Supplementary Information

1. Experimental process

Tables 1 and 2 list the cell structural parameters and experimental operating conditions, respectively.

Table 1 Structural parameters

Parameter	Value	Unit
Cell length	100	mm
Cell width	100	mm
Cathode thickness	400	μm
Electrolyte thickness	10	μm
Anode thickness	20	μm
Flow channel length	80	mm
Flow channel depth	1	mm
Parallel flow channel width	2	mm
Waveform flow channel amplitude	0.5	mm
Waveform flow channel period	2π	-
Rid width	1	mm

Table 2 Operation conditions

Parameter	Value	Unit
Cathode inlet gas composition	80%H_2O+20%H_2	mm
Cathode inlet gas flow velocity	0.5	slm
Anode inlet gas composition	Air	mm^2
Anode inlet gas flow velocity	1.22	slm

Cell temperature	1023.15	K
Operating pressure	1	bar
Current density	0-1	A/cm^2

2 Modeling approach

To reduce computational complexity and emphasize multiphysics phenomena in the reaction region, the following reasonable assumptions were adopted:

(1) The gas behaves ideally, neglecting intermolecular interactions.

(2) The SOEC operates under steady-state conditions.

(3) The effects of gravity on the cell and gas flow are negligible;

(4) All materials exhibit isotropic properties.

(5) Physical quantities such as temperature and pressure are uniformly distributed at each model node.

3 Evaluation indicators

Uniformity indicators are employed to evaluate the distribution uniformity of multiphysics fields, such as flow and electrochemical reactions. For example, the temperature distribution can be assessed using the following uniformity index:

$$u_x = \{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{(u_i - u_{avg})}{u_{avg}}\right]^2 \qquad (1)$$

where u_i is the local temperature at point i, u_{avg} is the average temperature across all n measuremnt points, and u_x represents the temperature uniformity index. A lower u_x value indicates improved temperature uniformity.

4 Model validation

Fig. 1(a) compares the experimental data with the simulation results for the single cell equipped with both a parallel flow channel and a waveform flow channel. The numerical predictions show excellent agreement with the

experimental measurements across the entire range of tested current densities, with the relative deviation maintained at less than 6%. In addition, Fig. 1(b) presents the temperature rise at nine measurement points on the cell at 0.5 A/cm^2, relative to the initial cell temperature, under both experimental and simulated conditions. The results indicate that the temperature trend predicted by the model closely matches the experimental data. The maximum temperature error does not exceed 2 K, and the relative error remains within 0.2%, primarily due to the measurement error of the thermocouple and the sealing performance of the cell. This high degree of accuracy validates the model's robustness and reliability, supporting its applicability for further SOEC-related investigations.

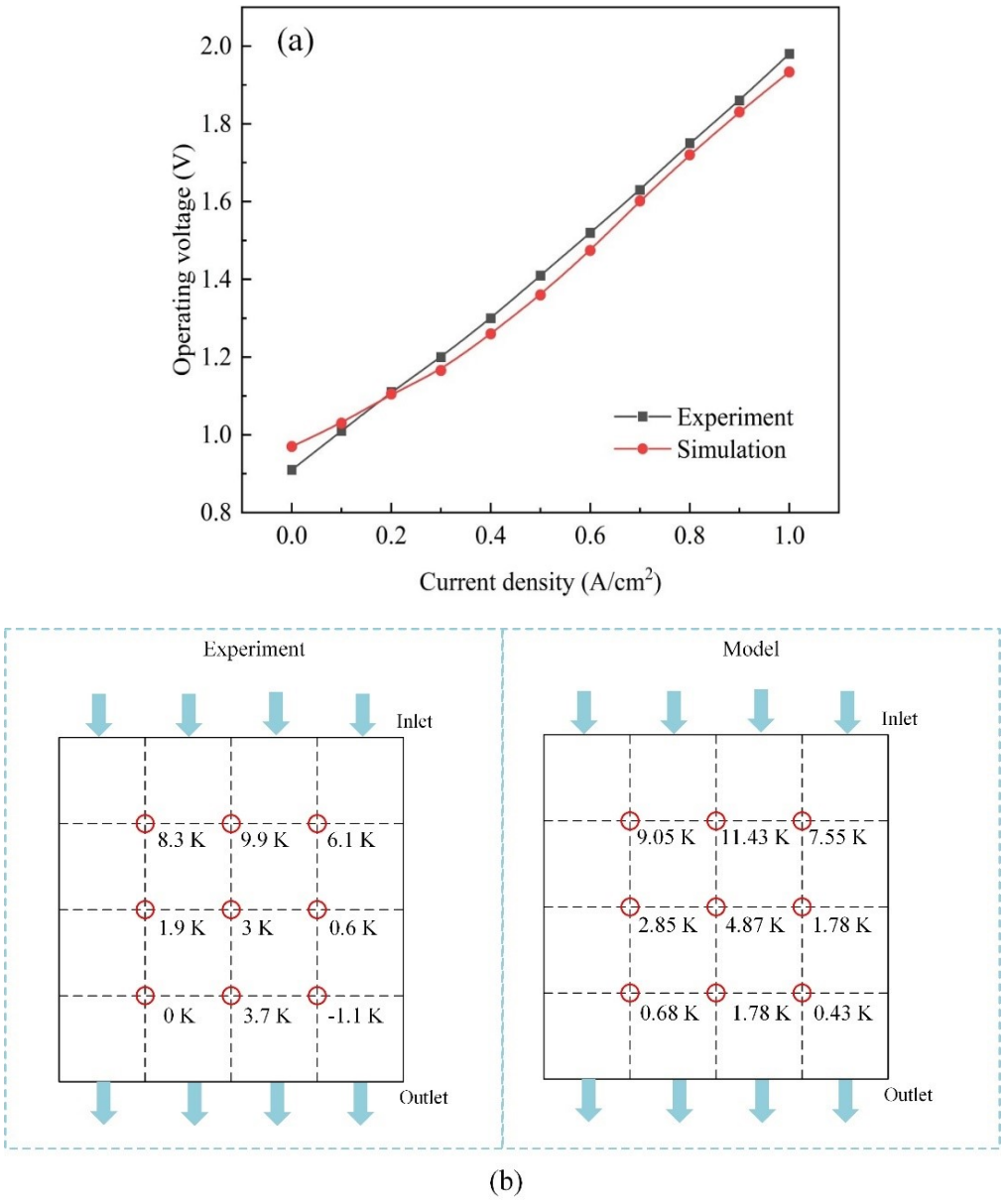

Fig. 1 Model validation: (a) comparison of polarization curves obtained from experimental data and simulation results and (b) temperature distribution comparison at nine measurement points under 0.5 A/cm^2