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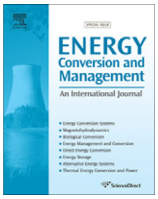

Competitiveness of hydrogen production by High Temperature Electrolysis: Impact of the heat source and identification of key parameters to achieve low production costs

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ABSTRACT

Among the more efficient and sustainable processes that are studied for massive hydrogen production, High Temperature steam Electrolysis seems a promising process. When operating in the autothermal mode, this process does not require a high temperature source for the electrolysis reaction but only a thermal energy source able to supply enough heat to vaporize water. Using a simplified economic model, we assess the impact of the temperature, pressure and thermal energy cost of the heat source on the process competitiveness. Results show that medium temperature thermal energy sources could be coupled to the High Temperature Electrolysis process without resulting in strong overcosts. Besides, key parameters are also identified among the electrolyzer characteristics. Relevant results indicate that R&D on electrolysis cells must continue focusing on the lifespan of these equipments, for which a target lifespan of 3 years could be established.

1. Introduction

Among the several processes currently studied, the perspective of higher efficiencies on hydrogen massive production aroused particular interest for High Temperature Electrolysis (HTE), which since the early 1980s has demonstrated thermodynamic advantages of steam electrolysis (at temperatures above 1023 K up to 1223 K) over liquid water [1]. Besides, on an environmental basis, Life Cycle Assessment results presented by Utgikar and Thiesen [2] and Lattin et al. [3] show HTE as a potential process driving towards hydrogen production with lower carbon dioxide emissions, especially when being fed by nuclear electricity and compared to Steam Methane Reforming (SMR).

Up to now, studies about the coupling of the HTE process with high temperature energy sources, such as the Very High Temperature nuclear Reactor (VHTR), have been carried out mainly suggesting the use of heat for the steam production and overheating, and for the electrolysis reaction [4–6]. However, providing this energy to the electrolyzer is yet to be technically demonstrated. Otherwise, when electrolyzers operate in autothermal mode (i.e. electricity-only operation), the process does not require a high temperature source. Consequently, recent works consider thermal energy sources with lower operating temperatures only for water vaporization. Sigurvinsson et al. [7] proposed the use of geothermal energy to produce steam further overheated in a heat exchanger network that recovers the heat from the oxygen and hydrogen streams exiting the electrolyzer (Fig. 1).

McKellar et al. [8] studied the coupling between HTE process and a Sodium Fast Reactor (SFR), which operates at lower temperatures than VHTRs. The water circuit of the reactor operating at 700 K supplies the heat needed to vaporize water for the HTE process, which reaches 529 K and is overheated afterwards up to the optimal temperature by recovering process heat. Once the heat from the hydrogen stream is recovered, the hydrogen mixed to remaining steam is separated by flash separators.

These works dealing with medium or low temperature energy sources enable to enlarge the list of thermal energy sources to be coupled with the HTE process. However, not all of them would be able to supply enough energy to produce steam in large amounts or be suitable because of their intrinsic economic variables. Therefore, this work on techno-economics of massive hydrogen production by HTE firstly focuses on the impact on the hydrogen production cost of technical issues such as the steam generation and thermal energy sources, and secondly focuses on the impact of the electrolysis cell lifespan and current density, as well as economic factors such as electricity and thermal energy costs, electrolysis cells investment cost and economies of scale.

In order to assess the impact of the heat source and electrolyzer characteristics as previously mentioned, we first perform the economic modeling of the process, which enables to calculate the

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Nomenclature

A	section, m^2
Cap	production capacity, items/yr
C_i	cost, €
c_i	unitary cost, €/m^2, €/kW, €/kW h
Cp_i	specific heat from gas, kJ/kg K
CTA	hydrogen production cost, €/kg
Dh	hydraulic diameter of the heat exchanger, m
E	electric potential, V
$E°$	standard electric potential, V
F	faraday constant, 96,500 C
f	friction factor
FS	entropy factor, V
h_c	height of the electrode channel, m
H_t	annual production of hydrogen, kg/yr
I_i	investment, €
j	electric current density, A/m^2
l	cell width, m
L	cell length, m
M_i	molecular weight, g/mole, kg/kmole
$\dot{m}_i$	mass rate, kg/s
NP	number of plates in the exchanger
PW_i	power, MW, kW, W
$\dot{Q}_i$	thermal power, kW, W
T	temperature, K
tx	partition ratio
W_i	work, MW

Greek symbols

ΔE_I	overpotential, V
ΔP	pressure drop, Pa
ε	reaction yield
ρ_i	mass density, kg/m^3
τ	discount rate, %
τ_i	thickness, m

Indexes

atm	atmospheric
act	activation
anode	anode
BP-TURB	low pressure turbine – SFR
B(X)–ent(Y)	exchanger *X*, inlet of fluid *Y*
B(X)–sort(Y)	exchanger *X* outlet of fluid *Y*
cathode	cathode
cell	electrolysis cell
compress	compressor
conso,elec	electric consumption
conso,th	thermal consumption
conc	concentration
electrolyte	electrolyte
flash	flash separator
H_2	hydrogen
HP-TURB	High Pressure turbine – SFR
i,flash	flash separator investment
i,rectifiers	current rectifier investment
i,transf-MT	mid-voltage transformer investment
i,transf-LT	low-voltage transformer investment
ielec	electrolysis zone investment
i,electrol	electrolyzer investment
inelec	electrolyzer inlet
inv,base,pump,i	investment base cost of pump *i*
inv,base,compress	investment base cost of compressor
kWhe	kiloWatt-hour electric
kWhth	kiloWatt-hour thermal
Na-loop	sodium loop of the SFR
ohm	ohmic
op,electrol	operating of electrolyzer
op-HX,i	operating of heat exchanger *i*
op,SX	operating of overheater SX
pump,i	pump *i*
PUMP1	pump 1 of SFR
PUMP2	pump 2 of SFR
steam	water steam
sys	system
tot	total

hydrogen production cost based on the physical modeling and component design of the process equipments. Finally, the HTE key parameters, trends and R&D targets for driving this process towards competitiveness are described.

2. Process flowsheet

The flowsheet here studied is based on different previous studies and is presented in Fig. 2. The demineralized water fed into the process (stream INH2O) is firstly preheated in the heat exchangers B7 and B8 before being vaporized by using the thermal energy supplied by the selected source. After steam generation, the steam stream is divided into two streams which are connected to a heat recovery network, as presented by Sigurvinsson et al. [7]. In the heat exchangers composing this network (named B1–B4) the steam is overheated by means of the recovered energy from hydrogen–water and oxygen streams exiting the electrolyzer. The heat exchangers are assumed to be plate type. At the outlet of this network, the temperature of the overheated steam is eventually increased by means of an electric heater (SX) that allows the steam to reach the optimal temperature at the inlet of the electrolyzer. From the electrolyzer outlet, part of the hydrogen produced is directed again to the electrolyzer inlet in order to reach a hydrogen concentration of at least 10%mol which avoids corrosion of the cathodes [9]. Also 50% of the oxygen at the outlet is recycled to the anode inlet as a sweep gas used to evacuate the oxygen produced by the electrochemical reaction [10]. Finally, we included a purification system consisting on flash vessels in which the hydrogen that exits the heat recovery network is separated from the remaining steam. Purified hydrogen is then compressed (B13) to the required delivery pressure [8,11,12].

3. Energy sources

3.1. Thermal energy sources

In previous works [13,14], we dealt with the potential for steam production of thermal energy sources of two different kinds: those involving incineration units, specifically the combustion of biomass and domestic wastes, and the development of techniques to produce steam by using the European Pressurized nuclear Reactor (EPR) and Sodium Fast nuclear Reactor (SFR). In the incineration units, the steam is generated conventionally inside the combustion chamber. As regards the EPR, steam is generated in the secondary loop that normally feeds the turbines with saturated steam in order to generate electricity. The coupling of this reactor with HTE assumes the drawing off of part of the steam generated in the