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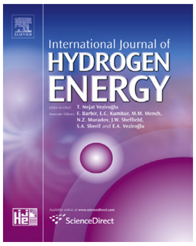

Thermodynamic analysis of the efficiency of high temperature co-electrolysis system for syngas production

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ABSTRACT

High temperature co-electrolysis (HTCE) technology provides a very promising way to store energy and utilization of carbon dioxide. In this paper, the overall efficiency of the HTCE system was calculated through electrochemical and thermodynamic analysis. A thermodynamic model in regards to the efficiency of the HTCE system was established and the effects of five key parameters, electricity generation efficiency of high temperature gas-cooled reactor (HTGR) (η_{el}), electrolysis efficiency of CO_2, electrolysis efficiency of H_2O, thermal efficiency and co-electrolysis temperature on the overall efficiency were investigated in detail. The results showed that although the introduction of CO_2 increases the complexity, it does not significantly reduce the overall system efficiency. Analysis of the impact coefficients gives the order of the impact factors.

Introduction

The rapid increase of energy consumption and the use of fossil fuels have resulted in serious environmental concerns worldwide [1]. Clean and efficient conversion of carbon dioxide has become a major challenge. High temperature co-electrolysis (HTCE) technology has become a new research focus in world's energy field [2–5], which can produce synthesis gas by dissociation of CO_2 and H_2O using a solid oxide electrolysis cell (SOEC). It can be operated reversibly in both fuel cell and in electrolytic mode, and the feed gas can use not only hydrogen but also hydrocarbon fuels and CO_2 [6,7]. Moreover, the co-electrolysis of steam and CO_2 for syngas ($H_2 + CO$) production is an advantage that facilitates both energy storage and production of energy carriers beyond electricity [8,9]. Syngas via F-T process can be further converted to liquid fuels, such as gasoline, which is suitable for use in the existing transportation infrastructure. Such flexibility of the product stream then allows the nuclear energy to alter its electricity output, follow the load for peak electricity, and provides a very promising route to decrease CO_2 emission and enable large-scale energy storage.

It is necessary to use the clean and reliable primary energy as the energy source of the HTCE from the perspective of closed carbon cycle. The promising clean alternative energies include solar, wind, geothermal, biomass and nuclear, while

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Nomenclature

HTCE	High Temperature Co-electrolysis
HTSE	High temperature steam electrolysis
HTGR	High Temperature Gas-cooled Reactor
F-T	Fischer–Tropsch
ΔH	Enthalpy change of the reaction, kJ mol^{-1}
ΔG	Gibbs free energy change of the reaction, kJ mol^{-1}
ΔS	Enthalpy change of the reaction, kJ mol^{-1} K^{-1}
E	Potential, V
T	Temperature, °C
$Q_{overall}$	Total thermal energy demand
$\eta_{overall}$	Overall efficiency of HTCE system
x	Mole percentage of H_2O electrolysis attributable to all the electrolysis reaction
y	Mole percentage of H_2 which generated by H_2O electrolysis occurs RWGS reaction
T	Co-electrolysis temperature
η_{El}	Generating efficiency of HTGR
η_{Heat}	Thermal efficiency of the HTCE system
η_{EsH_2}	Electrolytic efficiency of H_2O electrolysis
η_{EsCO}	Electrolytic efficiency of CO_2 electrolysis

nuclear power stands out above the rest with stable, efficient and clean characteristics [10–12]. Energy conversion efficiency is an important indicator for a technology. The overall efficiency performance of the HTCE routes using nuclear energy for the syngas production depends on the operating temperature, conversion efficiency of the processes, and parameter selection of the systems. The efficiency of high temperature steam electrolysis (HTSE) for hydrogen production coupled with nuclear reactors has been studied systematically in recent years [13–16]. However, few studies have investigated the thermodynamics and efficiency for an HTCE system.

Most of the present research in this field focuses on the electrochemical model and SOEC materials studies. Ni M. developed a thermal modeling and an electrochemical model for syngas production by co-electrolysis of H_2O and CO_2 [17,18], and two models of a SOEC for carbon dioxide electrolysis also were studied at different levels [19]. Aicart J et al. developed a 2D electrochemical and thermal model for the co-electrolysis, the modeling can be useful for the parameters optimization of the SOEC cell/stack operation [20]. Stempien J.P. et al. reports a method on the calculation of equilibrium potential of co-electrolysis of H_2O and CO_2 in a SOEC, and they also gave a thermodynamic analysis and simple optimization of a combined SOEC and F-T synthesis processes for sustainable hydrocarbons fuel production [21,22].

Although HTCE is developed based on the technology of HTE technology, the introduction of CO_2 greatly increased the complexity of the reactions and the whole system. It is of great importance to figure out whether the introduction of CO_2 significantly affects the efficiency and what are the key parameters on the practical limits for the $\eta_{overall}$ of the HTCE system. Therefore, the objective of this paper is to examine, in detail, the theoretical efficiency of the HTCE system and determine the quantitative and qualitative effects of various factors on the overall efficiency of the HTCE system.

The HTCE system

Fig. 1 shows the schematic of High Temperature Co-electrolysis (HTCE) systems powered by High Temperature Gas-cooled Reactor (HTGR) which is marked with block colored red. It mainly consists of two parts: HTGR and SOEC system. HTGR system supplies electrical and thermal energy to SOEC simultaneously. The desalinated water together with CO_2 obtained from air capture are preheated to the reaction temperature from the room temperature (20 °C) and then the mixed gas was introduced into the cathode of SOEC as feed gas. The outlet gas is composed of H_2O, CO_2, H_2 and CO as the production of High temperature co-electrolysis. Synthesis gas (mixture of CO and H_2) can be obtained by membrane separation and then converted into liquid hydrocarbons through Fischer–Tropsch reaction. Moreover, the heat of the product gas can be recycled to preheat the feed gas again. Therefore, HTCE system powered by HTGR is a promising technology to obtain hydrocarbons without fossil fuel consumption and CO_2 net emission, which can be realized as a carbon-neutral fuel cycle [3,23].

Thermodynamic model

High Temperature Co-electrolysis is a process to convert H_2O and CO_2 into H_2 and CO by electric energy under high temperature, which is showed as following.

$$H_2O + CO_2 \xrightarrow{Electricity+Heat} H_2 + CO \tag{1}$$

Hypothesis

To simplify the model, it can be assumed:

1. There are three reactions in the whole co-electrolysis process [23].

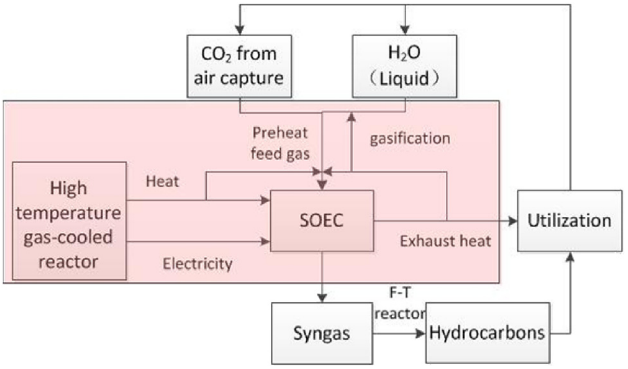

Fig. 1 – Schematic of HTCE system powered by HTGR.

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