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Part load operation of a solid oxide electrolysis system for integration with renewable energy sources

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ABSTRACT

100 % carbon-free energy economy might require the interconnection between electricity, gas and transport fuel energy systems and the development of large-scale energy storage systems. All of these can be achieved through electrolysis plants. These plants can produce hydrogen during renewable electricity surplus periods, which can be fed into the natural gas network or sold as transport fuel. In this study a complete model of a solid-oxide electrolysis process has been implemented in order to optimize the design of the process and its operation at part load. Different thermodynamic cell operational modes (constant cell inlet temperature vs. thermoneutral following point) and operational strategies (constant steam conversion vs. constant flow rate) have been analysed. Additionally, three different temperature-dependent area specific resistance equations have been implemented in order to analyse the influence of the dependency of the ionic conductivity of the electrolyte on temperature over the performance of the process.

As result of the analysis, it has been seen that the system is able to operate from 10 to 100 % power load improving the compatibility of solid-oxide electrolysis systems with high transient renewable energy sources. The study reveals that the hydrogen production system can achieve a very flat performance curve within the whole power load range, with overall efficiencies between 91 % and 97 % vs. HHV. This is possible if at low power loads the electrolyser is operated under constant steam conversion mode; whereas at high loads, this is switched to constant flow rate mode. Finally, cells with high variation of area specific resistance with temperature suffers the lowest temperature variation along the power load. This makes possible to increase the operational power range and might reduce thermal stress increasing the lifespan of the cells.

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Nomenclature	
ASR	Area specific resistance of a given cell ($\Omega \text{ cm}^2$)
C_p	Molar heat capacity of a given gas at constant pressure ($\text{J mol}^{-1} \text{ K}^{-1}$)
E	Cell voltage (V)
E_{act}	Activation overpotentials (V)
E_{conc}	Concentration overpotentials (V)
E_{Ohm}	Ohm losses potential (V)
E_{rev}	Reversible cell voltage (V)
E_{ThNeu}	Thermoneutral cell voltage (V)
$E_{\text{ThNeu}_{298\text{K}}}$	Thermoneutral cell voltage at 298 K (V)
Exp_M	Mass flow exponent used to scale convective heat transfer coefficients in heat exchangers (–)
F	Faraday's constant ($96,485 \text{ C mol}^{-1}$)
h	Convective heat transfer coefficient ($\text{W/m}^2\text{K}$)
HHV	Higher Heating Value of hydrogen ($286,000 \text{ J mol}^{-1}$)
HRS	Heat recovery system (–)
HX	Heat exchanger (–)
H_2	Hydrogen (–)
H_2O	Water/steam (–)
j	Cell current density (A cm^{-2})
LMTD	Logarithmic mean temperature difference (K)
M	Mass flow (kg/s)
\dot{n}	Molar flow rate of a given gas (mol s^{-1})
N_{cell}	Number of cells of the whole system (–)
N_2	Nitrogen (–)
O_2	Oxygen (–)
p	Partial pressure (kPa)
P_{std}	Standard pressure (100 kPa)
P_{cell}	Operational cell pressure (kPa)
$Q_{\text{elec_heaters}}$	Electric consumption of the electric heaters (kW)
Q_{elec}	Total electric consumption of the process (kW)
Q_{evap}	Heat required to evaporate the electrolyser feed water (kW)
Q_{gas}	Heat absorbed/released by the gas along the cell (kW)
Q_{HX}	Heat exchanged through a heat exchanger (kW)
Q_{Joule}	Internal Joule heating (kW)
$Q_{\text{SOEC_unit}}$	Electrolyser power demand (kW)
Q_{reaction}	Total energy requirement to split water into oxygen and hydrogen (kW)
$Q_{\text{reac th_needs}}$	Heat absorbed by the electrochemical reaction (kW)
Q_{rev}	Minimum power required to split one molecule of steam
$Q_{\text{turbomach}}$	Power consumed by the turbomachinery (kW)
R	Ideal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$)
S_{active}	Cell active surface area (cm^2)
SC	Steam conversion rate (%)
T_{cell}	Average cell temperature (K)
$T_{\text{cell_out}}$	New outlet cell temperature calculated in the last iteration (K)
T_{gas}	Gas temperature (K)
TTD	Terminal Temperature Difference within heat exchangers (K)
U	Overall heat transfer coefficient ($\text{W/m}^2\text{K}$)
V	Volumetric flow rate (m^3/s)
<i>Greek letters</i>	
α	Coefficient used in the ASR equation (U cm^2)
β, γ, δ	“Constants” used in the heat balance analysis
ΔE_{rev}	Reversible cell voltage variation between two iterations (V)
ΔP	Pressure drop (kPa)
$\Delta_r G_T$	Gibbs free energy change of reaction at a given average temperature (J mol^{-1})
$\Delta G_{\text{Tcell}}^0$	Standard Gibbs free energy change of reaction at standard conditions (J mol^{-1})
$\Delta_r H_T$	Enthalpy change of reaction at a given temperature (J mol^{-1})
ΔH	Enthalpy variation (J mol^{-1})
$\Delta_r S_T$	Entropy change of reaction at a given temperature (J mol^{-1})
ΔT_{cell}	Cell temperature variation between two iterations (K)
ΔT	Temperature difference (K)
$\eta_{\text{DSG-CRS}}$	Efficiency of the direct steam generation solar tower plant
η_{cell}	Electrical efficiency of the cell
η_{system}	Electrolysis system efficiency
χ	Molar fraction of a given gas
χ'	New molar fraction of a given gas obtained through the last iteration
<i>Sub-indexes</i>	
cold, hot	Cold and hot fluids of a heat exchanger
g	Gas state
in, out	Inlet, outlet of the cell
ref	Reference/design conditions
upper, lower	Hotter and colder sides of a heat exchanger

Introduction

Renewable energy sources (RES) have a large potential to mitigate global warming, reduce local and regional air pollution, decrease external energy dependence, and contribute to social and economic development. Consequently, some governments have developed pro-active

policies to promote RES in the energy mix [1,2]. Nevertheless, the analysis of scenarios with high penetration of wind and solar sources faces technical challenges due to their lack of controllability [3–5]. Thus, RES plants should incorporate large-scale energy storage systems in order to improve the stability of future electric grids [1,3,4]. Furthermore, the interconnection of the largest energy systems such as electricity, gas and transport fuel networks would make possible

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