrogen production

ABSTRACT

The objective of this study is to describe the steady-state behaviour of a Solid Oxide Electrolysis Cell (SOEC) system operated at different power loads without an external heat source and producing compressed hydrogen (3 MPa). A zero-dimensional model is proposed to describe the system, which is composed of an SOEC unit and a Balance of Plant. Results found that the system efficiency equals 91% vs. HHV and is slightly impacted by the operating load. However, due to the SOEC sensitivity to thermal gradients, the SOEC unit has to be operated close to the thermoneutral mode, which restricts the SOEC system power load to the range 60–100%. Control strategies, such as additional heating and independently operated SOEC units, should be employed below 60% load to enable the electrolyser operation across a wider load range.

1. Introduction

1.1. Need for interconnected energy networks

In 2010, the fossil fuels consumption accounted for 82% of the world energy consumption, shared between oil (34%), coal (26%) and gas (22%), whilst the contribution of renewables was 13%, dominated by biomass [1]. Many issues related to the fossil fuel based economy, such as global warming, air pollution, fuel reserves depletion or countries energetic dependence, motivate an evolution of the current energy system through the gradual replacement of fossil fuels by renewables, such as biomass, wind and solar.

In the European Union (EU), the 20–20–20 targets aim to achieve a 20% share of renewables in the energy mix as well as a 20% reduction of CO_2 emissions and a 20% increase in energy efficiency by 2020 with respect to the 1990 levels. Following these targets, the renewables installed capacity has increased from 22.7% (130 GW) in 2000 to 31.3% (280 GW) in 2011, which was driven by the exponential deployment of wind turbines (2.2–10.5%) and photovoltaic panels (0.0–5.1%) [2].

However, the introduction of large amounts of intermittent electricity into the current electrical grid creates grid instability issues that need to be solved through the development of a smart grid management based on interconnected energy networks. While storing large amounts of electrical energy is a challenge, storing large amounts of gas is not an issue since the gas storage capacity is generally considered as infinite. Therefore, the Power-to-Gas concept proposes to interconnect the electricity and gas networks in order to store excess electrical energy as gas [3]. Moreover, the interconnection with a heat network could maximise the processes

* Corresponding author. European Institute For Energy Research (EIFER), Emmy-Noether-Strasse 11, 76131 Karlsruhe, Germany. Tel.: +49 721 6105 1716; fax: +49 721 6105 1332.
E-mail addresses: petipas@eifer.org (F. Petipas), brisse@eifer.org (A. Brisse), chakib.bouallou@mines-paristech.fr (C. Bouallou).

0378-7753/$ – see front matter
http://dx.doi.org/10.1016/j.jpowsour.2013.03.027

Nomenclature

ASR_T stack Area Specific Resistance at a given temperature ($\Omega\,cm^2$)
$c_{p_{gas}T}$ constant pressure molar heat capacity of a given gas at a given temperature ($J\,mol^{-1}\,K^{-1}$)
e_{cell} single-repeated unit thickness (m)
$e_{endplate}$ endplate thickness (m)
$e_{insulation}$ insulation thickness (m)
E, E_N cell voltage, cell Nernst voltage (V)
F Faraday's constant (96,485 $C\,mol^{-1}$)
HHV Higher Heating Value of hydrogen (286,000 $J\,mol^{-1}$)
j cell current density ($A\,cm^{-2}$)
K_s cell heat capacity ($J\,K^{-1}$)
ℓ_{cell} cell length (m)
ℓ_{stack} stack length including manifolds (m)
$\dot{n}$, $\dot{N}$ cell, total molar flow rate of produced hydrogen ($mol\,s^{-1}$)
$\dot{n}_{gas}$, $\dot{N}_{gas}$ cell, total molar flow rate of a given gas ($mol\,s^{-1}$)
N_{cell} number of cells per unit
N_{cell_stack} number of cells per stack
N_{stack} number of stacks per unit
N_{stage} number of compression stages
$p_{c,1}$, $p_{c,2}$ inlet, outlet pressure of a compression stage (MPa)
p_{gas_in}, p_{gas_out}, p_{gas} cell inlet, outlet, average partial pressure of a given gas
p_{out} hydrogen pressure at the outlet of the system (MPa)
$p_{p,1}$, $p_{p,2}$ inlet, outlet pressure of the pumped water (MPa)
P_{BoP_heater}, P_{BoP_pump} BoP heater, BoP pump power (W)
P_{cell} cell power (W)
$P_{compressor}$ compressor power (W)
P_{gas_in}, P_{gas_out} cell inlet, outlet gases thermal power (W)
P_{unit_loss} unit heat losses (W)
$P_{reaction}$ cell power required for the reaction (W)
$P_{th\_heating}$, $P_{th\_cooling}$ heating, cooling BoP thermal power (W)
R ideal gas constant (8.314 $J\,mol^{-1}\,K^{-1}$)
R_{air} air ratio
S_{active} cell active surface area (cm^2)
SC steam conversion rate
S_{unit} unit insulated surface (m^2)
t time (s)
T considered temperature (K)
T_{amb} ambient temperature (K)
$T_{c,1}$, $T_{c,2}$ inlet, outlet temperature of a compression stage (K)
$T_{filtration}$ hydrogen filtration temperature (K)
T_{in}, T_{out}, T_{cell} cell inlet, outlet, average temperature (K)
$T_{p,1}$, $T_{p,2}$ inlet, outlet temperature of the pumped water (K)
T_{source} water temperature at the inlet of the system (K)
V_{unit_th} theoretical volume of the unit (m^3)
Z_{stage} average hydrogen compression factor for a given stage

Greek letters
ΔH_{vap} water enthalpy of vaporisation (40,668 $J\,mol^{-1}$)
ΔP_{cold_gases}, ΔP_{hot_gases} cold, hot streams required thermal power (W)
ΔP_{gas} required thermal power of a given gas (W)
ΔP_{vap} phase transition required thermal power (W)
$\Delta_r G_T^0$ standard Gibbs free energy change of reaction at a given temperature ($J\,mol^{-1}$)
$\Delta_r H_T$ enthalpy change of reaction at a given temperature ($J\,mol^{-1}$)
δT temperature difference in the pinch analysis (K)
ΔT temperature gradient across the cell (K)
ΔT_{cell} cell temperature variation between two iterations (K)
ε coefficient used in the ASR equation ($\Omega\,cm^2$)
η_{BoP_heater}, η_{BoP_pump} BoP heater, BoP pump efficiency
$\eta_{isentropic}$, $\eta_{mechanical}$ isentropic, mechanical efficiency of compression
η_{system} SOEC system efficiency
κ_{stage} hydrogen average heat capacity ratio for a given stage
λ_T insulation thermal conductivity at a given temperature ($W\,m^{-1}\,K^{-1}$)

Indices
H_2, N_2, O_2 hydrogen, nitrogen, oxygen
$H_2O_{(l)}$, $H_2O_{(g)}$, H_2O liquid water, steam, water

efficiency, which is developed in combined heat and power (CHP) plants and micro-CHP systems. Fig. 1 shows a possible 100% renewables based energy system, where the electricity, natural gas and heat networks are smartly interconnected in order to reach the highest efficiency.

1.2. Electrolysis

Independently from the hydrogen final use, the production of hydrogen from renewable electrical energy is performed within an electrolyser which should be flexible, efficient and affordable for electrolysis to become a cost-effective solution. The electrolysis reaction can be conducted below 373 K with liquid water using an Alkaline ELectrolyser (AEL) or a Proton Exchange Membrane ELectrolyser (PEMEL), or above 773 K with steam using a High Temperature ELectrolyser (HTEL, based on Solid Oxide Electrolysis Cells, SOECs).

Electrolysis is an endothermic reaction, thus both electrical and thermal energy must be provided. At the thermoneutral voltage (1.481 V at 298 K and 1.286 V at 1073 K), the electrolyser material Joule heating balances the reaction thermal energy needs. The cell electrical efficiency, which is the hydrogen Higher Heating Value (HHV) divided by the enthalpy change of reaction, equals 100% vs. HHV at 298 K and 115% vs. HHV at 1073 K. Cell efficiency values above 100% vs. HHV are obtained because of the definition of the HHV. Indeed, the HHV corresponds to the heat which can be recovered from the hydrogen combustion including the latent heat of condensation of water, without taking into account the temperature of the gases. Hence, when the temperature of the electrolyser is higher than 298 K, the reaction efficiency is greater than 100% vs. HHV.

Above the thermoneutral voltage (exothermic mode), the electrolyser material Joule heating is greater than the reaction thermal energy needs, hence the dissipation of excess heat causes a cell electrical efficiency decrease. Low temperature electrolysers are usually operated largely above the thermoneutral voltage (1.7–2.0 V), whereas SOECs operate usually much closer to the thermoneutral voltage, in the range 1.1–1.5 V, which leads to much higher cell electrical efficiencies, hence rendering HTEL a very promising technology.

Several studies are focusing on high temperature electrolysis coupled with renewable energy sources for the production of carbon-free hydrogen [4–7]. However, the behaviour of SOEC systems under various power loads and without an external heat source has not been reported yet. The present study addresses this issue through the use of an SOEC system model.