

Numerical study on the enhanced performance of the solid oxide electrolysis cell with a shared cathode flow channel for H₂O and CO₂ co-electrolysis

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Introduction

As the global carbon neutrality strategy advances, the large-scale integration of intermittent renewable energy into power grids has created an urgent demand for efficient energy storage and low-carbon hydrogen production technologies. Meanwhile, industrial decarbonization requires systematic approaches to carbon emission reduction and resource utilization [1]. The solid oxide electrolysis cell (SOEC), as a highly efficient and clean energy conversion device, is capable of converting electrical and thermal energy into chemical energy at elevated temperatures, and has thus gained extensive attention in the field of renewable energy storage and utilization. In particular, the SOEC co-electrolysis of H₂O and CO₂ not only enables the simultaneous utilization of CO₂ as a resource, but also directly produces syngas (H₂+CO), which can be further converted into liquid fuels or high-value chemicals via processes such as Fischer-Tropsch synthesis [3]. This provides a highly promising technological pathway for achieving "carbon cycling" and "green hydrogen" applications.

However, conventional straight flow channels often suffer from uneven gas distribution and severe concentration polarization [4]. Moreover, under co-electrolysis conditions, the reduction of H₂O and CO₂ involves complex electrochemical reactions as well as thermochemical reactions such as the reverse water-gas shift reaction. The gas composition changes continuously along the flow channel direction, thereby affecting the uniformity of local current density, temperature distribution, and reaction rate. Consequently, the rational design of high-performance flow fields has become a critical criterion for next-generation large-scale electrolysis systems [5].

Research objects

Fig.1 shows the geometric models of the conventional channel and the shared cathode flow channel for SOEC H₂O/CO₂ co-electrolysis investigated in this work. The core repeating unit of SOEC consists of cathode flow channel, porous cathode support layer, cathode catalyst layer, dense electrolyte layer, anode catalyst layer, anode flow channel and ribbed interconnect for current collection, and the two models adopt completely identical geometric dimensions and material property parameters to ensure the fairness of performance comparison. The conventional structure is equipped with independent cathode flow channels for each stacked unit, separated by metal interconnects, while the shared cathode flow channel structure is constructed by reversely placing the second layer of the conventional two-layer stacked unit, enabling the upper and lower cell units to share one integrated cathode flow channel, which is designed to shorten the gas diffusion path from the flow channel to the reaction interface and alleviate the mass transfer limitation in traditional structures.

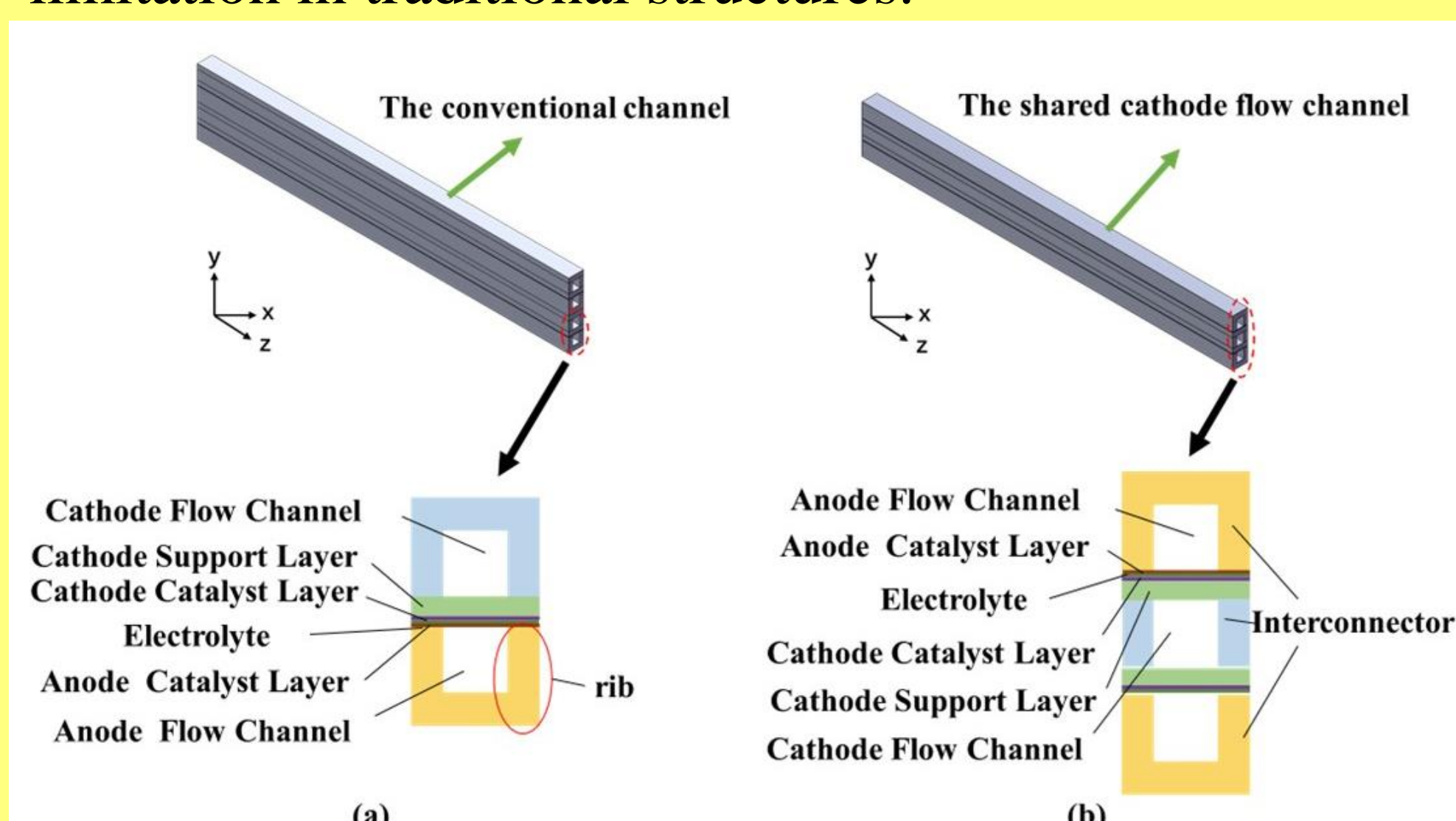


Fig. 1. (a) Geometric structure of conventional flow channel SOEC unit, (b) Geometric structure of shared cathode flow channel SOEC unit.

Method

The SIMPLE algorithm was adopted for pressure-velocity coupling in the flow field, and the model comprehensively coupled momentum conservation, mass conservation, species transport, energy conservation and charge conservation equations to describe the complex multi-physics process in SOEC; The computational domain was discretized with high-quality structured grids, and 128000 grids were finally selected for subsequent calculation after grid independence verification to balance calculation accuracy and efficiency. To verify the accuracy of the SOEC H₂O/CO₂ co-electrolysis model, the experimental conditions of Yang [6] were set as a temperature of 1073.15 K and an inlet gas composition of 45% H₂O, 45% CO₂ and 10% H₂. Under these conditions, the comparison of I-V curves obtained with the same electrochemical parameters is shown in Fig.2.

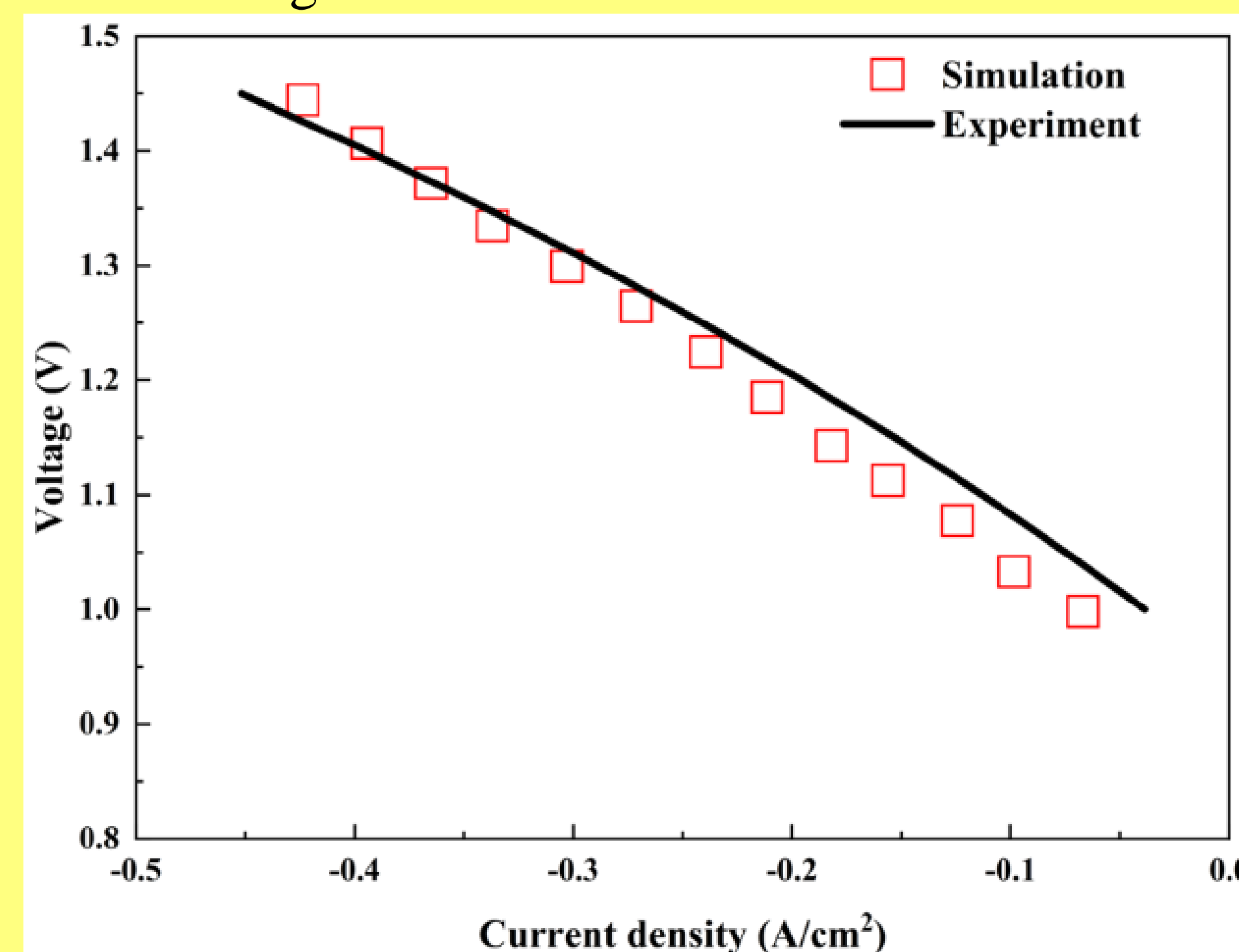


Fig. 2. Model validation

Results

Based on the operating conditions of 1073.15 K inlet temperature, 1.5 V operating voltage and cathode inlet composition of 45% H₂O + 45% CO₂ + 10% H₂ + 5% CO + 5% CH₄, the study of H₂O/CO₂ co-electrolysis performance of SOEC with shared cathode flow channel was carried out.

FLOW FIELD ANALYSIS

Fig. 3 shows the cathode velocity distribution of conventional and shared cathode flow channels. It can be seen that the high velocity region is concentrated at the channel inlet. With the novel structure, the maximum cathode velocity decreases from 5.91 m/s to 2.36 m/s, the flow field becomes more uniform, and the gas residence time is effectively prolonged.

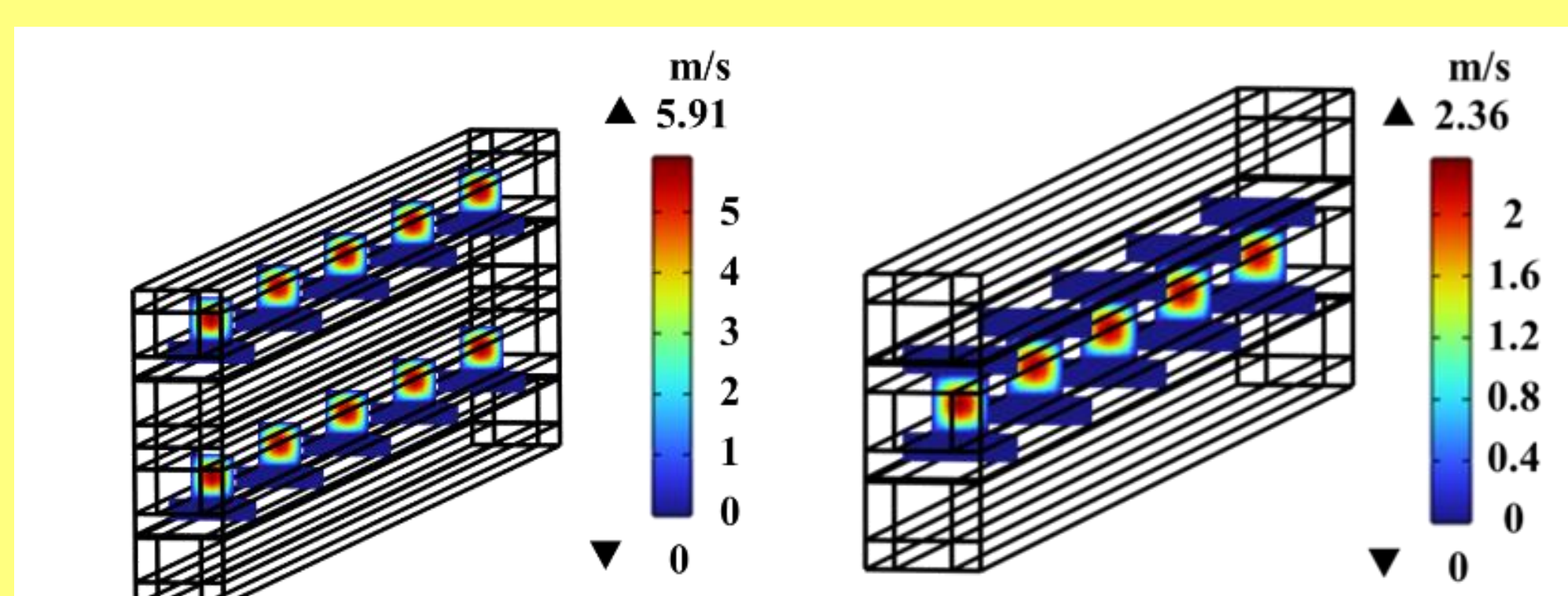


Fig. 3. Flow field distribution in the cathode region: (a) Conventional flow channel, (b) Shared cathode flow channel

ELECTROCHEMICAL PERFORMANCE

Fig. 4 shows the current density distribution along the flow direction of the two structures. As can be seen from the figure, the current density of the shared cathode flow channel is consistently higher than that of the conventional channel in the whole flow path. The novel structure reduces concentration polarization and significantly improves the overall electrochemical reaction intensity.

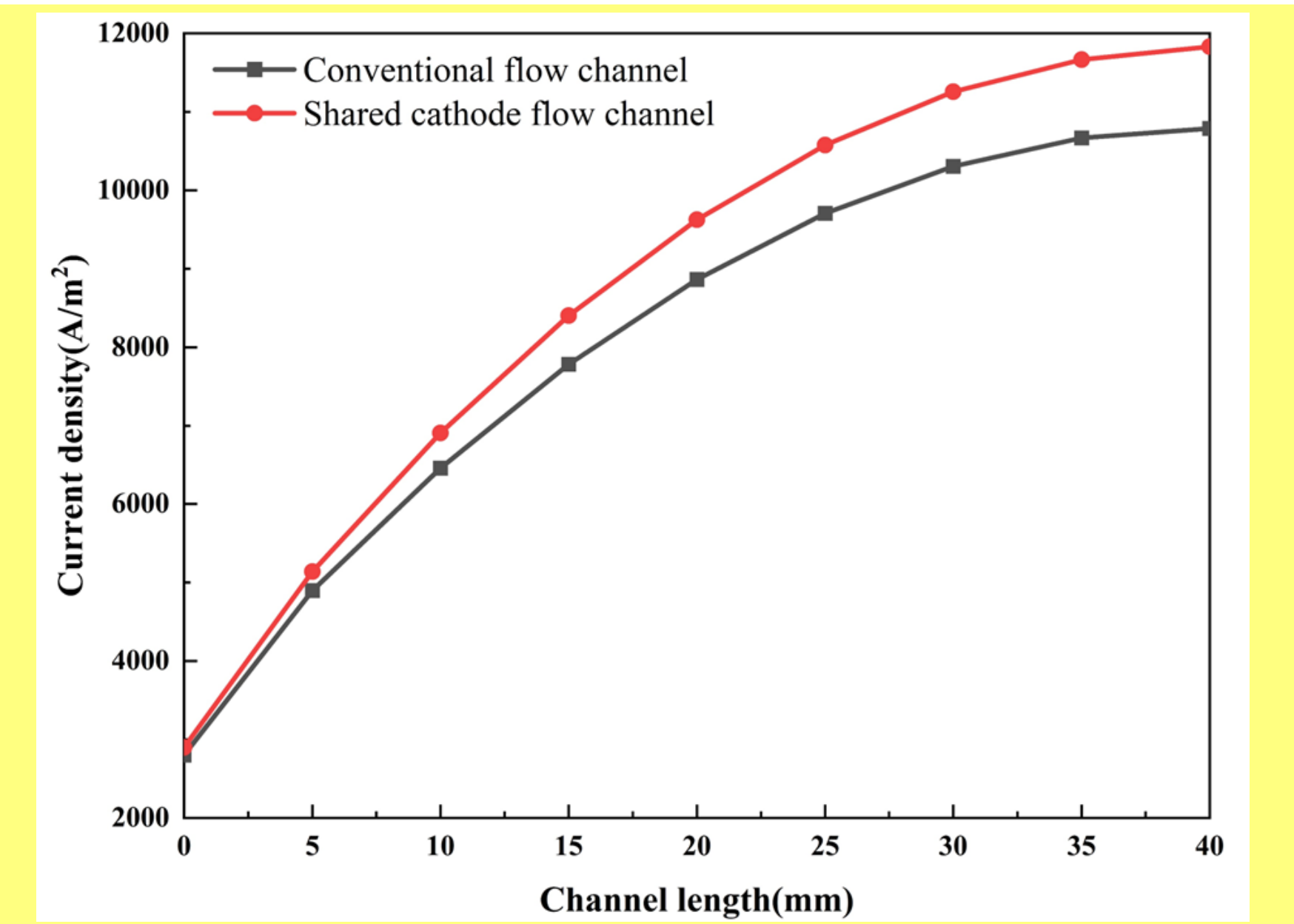


Fig. 4. Current density distribution along the flow direction for co-electrolysis in SOEC with conventional flow channel and shared cathode flow channel

DISTRIBUTION OF WGSR RATE

Fig. 5 presents the Water-Gas Shift Reaction (WGSR) rate distribution in the cathode catalyst layer for both structures. The conventional flow channel shows intense local reaction peaks, with a forward rate of 3.23 mol/(m³·s) and a reverse rate of -12.34 mol/(m³·s). By contrast, the shared cathode flow channel markedly lowers both forward and reverse WGSR rates to 1.56 mol/(m³·s) and -4.36 mol/(m³·s), respectively. The shared structure effectively suppresses excessive local reaction intensity and narrows the reaction rate range across the catalyst layer.

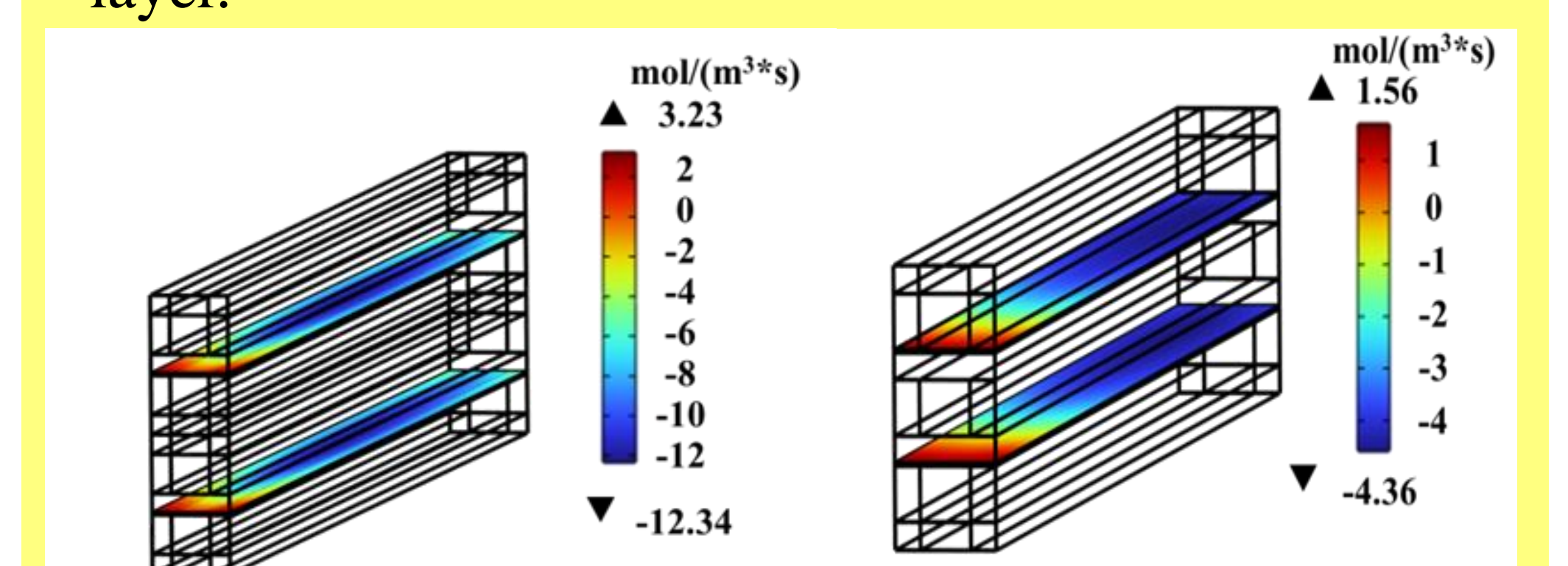


Fig. 5. WGSR rate distribution in the cathode catalyst layer of SOEC, (a) Conventional flow channel, (b) Shared cathode flow channel

Conclusions

- Established a three-dimensional multi-physics coupled numerical model to compare the H₂O/CO₂ co-electrolysis performance of SOECs with a shared cathode flow channel and conventional straight flow channel
- Optimized cathode flow field: reduced maximum flow velocity from 5.91 m/s to 2.36 m/s, prolonged gas residence time, and enhanced reactant mass transfer to the three-phase boundary
- Significant electrochemical performance enhancement: maximum current density increased from 10800 A/m² to 11830 A/m², outlet H₂ molar concentration raised by 16.5%, and methane conversion efficiency improved by ~40%
- Optimized WGSR rate distribution in the cathode catalyst layer, suppressed extreme local reaction fluctuation
- Provided valuable reference for flow field optimization and engineering application of high-performance SOECs

References

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