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Thermal Management of Solid Oxide Electrolysis Cell Systems Through Air Flow Regulation

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High Temperature ELectrolysers (HTEL) operate around 1,073 K, the temperature varying with the applied power. A restricted power range of 60-100 % should be respected to avoid thermal gradients higher than ±10 K cm^{-1}. The present paper aims to propose control strategies to lower thermal gradients and extend the power range. Two strategies, based on the use of air flow at the anode, are proposed and analysed in detail. The first strategy, consisting of a constant ratio between the air flow and the produced oxygen flow, leads to an extended power range of up to 22 -100 % for a ratio of 14. However, since the air flow is heated up to 1,073 K, the impact on the system efficiency is consequent. A second control strategy, consisting of adapting the air flow to the thermal needs of the system, is proposed. The regulated air flow enables to extend the power range to 1-100 % and has an impact on the system efficiency only below 60 % load.

1. Introduction

Due to the load fluctuations and the geographical dispersion of renewable energies, large scale installations cause grid instability issues. The grid stability can be ensured through the development of smart grid management combined with energy storage. The conversion of electricity into another energy carrier, which can be stored and used directly as a fuel, is an attractive option. In this framework, the Power-to-Gas concept (El Elmi et al., 2016) consists in converting electricity into hydrogen (H_2), which can be further converted into methane (CH_4). Power-to-Gas is a general concept for the production of gas from electricity and encompasses both power-to-hydrogen and power-to-methane.
The conversion of electrical energy into hydrogen is done electrochemically within an electrolyser. The water electrolysis reaction can be performed 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) (Petipas et al., 2015). Presently, AEL and PEMEL are implemented in numerous Power-to-Gas demonstration projects. The AEL is the most mature and affordable technology, however the power load is ranged to 20-100 %, which is an issue in the Power-to-Gas context. The PEMEL is also a commercial technology and has a larger power load range (0-100 %); however, the cost is still too high for energy markets such as Power-to-Gas. The HTEL is presently at the research and development stage, but has attractive potential due to the large power load range (0-100 %) reached under lab conditions at the cell and stack level, and the foreseen low cost.
HTEL is based on ceramic solid oxide cells, which are particularly sensitive to mechanical stresses caused by temperature variations. The temperature of the cells is only constant at one specific nominal load (thermoneutral mode), decreases at lower loads (endothermic mode) and increases at higher loads (exothermic mode). Experimentally, thermal variations are avoided because experiments are performed on cells or stacks placed in a furnace and being maintained at a constant temperature. Thus the power applied to the cells and stacks can vary down to 0 % of the maximum power without provoking thermal issues caused by the endothermic mode (Petipas et al., 2013a). In real conditions, power variations induce thermal variations. The impact of power variations on the temperature of the cells has been modelled and presented in a previous paper (Petipas et al., 2013b). It has been shown that the minimum and maximum operating powers should be set as the powers being

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reached when the endothermic and exothermic modes provoke thermal gradients of ±10 K cm^{-1}, without thermal management in the cells, in order to avoid thermal stresses. This restricts the power load range to 60 - 100 % of the maximum power (around the thermoneutral mode). Below 60 % of the maximum power, the endothermic mode would provoke thermal gradients lower than -10 K cm^{-1}, which could damage the cells, unless thermal management strategies are deployed.

Two concepts of thermal management strategies have been proposed in order to limit thermal gradients in the endothermic mode: 1) heating through the restitution of heat stored in the exothermic mode and 2) heating through the circulation of hot fluids within the stack. (Laurencin et al., 2012) have proposed to operate the high temperature electrolyser alternately in the exothermic and in the endothermic mode. The surplus heat generated in the exothermic mode is stored and used in the endothermic mode to balance heat requirements. This concept enables to manage the temperature in the stack, but it implies that the applied power should be controlled, which is not the case of an unpredictable electrical source such as renewable energies. (Dillig et al., 2012) have proposed to inject high temperature fluids in the stack in order to homogenise the temperature distribution within the stack. Different configurations were presented. (Le Gallo and Baurens, 2007) proposed to integrate additional channels in the stack and to inject the inlet gases in these channels before injecting them to the cathode and anode of the cells. (Dillig et al., 2012) proposed to integrate heat pipes into the stack structure and to inject heat transfer liquids such as sodium in the heat pipes. (Udagawa et al., 2008) proposed no change in the stack design but to sweep the anode with air, which is a common thermal management strategy in high temperature fuel cell systems. This control strategy is chosen to be implemented in this work because it can be deployed without design changes in the stack. (Udagawa et al., 2008) studied the effect of the air sweep on the temperature distribution at the cell level. The objective of this work is to analyse the effect at the system level and to optimise this control strategy in order to maximise the system efficiency.

2. Definition of the SOEC (Solid Oxide Electrolysis Cells) system

The SOEC system, presented in detail in (Petipas et al., 2015), consists of two modules: the SOEC unit and the Balance of Plant.

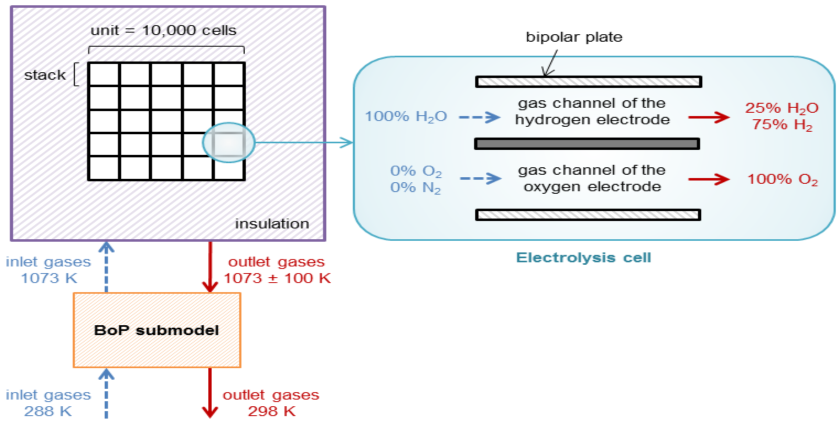

Figure 1: Schematic representation of the considered SOEC system

2.1 SOEC unit module

It is assumed that the SOEC unit is composed of 10,000 cells (N_{cell}) in total, distributed among 25 stacks of 400 cells. The nominal temperature is set to be 1073 ± 50 K, and a thermal insulation wall of 30 cm is provided around the SOEC unit. Each cell has an active surface area of 100 cm^2. The ASR (Area Specific Resistance) is temperature dependent and equals 0.5 Ω cm^2 at 1,073 K. At the inlet of the SOECs, pure steam at 1,073 K is provided and a constant steam-to-hydrogen conversion rate of 75 % is maintained, which means that the stream flow is proportional to the applied power. The outlet gases are composed of a mixture of unreacted steam (25 %) and produced hydrogen (75 %) at the cathode, and a mixture of air sweep and produced oxygen at the anode. In order to limit thermal gradients in the cells to 10 K cm^{-1}, the outlet temperature is set to be ranged between 973 K and 1,173 K, which sets a minimum SOEC unit power of 633 kW (endothermic mode) and a maximum SOEC unit power of 1,101 kW (exothermic mode) according to the simulations. The power range hence corresponds to 57-100 % of the maximum power at the SOEC unit level. The aim of the model being to analyze the system behavior in steady state, the model of the SOEC unit is based on the following assumptions:

pressure drop neglected; electrochemistry and mass transfer dynamics neglected; solid temperature equals gas temperature; lumped model.

2.2 Balance of Plant module

The Balance of Plant (BoP) is composed of a compressor, heat exchangers, a heater and a pump. The outlet gases are cooled down in the heat exchangers by the inlet water. According to the simulations, the temperature decreases from 1,073 ± 100 K down to 373 K, 30 % of the unreacted steam being condensed. Further cool-down from 373 K to 298 K is performed through pumped cooling water. Hydrogen is then compressed to 3 MPa in two steps and cooled down to 298 K after each step, a part of the heat being recovered to heat up the inlet gases. The inlet water enters the BoP at 288 K (T_{source}) and is 80 - 95 % vaporised by the heat recovery from the outlet gases and from the hydrogen compression. Further vaporisation and heat-up from 373 K to 1,073 K are ensured by an electrical heater. The model of the Balance of Plant is based on the following assumptions: pressure drop neglected; mass transfer dynamics neglected; the BoP power equals the power sum of the compressor, the cooling pump and the electric heater; electronic components neglected. The total system power (SOEC unit and Balance of Plant) is ranged between 807 kW and 1,346 kW, which corresponds to 60-100 % of the maximum power at the system level.

The system efficiency is calculated by considering the ratio between the Higher Heating Value (HHV) of the produced hydrogen and the HTEL system power (sum of the SOEC unit power and the BoP power). The simulated system efficiency equals 92 % vs. HHV in the reference case presented above, and is roughly constant within the power range. The next parts of this work are dedicated to defining control strategies which are able to extend significantly the power range without impacting on the system efficiency.

3. Results

3.1 Definition and evaluation of the constant air ratio strategy

Regulating the cell temperature by introducing air flow at the oxygen electrode has been studied at the cell and stack level in steady state. Indeed, (Udagawa et al., 2008) studied the case of an air flow rate proportional to the produced oxygen flow rate in order to minimise the thermal gradient both in the endothermic and in the exothermic modes. The air ratio corresponded to the ratio between the oxygen inlet flow rate (contained in the air flow), and the oxygen production rate. The operation in the endothermic mode was performed at an average current density of 0.5 A cm^{-2} and an inlet temperature of 1,123 K. The operating conditions with an air ratio of 0.4 led to an outlet temperature of 993 K, which was increased to 1,060 K and 1,086 K in the cases of an air ratio of 7 and 14. The operation in the exothermic mode was performed at an average current density of 0.7 A cm^{-2} and an inlet temperature of 923 K. The operating conditions with an air ratio of 0.4 led to an outlet temperature of 1,105 K, which was decreased to 1012 K and 985 K in the cases of an air ratio of 7 and 14. Since the cell length was 40 cm, using air flow enabled to decrease the thermal gradient across the cell from -3.25 K cm^{-1} to -1 K cm^{-1} in the presented endothermic case, and from 4.55 K cm^{-1} to 1.55 K cm^{-1} in the presented exothermic case.

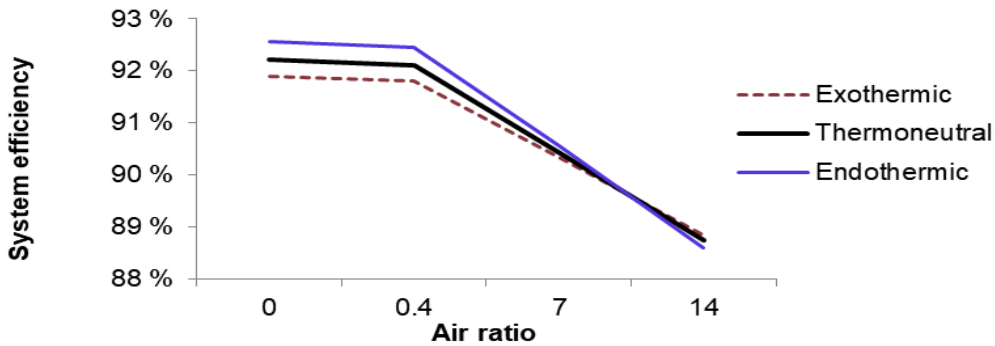

Figure 2: Impact of the air ratio (0; 0.4; 7; 14) on the system efficiency in three different modes

At the oxygen electrode (anode), it is technically feasible possible to inject no flow, since only steam at the hydrogen electrode (cathode) is required for the reaction. Sweeping the oxygen electrode with air flow is however common for safety reasons in SOEC testing and for the thermal management in SOFC systems. Results of (Udagawa et al., 2008) show that the higher the air ratio, the lower the temperature gradient along the cell at a fixed voltage. Nevertheless, the air ratio could have a non-negligible impact on the system efficiency because the air flow needs to be preheated up from 273 K to 1,073 K before being injected in the cells. In order to quantify this impact, it is necessary to study the whole system behavior operating in similar steady-state conditions as the stack modeled by (Udagawa et al., 2008). Thus we used the system model described in part 2. We implemented and studied the same parameters as (Udagawa et al., 2008) for the comparison to be relevant. The constant air ratio strategy has been simulated at the system level. Results have been studied in a sensitivity analysis at the system level, as shown in Figure 2. It has been found that increasing the air ratio from 0 to 14 implies a drop by 3.5 % of the system efficiency. The endothermic and exothermic modes correspond to applied powers for which the outlet temperature equals 973 K and 1,173 K respectively. With this control strategy, the system power range increases from 60 - 100 % (807-1,346 kW) to 22-100 % (464 - 2,137 kW). Detailed results are depicted in Table 1. The air ratio is therefore an effective control strategy in terms of thermal management, although the impact on the system efficiency is not negligible. It is therefore necessary to increase the ratio of the air without degrading the efficiency of the system whatever the mode of operation.

Table 1: Sensitivity analysis results: constant air ratio strategy. A - Endothermic mode: T_{out} = 973 K; B - Thermoneutral mode: T_{out} = 1,073; C - Exothermic mode: T_{out} = 1,173 K

	R_{air} =0 (reference case)			R_{air} =0.4			R_{air} =7			R_{air} =14		
	A	B	C	A	B	C	A	B	C	A	B	C
System efficiency (%$_{HHV}$)	92.56	92.21	91.88	92.46	92.10	91.80	90.55	90.43	90.33	88.59	88.74	88.84
H_2 production (g h^{-1} $cell^{-1}$)	1.90	2.49	3.14	1.95	2.58	3.29	1.57	2.74	4.12	1.04	2.76	4.82
Power range (kW_e)	60 %			59 %			38 %			22 %		
System power (kW_e)	807	1,064	1,346	829	1,106	1,411	683	1,196	1,796	464	1226	2,137
BoP heater (kW_e)	132	157	176	139	164	181	158	196	170	138	220	128
BoP pump (kW_e)	0.13	0.16	0.21	0.13	0.17	0.22	0.13	0.22	0.34	0.10	0.27	0.47
BoP compressor (kW_e)	42	55	70	43	58	73	35	61	92	23	61	107
SOEC module (kW_e)	633	852	1,101	647	884	1,157	490	939	1,534	471	1,245	2,170
Cell voltage (V)	1.255	1.287	1.319	1.250	1.287	1.324	1.173	1.287	1.402	1.092	1.287	1.484
Current density (A cm^{-2})	0.504	0.662	0.835	0.517	0.687	0.874	0.417	0.730	1.094	0.277	0.734	1.281

3.2 Definition and evaluation of the regulated air flow strategy

Since the control strategy consisting of maintaining a constant air ratio in the stack leads to a decreased system efficiency, this part aims at proposing an improvement of this control strategy via a regulation of the air flow rate. This control strategy consists in managing the temperature only outside the reference power range, where thermal gradients would be above ±10 K cm^{-1} without thermal management. The air flow is regulated based on the SOEC unit power (633 -1 ,073 kW). Hence, air flow is used only below 633 kW to maintain thermal gradients at the constant value of -10 K cm^{-1} (constant cell temperature of 1,023 K). Below 633 kW, the air flow rate is regulated in order to match the electrolyser thermal needs and to maximise the system efficiency.

The corresponding air flow rate is calculated for different powers in the range 0-633 kW using a dichotomy method based on the energy balance in steady state at the operating temperature of 1,023 K, as given in Eq(1). In this equation, P_{cell} is the electrical power applied to each cell, $P_{reaction}$ represents both the electrical and thermal powers required by the reaction, P_{gas_in} is the thermal power brought by the inlet gases, P_{gas_out} is the thermal power leaving the cell through the outlet gases, P_{unit_loss} represent the thermal losses of the entire unit through the thermal insulation and N_{cell} is the total number of cells.

$$P_{cell} + P_{reaction} + P_{gas\_in} + P_{gas\_out} + \frac{P_{unit\_loss}}{N_{cell}} = 0 \quad (1)$$

Figure 3 shows the calculated air flow rate which is required below 633 kW (57 %) electrolyser unit power load to maintain the system at an operating temperature of 1,023 K. Three observations can be made from these results. First, it can be noticed that the required air molar flow rate at the oxygen electrode (anode) is much higher than the steam molar flow rate at the hydrogen electrode (cathode). Second, the curve slope of the required air molar flow rate can be explained by the fact that the thermal balance of the electrolyser unit is driven both by the thermal power absorbed by the electrolysis reaction and by the thermal power dissipated by the Joule Effect. Because the electrolysis reaction needs are proportional with the current, whereas the Joule Effect is proportional with the square of the current, their difference has a negative minimum of 36 kW at 28.5 % load. This missing thermal power is provided by the air flow. Third, it can be noticed that the air flow decreases promptly at 57 % load. This is due to the amplified effect of the oxygen average partial pressure on the cell voltage. Below 57 % load, the produced oxygen flow is much lower than the air sweep at the anode, thus the oxygen average partial pressure is slightly above 21 %. At loads above 57 %, no air flow is injected, thus the oxygen average partial pressure is 100 %. At 57 % load, the air flow decreases, which increases the oxygen average partial pressure, which in turns increases the cell voltage and decreases the current density at constant power. The higher cell voltage leads to higher Joule heating in the cell, thus to a lower air flow. The air flow decrease is thus amplified by the effect of the oxygen average partial pressure on the cell voltage.

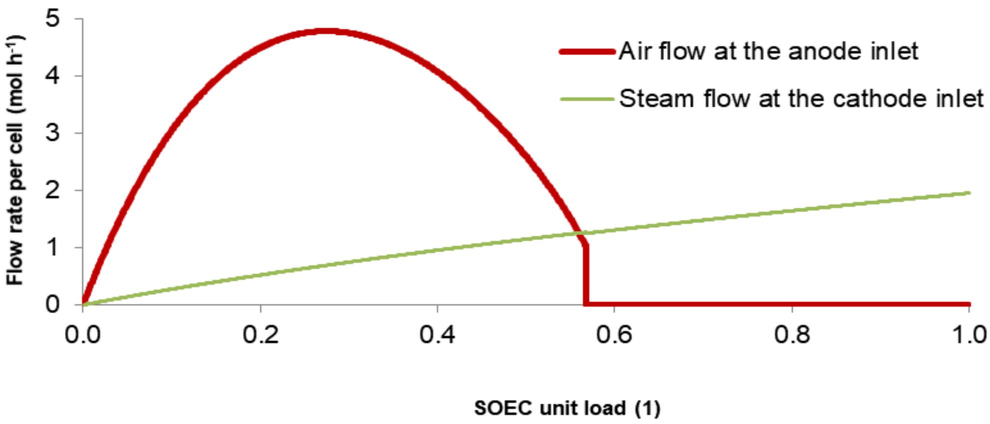

Figure 3: Inlet regulated air and steam flow rates as a function of the electrolyser unit power load

Introducing air at the inlet of the cell implies the use of air heat exchangers in the Balance of Plant and implies additional investment costs. Moreover, the air flow rate increase has an impact on the heating requirements in the Balance of Plant. This part aims to quantify the impact on the system efficiency as a function of the operating load. Table 2 details the system power distribution at 28.5 % electrolyser unit load, for which the air flow is maximum. Although the inlet air flow is preheated by the outlet gases, the additional quantity of gases which has to be heated up leads to a significant BoP heater consumption increase. Indeed, the BoP heater power increases from 16 % of the system power (807 kW) at 57 % SOEC unit power load (endothermic power in the reference case), without control strategy, to 29 % of the system power (481 kW) at 28.5 % load. As a consequence, the system efficiency decreases from 92.6 % to 88.7 %.

Table 2: Power distribution at 28.5 % (regulated air flow) and at 57 % of the maximum electrolyser unit load

	Power (kW)	Power distribution	Efficiency (vs. HHV)	Power (kW)	Power distribution	Efficiency (vs. HHV)
System (total)	481	100 %	88.67 %	807	100 %	92.56 %
Electrolysis reaction	317	66 %	134.90 %	633	78 %	118.00 %
BoP electric heater	140	29 %	-	132	16 %	-
BoP compressor	24	5 %	-	42	5 %	-
BoP pump	0.10	0 %	-	0.13	0 %	-

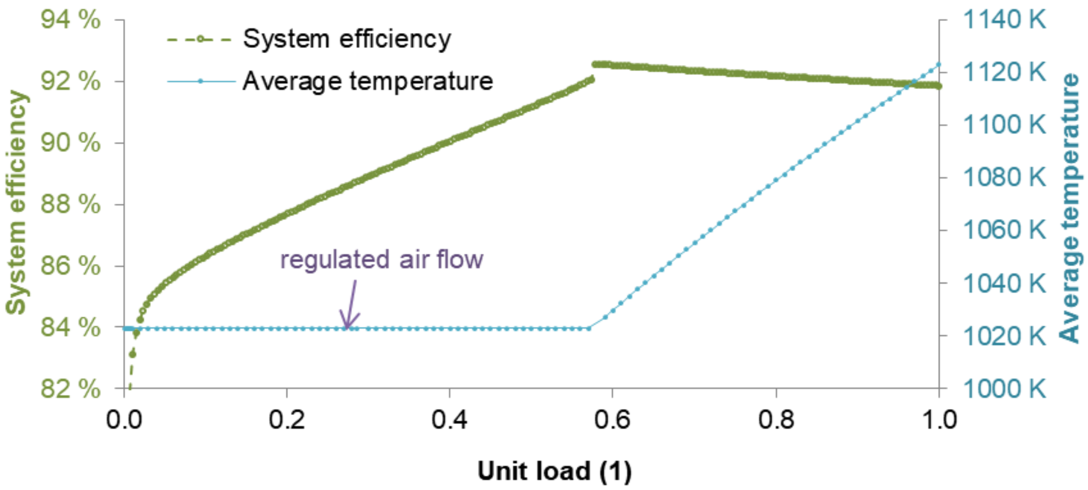

Figure 4: System efficiency and average temperature as a function of the system load in steady state, with a regulated air flow

For the whole range 1-100 %, simulations found that the system efficiency is significantly impacted by this control strategy since the decrease is inversely proportional to the power from 92.6 % at 57 % load down to 85.4 % at 5 % load (Figure 4). Below 3 % load, the heat losses through the unit insulation become significant in comparison to the cell power, thus a drop in the system efficiency.

4. Conclusions

In order to lower thermal gradients in the cells and the associated limited power range of 60 - 100 %, two control strategies, based on the use of an air flow at the anode, are proposed and analysed in detail. The first strategy, consisting of a constant ratio between the inlet air sweep and the produced oxygen molar flow rates, leads to an extended power range of up to 22 - 100 % for an air ratio of 14 and a system efficiency drop by 3.5 %, independently from the power applied due to the need for heating up the inlet air to 1,073 K. A second control strategy, consisting of an air flow rate being adapted to the thermal needs of the reaction, is proposed. The regulated air flow enables to extend the power range to 1 - 100 % and has an impact on the system efficiency only below 60 % load. As a conclusion, regulating the air flow as a function of the applied power enables the HTEL system to be very flexible in terms of power range, while maintaining the system efficiency above the one of conventional low temperature electrolysers. However, both control strategies imply additional investments, in particular in larger heat exchangers.

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