A novel control strategy to neutralize internal heat source within solid oxide electrolysis cell (SOEC) under variable solar power conditions

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ABSTRACT

The integration of solid oxide electrolysis cells (SOECs) with a photovoltaic (PV) system presents a viable method of storing variable solar energy through the production of green hydrogen. To ensure the safety and longevity of SOEC amidst dramatic fluctuations in solar power, control strategies are needed to limit temperature gradients and rates of temperature change within the cell. Recognizing that the supply of the reactant influences the current, a novel control strategy is developed to modulate internal heat source in the SOEC by adjusting the steam flow rate. The effectiveness of this strategy is assessed through numerical simulations conducted on a coupled PV-SOEC system using actual solar irradiance data. The irradiance data are recorded at two-second intervals to account for rapid changes in solar exposure. The results indicate that conventional control strategies, which increase airflow rates, are inadequate in effectively suppressing the rate of temperature variation in scenarios of drastic changes in solar power. In contrast, our proposed strategy demonstrates precise management of SOEC internal heat generation, thus reducing the temperature gradient and variation within the cell to less than 5 K cm⁻¹ and 1 K min⁻¹, respectively, and maintaining a high electricity-to-hydrogen conversion efficiency of 94.9%.

1. Introduction

Renewable energy sources, especially solar and wind, are increasing their significance in the energy structure of today [1]. Renewable energy is expected to account for 80% of the new power capacity by 2030, with solar PV alone contributing more than 50% [2]. However, the grid integration of solar and wind power still faces challenges. For instance, the intermittency and variability of power generation can introduce great difficulties in the system operation and management (e.g., a mismatch between generation and load). The uncertainty in power generation necessitates a time-spanning storage system, where green hydrogen emerges as a potential solution to these challenges, serving as a promising seasonal energy storage medium. Due to its long-term chemical stability, transportability, and carbon-free energy conversion [3], hydrogen is increasingly viewed as a viable option for the storage of renewable energy. Consequently, power-to-hydrogen systems have received significant attention in recent years [4].

The SOEC is a promising high-temperature electrolysis device for hydrogen production, because of its high efficiency and operational flexibility. Notably, the SOEC can switch to a solid oxide fuel cell (SOFC) mode of power generation and can accommodate various types of fuels [5,6]. The integration of a PV system with SOEC offers an effective approach to store solar energy in the form of chemical energy contained in hydrogen. PV panels harness solar energy to generate electrical power, which is subsequently utilized by the SOEC for water splitting and hydrogen production. However, the intermittent nature of solar power is a challenge to the thermal management of SOEC. During SOEC operation, temperature gradients can induce thermal stress [7], potentially leading to delamination and cracks in the electrolyte and electrodes [8]. Furthermore, the rapid rate of variation in temperature can result in thermal fatigue [9] and undermine the durability of SOEC.

Numerous studies have investigated the dynamic thermal management of SOEC and SOFC in various scenarios, such as operations under fluctuating wind [9,10] and solar power [11], the switch between fuel cell and electrolyzer [12,13], and load changes [14–16]. Several parameters have been found to be effective for temperature control of SOEC and SOFC, including air flow rate [13–15,17–19], steam/fuel flow rate [19–21], inlet temperature [22,23], and inlet gas compositions [8,24–26]. For example, Wang et al. [9] modulated

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To fill the research gap, we introduce a novel strategy for controlling the internal heat source in SOEC under fluctuating solar power. This is
achieved by modulating the steam supply rate according to real-time solar irradiance level. The control of internal heat source represents a novel direction in SOEC thermal management research, diverging from previous studies that primarily focused on mitigating temperature fluctuations through external interventions, such as increasing airflow. The effectiveness of the proposed control strategy is evaluated using a three-dimensional transient numerical model of SOEC. Besides, we notice that the renewable power data utilized in previous studies are often recorded with low temporal resolution, such as 5 min [26] or 15 min [9,12]. The large time interval in solar data, however, overlooks the highly dynamic nature of renewable power sources. For instance, the solar irradiance can drop from 1000 W m\(^{-2}\) to 300 W m\(^{-2}\) within several seconds due to cloud attenuation. Thus, using solar data with low temporal resolutions could fail to capture these abrupt changes in irradiance, thereby potentially skewing the evaluation of PV-SOEC performance. To address this gap, we captured solar irradiance data at a significantly smaller time interval — every 2 s. This high-resolution data was then used to assess the effectiveness of our proposed control strategy.

In the following, Section 2 introduces the methodologies employed in this study, including data acquisition and numerical models; Section 3 provides comprehensive derivation and discussion of the proposed control strategy. Overall conclusion follows in Section 4.

2. Methods

As shown in Fig. 1a, this study aims to control the temperature of SOEC under fluctuating solar power supply. To numerically evaluate the effectiveness of our control strategy, we simulate an integrated PV-SOEC system as a case study. The PV panels convert the solar irradiance into electrical power, which is subsequently used in SOEC to split water to produce hydrogen. Note that here we assume the PV panels to be placed horizontally, so they will utilize global horizontal irradiance (GHI) instead of plane-of-array irradiance. In our numerical model, the measured solar irradiance is converted into solar power data through a PV model. The solar power is then applied in our SOEC model for numerical simulation. The proposed control strategy is to dynamically adjust the SOEC steam flow rate in response to solar power, ensuring the thermal safety of the SOEC.

2.1. Solar irradiance measurement

The GHI is measured using a pyranometer with a field of view of 180° (CMP10 produced by Kipp&Zonen, ISO 9060 spectrally flat Class A), installed on the rooftop located on the campus of The Hong Kong Polytechnic University (22.3046°N, 114.1796°E). The GHI data is collected every 2 s to generate a high-temporal-resolution dataset. In addition, to capture the cloud field of the sky, sky images are captured every minute using a 180° fisheye camera (FE9380-HV produced by VIVOTEK Corporation).

2.2. PV model

The PV model utilized in our study is adapted from Refs. [29,33]. As depicted in Fig. 1a, the PV system under investigation comprises two monocristalline PV panels, each with a nominal power rating of 270 W. The number of PV panels is designed based on the operating range of the SOEC stack, which will be detailed in Section 2.4. An equivalent diode circuit model [29], shown in Fig. 1c, is utilized to calculate the operating current and voltage of a PV panel. This model operates under the assumption that the series internal resistance \(R_s\) is nearly zero and the shunt resistance \(R_{sh}\) approaches infinity. The mathematical model for the two-panel system can be expressed as

\[
I_{PV} = n_{PV} \left\{ I_0 - I_0 \exp \left( \frac{qU_{PV}}{mK_B T_{PV} n_{PV} \mu} \right) \right\},
\]

where, \(n_{PV} = 2\) represents the number of PV panels connected in parallel, \(n_{PV} = 60\) denotes the number of solar cells connected in series within a single PV panel. \(q = 1.60 \times 10^{-19}\) C is the elementary charge. \(m = 1\) is the ideal factor of the diode. \(K_B = 1.38 \times 10^{-23}\) J K\(^{-1}\) is the Boltzmann constant. The photo-generated current \(I_{ph}\) is calculated as

\[
I_{ph} = \frac{G}{G_{PV,ref}} \left[ I_{ph,ref} + \mu (T_{PV} - T_{PV,ref}) \right].
\]

where, \(G_{PV,ref} = 1000\) W m\(^{-2}\) is the reference solar radiation. \(T_{PV,ref} = 298\) K is the reference temperature. \(I_{ph,ref} = 9.43\) A is the photo-generated current under the reference solar irradiance. \(\mu = 0.00047\) A K\(^{-1}\) is the short-circuit current temperature coefficient. The diode reverse saturation current \(I_0\) is calculated as

\[
I_0 = I_{0,ref} \left( \frac{T_{PV}}{T_{PV,ref}} \right)^3 \exp \left[ \frac{qE_g}{k_B} \left( \frac{1}{T_{PV,ref}} - \frac{1}{T_{PV}} \right) \right].
\]

where, \(I_{0,ref} = 1.25 \times 10^{-9}\) A is the diode reverse saturation current in the reference state. The band gap \(E_g\) of the PV cell is calculated as [29]

\[
E_g = 1.17 - \frac{4.73 \times 10^{-4} T_{PV}^2}{T_{PV} + 636.45}.
\]

Combining Eqs. (1)–(4), it is convenient to acquire the current–voltage curve of the PV system given a solar irradiance value \(G\), as shown in Fig. 1e. The maximum power point (MPP) tracker can be used to operate the PV system at its MPP. When \(\eta_{PV},\ \phi_{PV}\) and \(T_{PV}\) of the PV system are held constant at 25 °C, the maximum power \(P_{MPP, PV}\) can be determined from Fig. 1e and the following equation

\[
P_{MPP, PV} = I_{MPP, PV} U_{MPP, PV}.
\]

The relationship between the maximum power \(P_{MPP, PV}\) and solar irradiance \(G\) can be extracted from Fig. 1e, which is then regressed as follows to implement into our numerical model,

\[
P_{PV} = 3.4737 \times 10^{-5} \cdot G^2 + 0.5106 \cdot G - 3.4792.
\]

2.3. SOEC single-channel model

Fig. 1d shows the geometry and working principle of SOEC. The electron conductors within SOEC include interconnects, Anode Diffusion Layer (ADL), Anode Functional Layer (AFL), Cathode Functional Layer (CFL), and Cathode Diffusion Layer (CDL). The ADL, AFL, CDL, and CFL are porous mediums for gas transport. At high temperatures, oxygen ions can travel within the AFL, CFL, and solid oxide electrolyte. In functional layers where electrons, ions, and gases gather, \(H_2O\) is split into hydrogen and oxygen through electrochemical reactions.

To simulate the performance of the SOEC stack, we have developed a 3-D single-channel Computational Fluid Dynamics (CFD) model, ensuring a balance between computational cost and accuracy [34,35]. The 3D CFD model, shown in Fig. 1d, is an established model developed and validated in our previous work [31]. This model was built using Ansys Fluent R18.1, a commercial CFD software.

The model solves a coupled set of conservation equations for momentum, mass of species, energy, electronic charge, and ionic charge. These solutions yield transient results for velocity, mass fractions of species, temperature, and electrical and ionic potentials within SOEC. Our model [31] incorporates the following theoretical principles:

- Fick’s Law is employed to model gas diffusion within fluid channels. This process accounts for variations in temperature and pressure. In porous media, Extended Fick’s law is used to consider the influence of microstructure on gas diffusivity.

- Electrochemical reactions are modeled using the Butler–Volmer equation.
The ideal gas law is utilized for the calculation of fluid densities. Properties such as viscosity, specific heat and thermal conductivity, under ambient pressure, are sourced from the NIST database [36] and integrated into the model using piecewise linear interpolation.

For solid materials, properties such as ionic, electronic, and thermal conductivities are assumed to be constant, except for the temperature-dependent ionic conductivity of the electrolyte. The effective properties of porous media are computed by volumetric averaging of the fluid and solid properties.

In this work, the boundary conditions (BC) used are presented in Table 1. The electrical BC is modified to allow the single-channel SOEC model to represent the coupling between the PV system and the SOEC stack. The detailed coupling method is explained in the following section.

2.4. Indirect coupling between PV and SOEC

The coupling between PV and electrolyzer can be classified into direct and indirect coupling [37]. In the case of direct coupling, the electrolyzer is directly linked to the photovoltaic system, implying that both systems operate at identical current and voltage. However, it poses a challenge to maintain their operating point proximate to the MPP of the PV, thereby reducing the efficiency of PV and the coupled system. To track the MPP of PV, the indirectly coupled PV-electrolyzer is integrated with an MPP tracker and a DC/DC converter [38], as shown in Figs. 1a and e. In this way, the PV can be operated at MPP under various conditions, and the power transmitted to the electrolyzer approximates the maximum power output of the PV. Therefore, in this work, the indirect coupling approach is selected.

The PV-SOEC system, as shown in Fig. 1a, includes 2 PV panels connected in parallel (\(n_{PV} = 2\)) and an SOEC stack composed of 23 SOEC units connected in series (\(n_{SOEC} = 23\)). As illustrated in Fig. 1e, the numbers of PV panels and SOEC units are tuned to ensure that the SOEC system approximates 90% of its maximum current when the PV is operating under \(G = 1000 W m^{-2}\). The maximum power output of the PV system is configured to equal the power input of the SOEC system, \(P_{SOEC,stack} = P_{MPP, PV}\).

In Fig. 1e, the steady-state operating point of the PV-SOEC system is depicted as the intersection between the SOEC current–voltage curve and the iso-power line of the PV system.

In the SOEC stack, each individual SOEC unit consists of five parallel channels, with a total active area of 10 cm² (\(A_{SOEC, unit}^{act} = 10 cm^2\)). That said, the SOEC single-channel model has an active area of 2 cm² (\(A_{SOEC, Sch}^{act} = 2 cm^2\)). To apply the electrical conditions from the stack level to the single-channel model, the following equation is used,

\[
P_{SOEC,stack} = P_{MPP, PV}^{*}.
\]

In Fig. 1e, the steady-state operating point of the PV-SOEC system is depicted as the intersection between the SOEC current–voltage curve and the iso-power line of the PV system.

In the SOEC stack, each individual SOEC unit consists of five parallel channels, with a total active area of 10 cm² (\(A_{SOEC, unit}^{act} = 10 cm^2\)). That said, the SOEC single-channel model has an active area of 2 cm² (\(A_{SOEC, Sch}^{act} = 2 cm^2\)). To apply the electrical conditions from the stack level to the single-channel model, the following equation is used,
Then, the current density applied on the SOEC single-channel model can be computed as

\[
\iota_{\text{SOEC}, \text{SCh}} = \frac{I_{\text{SOEC}, \text{SCh}}}{\Delta \mathcal{A}_{\text{SCh}}}.
\]

Combing Eqs. (6)–(9), the electrical BC \((\iota_{\text{SOEC}, \text{SCh}})\) of the SOEC model listed in Table 1 is determined. This BC is incorporated in Ansys Fluent by User Defined Function (UDF).

The electrical efficiency of the SOEC is calculated as [3,39],

\[
\eta_{\text{ele}} = \frac{\Delta G_{f}^{0} \cdot (\iota_{\text{SOEC}, \text{unit}} / n_{\text{F}}} {U_{\text{SOEC, \text{unit}}}} = \frac{\Delta G_{f}^{0} \cdot (\iota_{\text{SOEC}, \text{unit}} / n_{\text{F}}} {U_{\text{SOEC, \text{unit}}}},
\]

where, \(\Delta G_{f}^{0} = -237.14 \times 10^{3} \text{J mol}^{-1}\) is the standard Gibbs free energy change of water formation, \(n_{\text{F}}\) is the number of participating electrons for hydrogen production, \(F = 96485 \text{C mol}^{-1}\) is the Faraday constant, \(U_{\text{SOEC, \text{unit}}} = 1.229 \text{V}\) is the equilibrium potential at standard condition [39].

The hydrogen production rate is,

\[
\dot{Q}_{\text{H2}} = \frac{3600 \cdot \iota_{\text{SOEC, \text{SCh}}} \cdot M_{\text{H2}}}{nF_{\text{H2}}},
\]

where, \(\dot{Q}_{\text{H2}}\) is the hydrogen production rate with unit \(\text{L h}^{-1}\), \(M_{\text{H2}} = 0.002 \text{kg mol}^{-1}\) is the molar mass of hydrogen, \(\iota_{\text{SOEC, \text{SCh}}} = 89.88 \text{kg L}^{-1}\) is the hydrogen density under the standard condition.

2.5. Control strategies of SOEC

Wang et al. [9] suggested that keeping the magnitudes of temperature gradient and temperature variation rate below 5 K cm\(^{-1}\) and 1 K min\(^{-1}\) respectively could reduce the failure probability of SOEC. In this study, the average temperature gradient is defined as

\[
\text{Temperature gradient} = \frac{T_{\text{out}} - T_{\text{in}}}{L_{\text{SCh}}},
\]

where, \(T_{\text{out}}\) and \(T_{\text{in}}\) are the temperatures at the outlet and inlet of channel, and \(L_{\text{SCh}}\) denotes the length of the cell channel. Considering that the extreme temperature values within the SOEC typically appear near the inlet and outlet in the co-flow configuration [8] and thermally insulated boundary conditions, as shown in Fig. 3, the temperature gradient defined by Eq. (12) effectively captures the stream-wise average temperature gradient across the SOEC.

The temperature variation rate is defined as

\[
\text{Temperature variation rate} = \frac{T_{\text{ave}} - T_{\text{ave}}-1}{\Delta t}.
\]

Table 1

<table>
<thead>
<tr>
<th>Inlet(^{a})</th>
<th>Outlet</th>
<th>(x = 0)</th>
<th>(z = 0)</th>
<th>(z/\Delta z = 1)</th>
<th>Other surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>Base: (V_{\text{in}}^{\text{ave}} = 2), (V_{\text{in}}^{\text{fuel}} = 2)</td>
<td>(p_{\text{ave}} = 0)</td>
<td>Zero flux</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Strategy A: (V_{\text{in}}^{\text{ave}} = 10), (V_{\text{in}}^{\text{fuel}} = 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy B: (V_{\text{in}}^{\text{ave}} = 2), (V_{\text{in}}^{\text{fuel}} = \text{Eq. (14)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strategy C: (V_{\text{in}}^{\text{ave}} = 2), (V_{\text{in}}^{\text{fuel}} = \text{Eq. (15)})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>(T_{\text{in}} = 1073) K</td>
<td>O.B.</td>
<td>Zero flux</td>
<td>Zero flux</td>
<td>Zero flux</td>
</tr>
<tr>
<td>Species</td>
<td>(X_{\text{H}<em>2}^{\text{in}} = 0.2), (X</em>{\text{H}<em>2}^{\text{SCh}} = 0.8), (X</em>{\text{H}<em>2}^{\text{fuel}} = 0.9), (X</em>{\text{H}_2}^{\text{out}} = 0.1)</td>
<td>O.B.</td>
<td>Zero flux</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Electrical</td>
<td>N.A.</td>
<td>Zero flux</td>
<td>(f_{\text{ave}} = 0)</td>
<td>(\iota_{\text{SOEC, SCh}})</td>
<td>Zero flux</td>
</tr>
</tbody>
</table>

\(^{a}\) The cell encompasses two inlets: the fuel channel inlet and the air channel inlet. The fuel inlet solely comprises \(\text{H}_2\) and \(\text{H}_2\), while the air inlet only comprises \(\text{O}_2\) and \(\text{N}_2\). Controlling SOEC operation is achieved by manipulating the inlet velocity (m s\(^{-1}\)).

\(^{b}\) The effective operating strategies for temperature control should be based on the fast-response factors such as current and gas flow rates. 

Before delving into our heat source-based control strategies, we conducted a simulation to explain the transient characteristics of the PV-SOEC system in response to a sudden change in solar irradiance. The transient characteristics will provide guidance for control strategies.

In an indirectly coupled PV-SOEC system, fluctuations in solar irradiance can affect the power supply to the SOEC. These changes in the electrical state can, in turn, alter the heat and mass fields within the SOEC. In simulation, GHI undergoes a rapid ramp-down, characterized as a linear decrease from 1000 to 200 W m\(^{-2}\) in 1 ms, and hold constant at 200 W m\(^{-2}\). The simulation adopted an adaptive time-step size to accurately capture the responses of SOEC [31]. The BCs of the SOEC are presented as the base case in Table 1. The animation of electrical responses of the coupled system is provided in the Supplementary Video S1. Fig. 2 depicts the electrical, gaseous, and thermal responses of SOEC to the sudden change in irradiance. Although electrical parameters (including current, voltage, and power) can adapt quickly to the GHI rampdown, the gaseous response is slower, persisting for approximately 0.1 s. The slowest response is that of temperature, which takes thousands of seconds to reach a new steady state. These differential speeds of electrical, gaseous, and thermal responses were previously discussed in our previous studies [31,32]. In light of the response speeds, fast response factors, such as current and gas flow rates, can be employed to control slow response factors, such as temperature. To adapt to highly fluctuating solar power, effective operating strategies for temperature control should be based on the fast-response factors such as current and gas flow rates.
The temperature difference between inlet and outlet can be further heat capacity, and volumetric flow rate of gases through the SOEC.

\[ \Delta T = \frac{S_0}{\dot{\rho}_{ave}}. \]  

Eq. (17) indicates the two general control strategies to reduce temperature difference \( \Delta T_{in-out} \): one is to increase \( \dot{V}_{ave} \), and the other is to reduce \( S_0 \). The conventional control strategy based on air flow rate is equivalent to the adjustment of \( \dot{V}_{ave} \). When \( S_0 \) is high, adjusting \( \dot{V}_{ave} \) shows a reduced performance to constrain \( \Delta T_{in-out} \) within SOEC due to the low specific heat capacity \( c_p \) of air [9]. To effectively constrain \( \Delta T_{in-out} \), it is important to develop a control strategy that can control the heat source \( S_H \) in SOEC.

3.2. Limitations of conventional control strategies based on air flow rate

As discussed in Section 3.1, gas flow rate is a factor that has sufficiently fast response dynamics for the temperature control of SOEC. The strategy of controlling air flow rate has been widely adopted in the literature [13–15,17,18]. However, this control strategy shows limited performance for SOEC temperature control under severe power fluctuations [9]. In this section, we use steady simulations to analyze the limitations of controlling air flow rate and point out the importance of controlling the internal heat source.

Fig. 3c–f illustrate that, as the air velocity increases from 2 to 30 m s\(^{-1}\), the values of the total heat sources show a slight difference, while the overall temperature of the SOEC increases significantly and the temperature gradient decreases. These observations, on the one hand, suggest that increasing air flow rate is an effective strategy for reducing the temperature gradient. On the other hand, the thermal effect of increasing the air flow rate is similar to the 'dilution' of the endothermic effect, without drastically altering the internal heat source within the SOEC. However, when the magnitude of the heat source is large, a considerably high air flow rate is needed to dilute the heat source to ensure an acceptable temperature gradient [9]. This, in turn, necessitates substantial compressor work and rigorous gas-tight sealing of the SOEC.

To better understand temperature control strategies, the SOEC can be considered as a control volume, as shown in Fig. 3a. Steam and air flows represent heat flux across the boundaries of the control volume. Within the control volume, electrochemical reactions and Joule heating function as an internal heat source \( S_H \). Upon reaching a thermal steady state within the control volume, the heat source is equal to the enthalpy difference between the heat fluxes

\[ 0 = H_0 - H + S_H = \dot{\rho}_{ave} \dot{V}_{ave} (T_{in} - T_{out}) + S_H, \]  

where \( H_0 \) and \( H \) denote the enthalpy flow rates at the inlet and outlet, respectively. \( \dot{\rho}_{ave} \) and \( \dot{V}_{ave} \) denote the average density, specific heat capacity, and volumetric flow rate of gases through the SOEC. The temperature difference between inlet and outlet can be further expressed as

\[ \Delta T_{in-out} = T_{out} - T_{in} = \frac{S_0}{\dot{\rho}_{ave}}. \]

The water-splitting reaction acquires energy from the electrical power source \( \Delta G/|nF| \) and the thermal environment \( (T|\Delta S_|/|nF|) \). Besides, the excess electrical power \( (\eta_{electric}) \) input to SOEC is dissipated as heat, where \( \eta_{total} \) signifies the total overpotential that depends on electrochemical kinetics, Ohmic resistances, and the operational conditions of SOEC. By examining the thermal energy balance, the total heat source \( S_H \) of SOEC can be determined,

\[ S_H = I_{\eta_{total}} - I T|\Delta S_|/|nF|. \]

The sign and magnitude of \( S_H \) determine the thermal behavior of the SOEC. From Eq. (19) and Fig. 4, we identify four variables that can be adjusted to control the magnitude of the heat source:

- **Reaction pathway.** SOEC can accommodate different fuels [5]. By supplying different reactants, such as steam and carbon dioxide mixture, the \( \Delta H \) and \( \Delta S \) of reaction within the SOEC can be regulated [20].
- **Temperature** [23,26]. Temperature has wide-ranging effects on factors such as the Ohmic resistance of the solid electrolyte, current, voltage, and enthalpy change. However, as discussed in Section 3.1, the temperature responds more slowly than gas and...
Fig. 3. Heat transfer within SOEC. a Energy conservation of the control volume. b–g Distributions of temperature (left panel) and heat source (right panel) in steady state with different solar irradiance ($G$ [W m$^{-2}$]) and inlet velocities of air and fuel channels ($V_{in,air}$, $V_{in,fuel}$ [m s$^{-1}$]). The length scales of SOEC have been adjusted in this figure for better visualization.
electricity [22,31]. Thus, it might be challenging to regulate the heat source by only manipulating the temperature field, especially under conditions of highly fluctuating power.

- Current $I$. The change in current will vary the overpotential $\eta_{\text{total}}$. The net current flowing through the system can be controlled by adjusting the series and parallel connections of the SOEC units during operation [41,42]. This, in turn, allows for the regulation of the heat source.

- Inlet flow rate of the reactant. The maximum achievable current is limited by the supply of reactants in SOEC. Thus, we can control the heat source by adjusting the flow rate of the reactant. The limiting current ($I_{\text{lim}}$) is presented as

$$I \leq I_{\text{lim}} = \frac{nF \rho_0 \Delta H_{\text{f}}}{R T_{\text{f}}}.$$ (20)

where, $A_{\text{ch}} = 10^{-6}$ m$^2$ is the cross area of fluid channel, $R = 8.314$ J mol$^{-1}$ K$^{-1}$ is the ideal gas constant.

Considering the applicability of control strategies and the fast-response dynamics of gases (Section 3.1), we propose to only adjust the inlet steam velocity in the fuel channel ($V_{\text{fuel}}$) to continuously neutralize the heat source within the SOEC under varying power supply.

3.3.2. Theoretical feasibility of thermoneutral control strategy

Theoretically, by adjusting $V_{\text{fuel}}$, the SOEC can be maintained at thermal neutrality for high thermal uniformity. Based on Eq. (19), SOEC achieves thermal neutrality ($\eta_{\text{f}} = 0$) when

$$\eta_{\text{total}} = \frac{T}{nF} \Delta S_{\text{f}}.$$ (21)

Then, based on Fig. 4, the theoretical electrical power required to maintain SOEC at thermal neutrality can be expressed as

$$P_{\text{theo, SOEC}} = I \frac{\Delta G}{nF} + I \eta_{\text{total}} = I \frac{\Delta G}{nF} + I \frac{T}{nF} \Delta S_{\text{f}} = I \frac{\Delta H_{\text{f}}}{nF} = I U_{\text{theo, TN}}.$$ (22)

Consequently, the theoretical thermoneutral voltage $U_{\text{theo, TN}}$ for the water-splitting reaction [43] is derived as

$$U_{\text{theo, TN}} = \frac{\Delta H_{\text{f}}}{nF}.$$ (23)

According to the NIST database [36], at the ambient pressure and the temperature of 1073 K, the values of $\Delta H_{\text{f}}$ and $U_{\text{theo, TN}}$ for water are $246.4$ kJ mol$^{-1}$ and $1.28$ V, respectively.

To theoretically derive the thermoneutral control strategy, a high conversion rate of reactant H$_2$O is assumed at the thermal neutrality of SOEC and hence the current approximates the limiting current,

$$I \approx I_{\text{lim}}.$$ (24)

Combining Eqs. (20)–(24), the thermoneutral control strategy based on $V_{\text{fuel}}$ is theoretically derived,

$$V_{\text{fuel}} = \frac{R T_{\text{f}}}{nF \rho_0 \Delta H_{\text{f}} + \Delta S_{\text{f}} I_{\text{lim}}} \rho_{\text{f}}.$$ (25)

Given the values of $T_{\text{f}}$, $\Delta H_{\text{f}}$, and $\rho_0$ in Table 1, Eq. (25) can be written as a linear formula,

$$V_{\text{fuel}} = 0.3961 \cdot \rho_{\text{f}}.$$ (26)

3.3.3. Acquisition of heat source-based control strategies

Eq. (25) determines the theoretical feasibility of neutralizing the heat source within the SOEC by adjusting $V_{\text{fuel}}$ under different power inputs. However, the theoretical derivation is based on assumptions such as $\eta_{\text{f}} = 0$. Thus, $V_{\text{fuel}}$ calculated from Eq. (25) cannot exactly lead to the thermal neutrality of SOEC in reality, but gives the initial guess of the actual $V_{\text{fuel}}$ under the initial guess, the $V_{\text{fuel}}$ to achieve thermal neutrality ($\Delta T_{\text{in, out}} = 0$, $\eta_{\text{f}} = 0$) for different GHI levels is inferred by performing a number of steady state numerical simulations of the PV-SOEC system, as shown in Fig. 5(a).

3.4. Controlling heat source in SOEC under fluctuating solar conditions

Effectiveness of temperature control

Fig. 6 shows the comparison of four different operating strategies for the SOEC under fluctuating solar irradiance. The one-hour GHI data with a temporal resolution of 2 s collected in Hong Kong from 11:59:10 on August 30th, 2023, serve as input for the coupled PV-SOEC model. Transient simulations were performed with a constant timestep of 2 s. The four operating strategies applied on the SOEC are detailed in Table 1. The base case refers to a scenario with constant operating parameters. In Strategy A, the air flow rate is increased to five times that of the base case. Strategies B and C manipulate the steam operating parameters. In Strategy A, the air flow rate is increased to five times that of the base case. Strategies B and C manipulate the steam operating parameters.
within the hour. The corresponding functions in the PV power are presented in Fig. 6b. As shown in Fig. 6c, the oscillating solar irradiance induces a temperature gradient within the SOEC in the base case. This gradient exceeds the recommended limit of 5 K cm\(^{-1}\) \([9,21]\) during periods of high solar variability. For Strategy A, increasing the air flow rate can reduce the temperature gradient to below the suggested limit. For Strategy B, by manipulating the steam velocity according to solar power, the temperature is regulated towards thermal neutrality, and the temperature gradient is nearly eliminated. Strategy C also successfully maintains the SOEC in a slightly endothermic state with a safe temperature gradient of around -3 K cm\(^{-1}\).

Fig. 6d compares the variation rates of the average SOEC temperature in the four cases. The temperature variation rates in the base case and Strategy A are heavily influenced by GHI fluctuations and frequently exceed the recommended limit of 1 K min\(^{-1}\) \([9]\). These rates even exceed 5 K min\(^{-1}\) at certain times, such as at 12:07, 12:15, and 12:28. Such high temperature variation rates can induce thermal fatigue and increase the likelihood of SOEC failure. For Strategy B, the temperature variation rate exceeds 1 K min\(^{-1}\) within the initial 7 min due to an overshoot of the heat source, as shown in Fig. 6e. Afterwards, the SOEC operates safely and stably within the limit. In general, in Strategies B and C, the control of the steam velocity successfully reduces the rate of temperature variation to below the suggested limit of 1 K min\(^{-1}\).

The effectiveness of Strategies B and C is demonstrated by Fig. 6f, which compares the total heat sources within the SOEC. For the base case, the heat source within the SOEC is highly sensitive to fluctuating solar power. Large-amplitude variations in the heat source lead to rapid temperature changes. Strategy A is unable to maintain the rate of temperature change within the recommended limits by merely increasing the air flow rate. In contrast, Strategies B and C achieve success in managing the heat source by adjusting the steam flow rate of SOEC. On the one hand, they suppress large-amplitude variations of the heat source, resulting in a reduced rate of temperature change. On the other hand, they maintain the magnitude of the heat source at a low level, which contributes to a small temperature gradient within the SOEC.

In addition, the slow temperature regulation process of SOEC should be highlighted in Fig. 6f. Due to the regulation of Strategy B, the outlet temperature \(T_{\text{out}}\) of SOEC increases from the initial state of 1040 K to the thermoneutral point of 1073 K. The temperature increase lasts for approximately 20 min. This long time required for SOEC temperature regulation is also observed by Aguiar et al. \([18]\). We propose that the considerable time for temperature regulation is associated with the characteristic time of heat transfer of the SOEC \([32]\), which represents the time necessary for the SOEC to achieve a new thermal equilibrium after a variation of the heat source. In our previous work \([32]\), we have explained the physics of the long time for temperature regulation through Eq. (27), which is comparable to the time required for heat fluxes to ‘fill’ the heat capacity of SOEC. Eq. (27) can be used to estimate the characteristic time of heat transfer, where, \(H\) is the enthalpy flow rate, \(m\) is mass and \(\dot{m}\) is mass flow rate. The subscripts ‘E’, ‘int’, and ‘ch’ correspond to the electrolyte, the interconnect, and the fluid channel, respectively.

**Comparison of efficiencies**

Although Strategy B exhibits superior uniformity of temperature and thermal stability, it shows an electrical efficiency of 91.2%, lower than the 100.7% of base case and the 103.0% of Case 1, as shown in Fig. 6f. Interestingly, at low GHI, the efficiency of Strategy B decreases, while the efficiency of the base case and Case 1 can increase to even higher than 100%. This phenomenon is attributed to the energy utilization of the SOEC. Given a low GHI, such as 400 W m\(^{-2}\), the base case and Strategy A exhibit reduced voltages due to the low solar power and the electrical characteristics of SOEC (see Fig. 1e), while Strategy B maintain the voltages at high levels. According to Eq. (10), a lower voltage correlates with an increase in electrical efficiency. This relationship elucidates the higher efficiencies observed in the base case and Strategy A, in contrast to the lower efficiency of Strategy B. However, the high electrical efficiency necessitates significant heat absorption from the surrounding environment to compensate for the reduced electrical energy consumption. Thus, the strategy demonstrating high electrical efficiency leads to strong endothermic effects and temperature gradient, as shown in Fig. 6e, e, and f. This situation reveals an inherent contradiction between temperature control and the maximization of efficiency. Strategy C presents a solution to this dilemma by operating the SOEC in a slightly endothermic state, achieving an electrical efficiency of 94.9%. Compared to thermal neutrality, the slight endothermicity allows for an acceptable temperature gradient within SOEC (< 5 K cm\(^{-1}\)) while maintaining the high electrolysis efficiency.
Fig. 6. Comparison of four different operating strategies on the PV-SOEC system under fluctuating solar irradiance. (a) shows the one-hour GHI data and sky image. (b) presents the maximum power output from PV system and the power density applied on SOEC. The variables for comparison includes: (c) outlet temperature and temperature gradient, (d) temperature variation rate, (e) the total heat source within the single-channel SOEC model, (f) voltage and electrical efficiency, and (g) current density and hydrogen production rate.

Fig. 6g provides an additional comparison of currents and the hydrogen production rate in the four cases. Based on Eq. (11), the average hydrogen production rates for the base case and Strategies A–C are 140.9 L h$^{-1}$, 144.1 L h$^{-1}$, 130.4 L h$^{-1}$, and 135.5 L h$^{-1}$. This outcome further illustrates that the operation of SOEC at a slight endothermicity can effectively balance thermal management and system efficiency.
4. Conclusion

To improve the thermal safety of SOEC when integrated with PV panels under fluctuating solar irradiance, theoretical analysis and numerical simulation are conducted to investigate the control strategies for SOEC. Recognizing that the maximum current of SOEC is intrinsically limited by the steam supply rate, we developed control strategies that adaptively adjust the steam velocity according to real-time solar power. In this way, the magnitude of the heat source within the SOEC can be maintained at a low level, ensuring that the temperature gradient and variation within SOEC remain below 5 K cm$^{-1}$ and 1 K min$^{-1}$, respectively, even under highly fluctuating solar power. This would enhance the durability and safety of SOEC when integrated with intermittent power sources.

In addition, we found that while the thermoneutral operation of SOEC shows superior temperature uniformity and stability, it lags behind the endothermic operations in terms of electrical efficiency, because it lacks the utilization of thermal energy to compensate for electrical energy. This observation indicates a contradiction between temperature uniformity and the maximization of efficiency in SOEC. To strike a balance for this contradiction, our control strategy can alternatively maintain the SOEC in a slight endothermic state for a high efficiency of 94.9% and an acceptable temperature gradient below 5 K cm$^{-1}$ under fluctuating solar power.

**CRediT authorship contribution statement**

**Zhaojian Liang:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Shanlin Chen:** Writing – review & editing, Software, Methodology, Data curation. **Meng Ni:** Writing – review & editing. **Jingyi Wang:** Writing – review & editing, Visualization, Project administration, Funding acquisition. **Mengying Li:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

Data will be made available on request.

**Declaration of Generative AI and AI-assisted technologies in the writing process**

During the preparation of this work, the authors used GPT-4 to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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**Appendix A. Supplementary data**

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**References**


