Experimental Investigation of Efficiency Maximization in Solid Oxide Electrolysis Systems by Internal Steam and Heat Recovery

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This study presents the development of a scalable steam generator for a reversible solid oxide cell system with 40 kW of power in electrolysis mode. As solid oxide electrolysis can be conducted under thermal-neutral conditions, efficiency is primarily governed by the system's heat and steam loss. The steam generator presented herein recovers heat and steam from the fuel side off-gas in order to preheat the feed water and superheat the electrically-generated saturated steam. The design is based on a pinch analysis intended to optimize the temperature levels. In the considered system, the steam generator was estimated to increase electrolysis efficiency from 70% to more than 74%.

Introduction

Solid oxide electrolysis cells (SOECs) have recently attracted increasing research attraction in accordance with the rising demand for non-fossil fuels, energy, and educts for the chemical industry. One major challenge for the replacement of fossil fuels with renewable energy sources is the long-term storage of electrical energy. For this purpose, hydrogen constitutes a promising energy carrier. The roundtrip efficiency of the conversion of electrical energy to hydrogen and back into electrical energy has a major impact on the total costs of energy storage. SOEC systems provide one of the highest levels of efficiency for the production of hydrogen from water and electrical power (1). With current cell technology, an SOEC can be operated in thermally-neutral conditions, meaning that the stack itself generates no waste heat at all. Therefore, the SOEC's system efficiency is limited by the loss of heat and steam to the environment. By minimizing these losses, an SOEC can be operated very close to the thermodynamic optimum.

SOEC System

The results from the recent developed and build rSOC system at the Forschungszentrum Jülich in Germany, with a nominal electrolysis power of 40 kW, are still pending. Therefore, this study is based on measurements taken from its predecessor, a reversible solid oxide cell (rSOC) system also developed and built at Jülich in 2018. Although it was designed as an rSOC system, it was not specifically optimized for electrolysis operation. The system was based on the "Integrated Module" (see Figure 1), which was initially developed for an SOFC system and then modified for rSOC operation. This module consisted of a 40-layer stack with a total active cell area of 1.28 m². It contained a steam/hydrogen and air heat exchanger, arranged at the top and bottom of the stack. Integrated, electrically-powered heating plates provided heat for the heating up process, as well as endothermal electrolysis operation. A detailed description and performance analysis of the system was given by Peters et al. (2, 3).

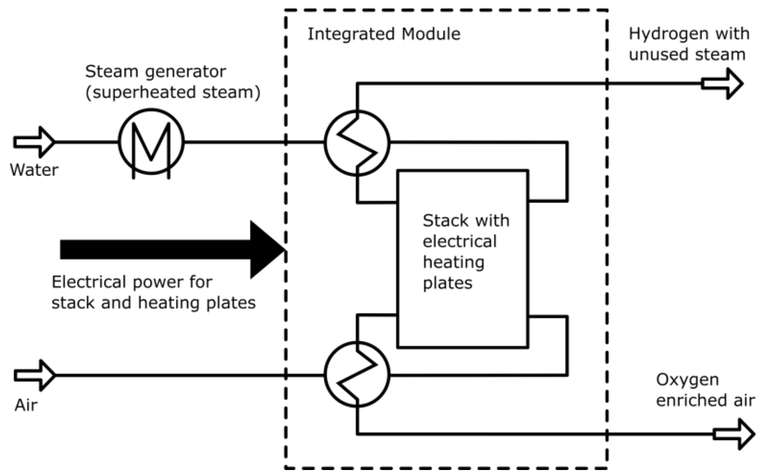

Figure 1. Simplified flow sheet for the rSOC system in SOEC operation.

Heat Recovery

The heat loss of an SOEC system can be reduced by means of the proper thermal insulation of the hot components and limiting the impact of thermal bridges at the sensor and electrical connections from the stack to the environment. However, the major loss of energy from a well-designed SOEC system is typically caused by the steam and heat content of the off-gases (4). As is shown in Figure 2 of the system under consideration, these losses contribute to 11% of the total input power, including heating plates and steam generation.

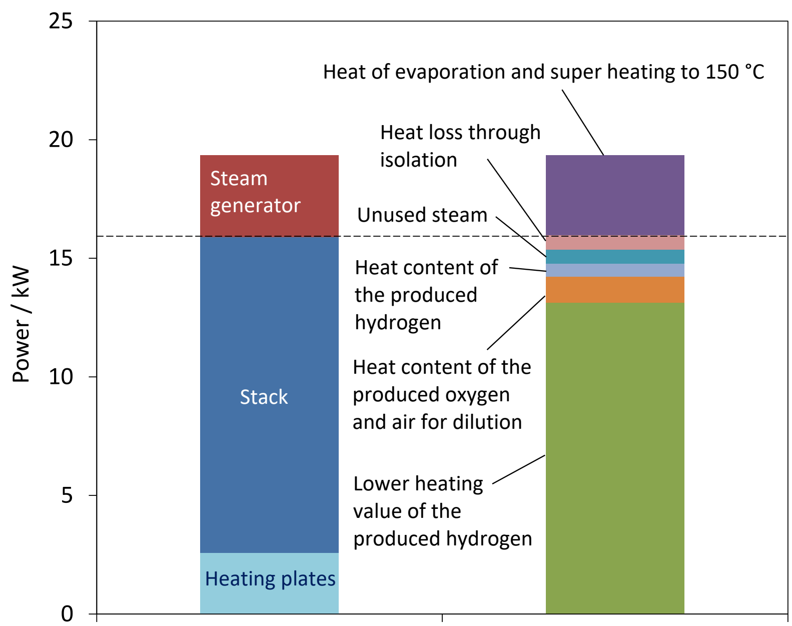

Figure 2. Energy demand of the Jülich rSOC system for electrolysis.

Table I presents the operating conditions for this analysis. The data does not include the rectification losses for the AC-to-DC conversion.

TABLE I. Electrolysis operation conditions of the rSOC system.

Parameter	Value	
Electrical input power	19.4	kW
Cell power (DC)	8.1	kW
Heating plates	2.6	kW
Steam generator	3.4	kW
Air blower	< 0.05	kW
Generated hydrogen	0.056	Mol s^{-1}
Current density	0.84	A cm^{-2}
Stack steam utilization	80.1	%
Off-gas temperatures	~ 400	°C

The contribution of the heat content of the produced oxygen itself is usually of minor importance. However, it becomes more noticeable when additional air is fed into the stack for diluting the generated oxygen in order to reduce the potential hazard of dealing with pure oxygen at high temperatures. This method was applied to the discussed system. Nevertheless, the most significant contribution of the energy loss is due to the hydrogen/steam mixture, as is shown in Figure 3.

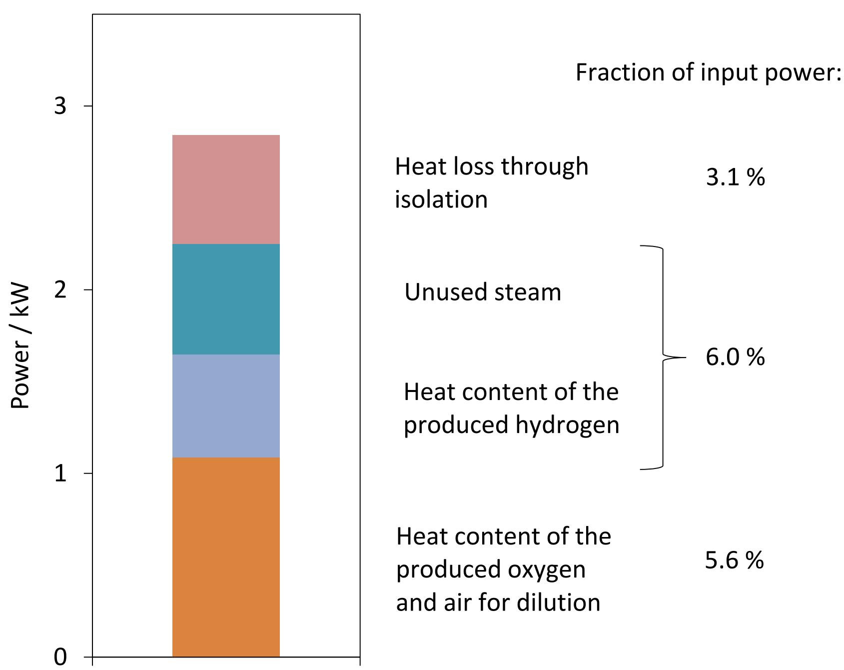

Figure 3. Breakdown of the energy loss during electrolysis.

The key component for potential heat recovery from the off-gas in an SOEC system is the steam generator, which is by far the largest consumer of energy apart from the solid oxide electrolysis cell stack itself. Therefore, a scalable steam generator to recover heat and steam has been developed (Figure 4). It was designed as the successor of the rSOC system described above, and is capable of supplying steam for electrolysis operation at 40 kW. In this design, steam recovery is accomplished indirectly through the partial reuse of the steam condensation heat in the off-gas. The recovered heat is used to preheat the feed water in the heat exchanger HX1. The feed water stream is feedback-controlled by a proportional level sensor and proportional valve (V1) to ensure a continuous water flow in the heat exchanger. The preheated liquid water enters the heat exchanger HX2 at about boiling temperature. This heat exchanger is electrically-heated and the heating power is feedback-controlled by the measured pressure within the vessel. The saturated steam generated is then fed into the heat exchanger HX3. A feedback controller ensures the required steam flow with the proportional valve (V2) and a vortex flow meter. In the heat exchanger HX3, the saturated steam is superheated in a counter flow by the hydrogen/steam off-gas from the "Integrated Module". The design is based on our long-term experience with different types of steam generators for SOECs.

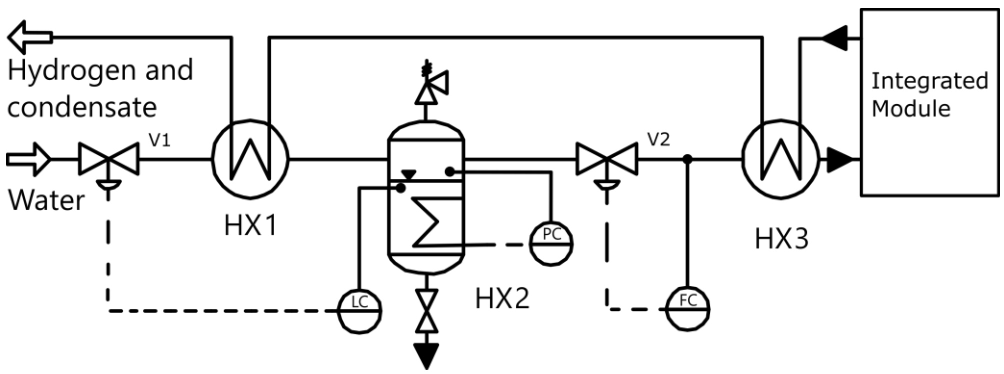

Figure 4. Steam generator with heat and (indirect) steam recovery.

In order to analyze the temperature levels of the available and required heat, a pinch analysis has been conducted, as shown in Figure 4. The specific heat, indicated on the x-axis, applies to the feed as well as the off-gas stream due to the identical molar flows. The pinch analysis shows clearly that a high degree of energy recovery requires preheating of the feed water. As the partial pressure of water vapor in the off-gas is quite low due to the hydrogen content, a temperature of well below 100 °C is needed for the partial condensation of water vapor in the off-gas.

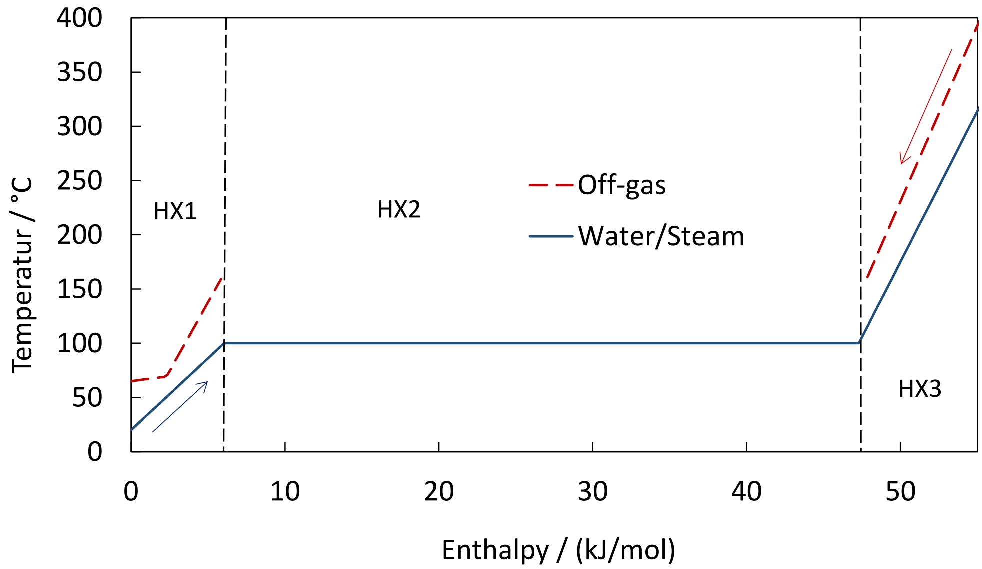

Figure 5. Steam generator with heat and (indirect) steam recovery.

With respect to the energy balance and temperature levels, there is no difference between using the remaining heat (which is not required to preheat the water) for boiling or superheating. The presented design with a gas–gas heat exchanger for superheating the steam was chosen due to the advantage of it requiring no electric superheater for this purpose. Although direct electric evaporation and superheating can be simply achieved on the laboratory scale, it does not scale very well for larger units. This design is based on widely available components and can be easily scaled up to any size required. Furthermore, the design has the advantage that the steam delivery can be controlled very rapidly, with the dynamic response only limited by the characteristic of the steam control valve.

Impact on System Efficiency

The higher heating value of hydrogen (HHV) is, by definition, the minimal amount of energy (electric and thermal in the case of electrolysis) required to generate hydrogen from liquid water. Therefore, an efficiency based on the lower heating value (LHV) is limited to the ratio of these (eq. 1). A higher efficiency than this ratio, based on the total input power, is impossible (5).

$$\eta_{LHV,max} = \frac{LHV_{H2}}{HHV_{H2}} = 84{,}6\% \qquad [1]$$

Defining the efficiency based on the heat loss ($\dot{Q}_{loss}$) and input energy ($P_{in}+\dot{Q}_{in}$) shows that the fractions of input power as shown in Figure 3 are equivalent to the reduction in the overall system (DC) efficiency:

$$\eta_{LHV} = \frac{LHV_{H2}}{HHV_{H2}} - \frac{|\dot{Q}_{loss}|}{|P_{in}+\dot{Q}_{in}|} \qquad [2]$$

For the investigated operating condition (Table I), the sum of the energy loss was determined to be 14% of the input power. Therefore, the system efficiency totaled about 70%. As is shown in Figure 5, it is assumed that about 13 kJ/mol of specific energy can be recovered from the fuel off-gas with the new steam generator, which is approximately 4.7% of the input power. Therefore, an overall system efficiency increase by the same amount is to be expected.

Conclusions and Outlook

An analysis of an rSOC system operated in electrolysis mode is presented herein. The data shows the different aspects that reduce the system efficiency compared to the thermodynamic maximum. The breakdown of energy losses for the system reveals that multiple independent properties have a more or less similar impact on the system's efficiency. Therefore, the optimization of a single aspect yields, on its own, only a moderate overall improvement in efficiency. Nevertheless, we addressed the aspect with the largest impact by designing and building a steam generator with the capability of recovering heat and steam from the fuel side off-gas. Based on the presented analysis, we anticipate an efficiency (LHV) increase from 70% to more than 74% for the investigated operating condition.

It should be noted that the presented numbers depend not only on the system design but also on the specific operating conditions. The experimental examination of the steam generator will be presented at the conference and reveal if it matches the expected performance benefits.

Acknowledgments

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References

1. O. Posdziech, K. Schwarze and J. Brabandt, *Int. J. Hydrog. Energy*, 35, 19101 (2019).
2. Ro. Peters, M. Frank, W. Tiedemann, I. Hoven, R. Deja, N. Kruse, Q. Fang, L. Blum and R. Peters, *J. Electrochem. Soc.*, 168, 014508 (2021).
3. Ro. Peters, M. Frank, W. Tiedemann, I. Hoven, R. Deja, V.N. Nguyen, L. Blum and D. Stolten, *ECS Trans.*, 91 (1), 2506 (2016).
4. M. Frank, R. Deja, R. Peters, L. Peters and D. Stolten, *Appl. Energy*, 217, 112 (2018).
5. S.D. Ebbesen, S.H. Jensen, A. Hauch and M.B. Mogensen, *Chem. Rev.*, 114, 10734 (2014).