Performance Enhancement of PEM Electrolyzer by Sinusoidal Flow Channel with Mass Transport Intensification

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Introduction

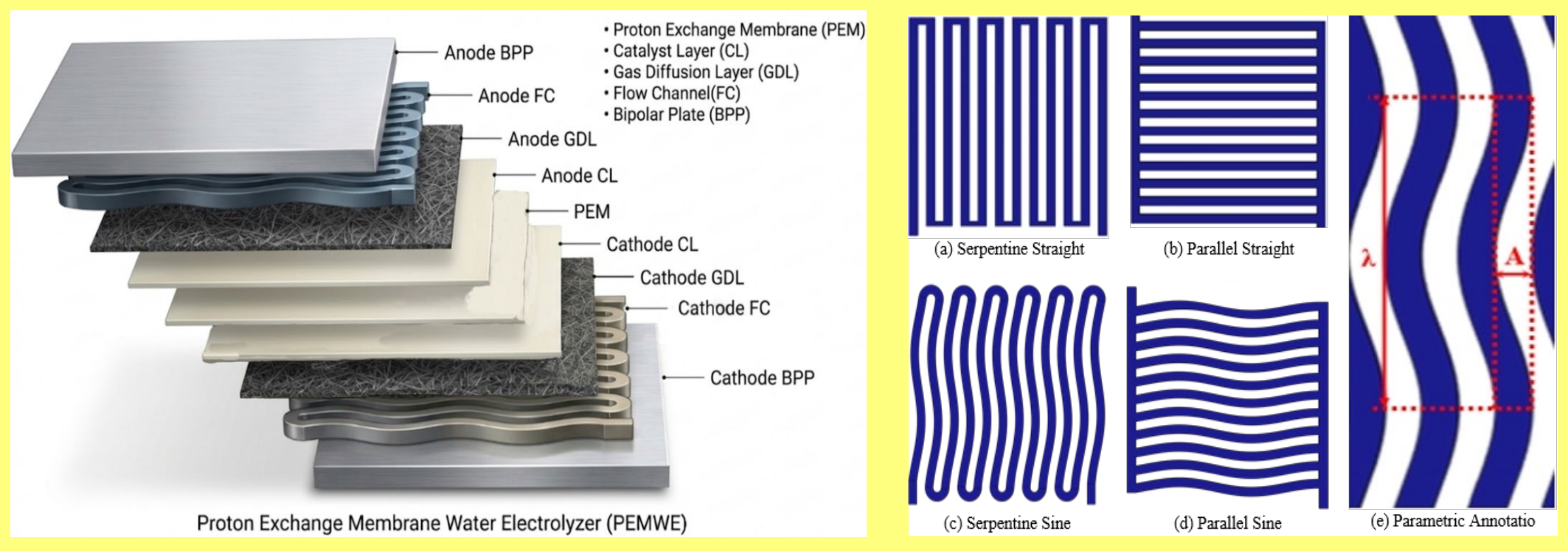
Hydrogen energy is regarded as an ideal alternative to fossil fuels due to its high energy density and zero carbon emission. Integrating renewable energy for hydrogen production can further reduce CO_2 emissions by 75%. Proton exchange membrane water electrolyzers (PEMWE) are well suited for coupling with fluctuating renewable energy owing to high current density and rapid dynamic response.

However, conventional PEMWE flow channel structures are prone to bubble blockage and mass transfer limitations at high current densities, leading to severe performance degradation. Traditional parallel channels feature low pressure drop but suffer from uneven flow distribution and stagnant zones. Serpentine channels offer more uniform fluid flow but induce higher pressure loss. Although various optimized designs (trapezoidal, biomimetic, etc.) have been developed, they either fail to suppress boundary layer restriction for rapid degassing or involve complex topologies that raise machining difficulty and limit mass production.

To address these issues, this work proposes a parametric sinusoidal serpentine flow channel that induces secondary flow via smooth curvature to intensify gas-liquid transport without increasing manufacturing complexity. Multiphysics numerical simulations are conducted to compare four flow channel configurations, analyze bubble detachment, gas-liquid uniformity and electrochemical performance, and perform multi-objective optimization of the amplitude parameter k using the TOPSIS model.

Design & Methodology

This study proposes a sinusoidal serpentine flow channel to enhance mass transport and bubble removal in PEM electrolyzers. Four flow field configurations are investigated: serpentine straight (SS), serpentine sine (SSi), parallel straight (PS), and parallel sine (PSi). A multi-physics numerical model is established to simulate electrochemical performance, two-phase flow, wall shear stress, and pressure drop. Key evaluation indicators include current density, hydrogen production rate, gas distribution uniformity, and effective shear stress ratio (ESSR). The TOPSIS model is used for multi-objective optimization of the amplitude parameter k, with weights set for productivity, uniformity, and pressure drop. Grid independence and literature validation ensure model reliability.

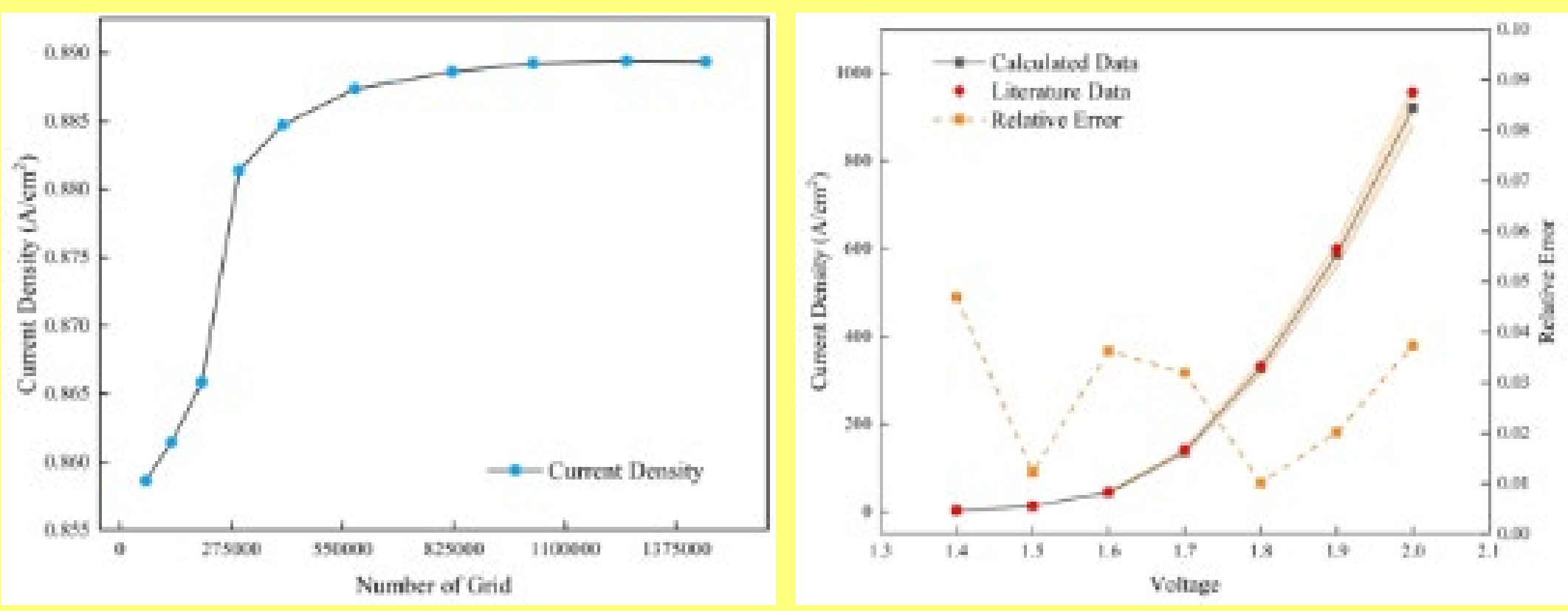


(a) Geometric Structure of PEMWE

(b) Flow channel configuration and parameter characteristics

Fig. 1. PEMWE structure and flow channel configurations

To ensure the accuracy and reliability of the numerical model, grid independence verification and comparison with literature data were conducted. Fig. 2(a) shows the grid independence analysis. When the number of grids reaches 5.68×10^5, the calculation deviation is less than 0.02%. Fig. 2(b) demonstrates that the model prediction results are highly consistent with the experimental data from the literature.



(a) Grid independence

(b) Polarization curve

Fig. 2. Model Reliability

Results and Discussion

Fig. 3 presents the polarization curves of the electrolyzer with different flow field configurations. The SSi exhibits the best performance. In the activation overpotential-dominated region (1.4–1.6 V), the current responses of the four configurations are nearly identical. At 1.8 V, the current density of the SSi is 3.6% higher than that of the PSi and 4.6% higher than that of the SS. At 2.2 V, SSi reaches 2.0267 A/cm², representing a 5.0% improvement over the SS, a 7.8% improvement over the PSi, and a 12.9% improvement over the PS. These results demonstrate that the serpentine sine design offers significant advantages under high-power operating conditions.

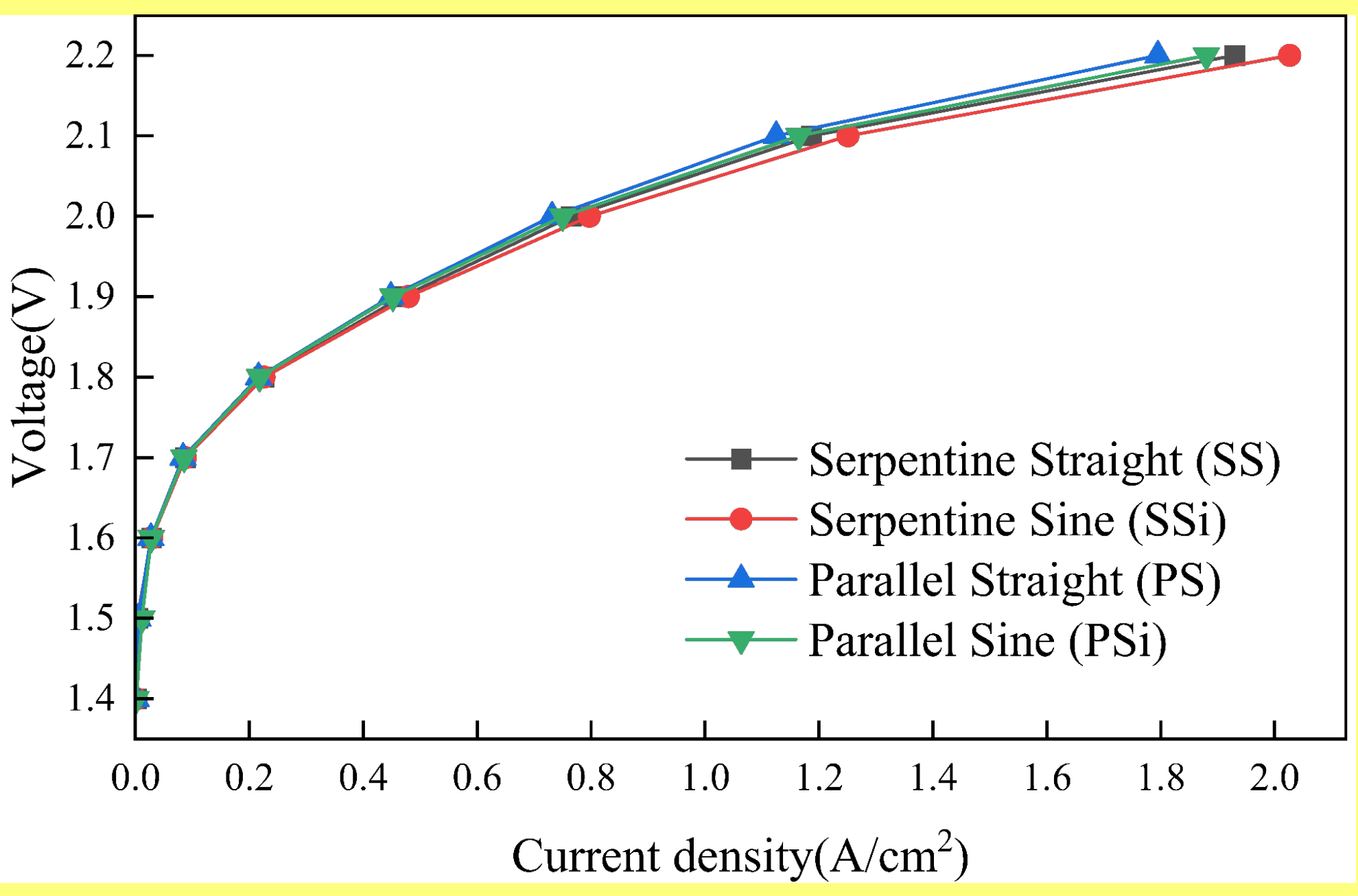
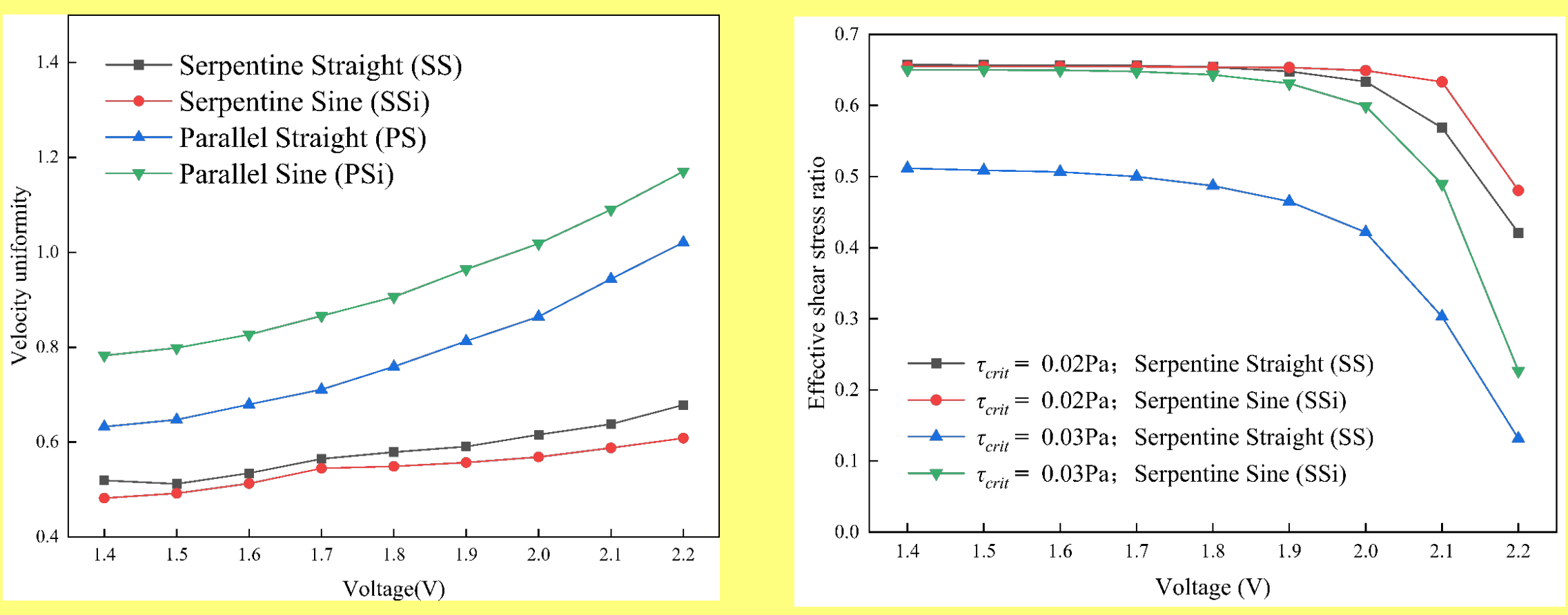


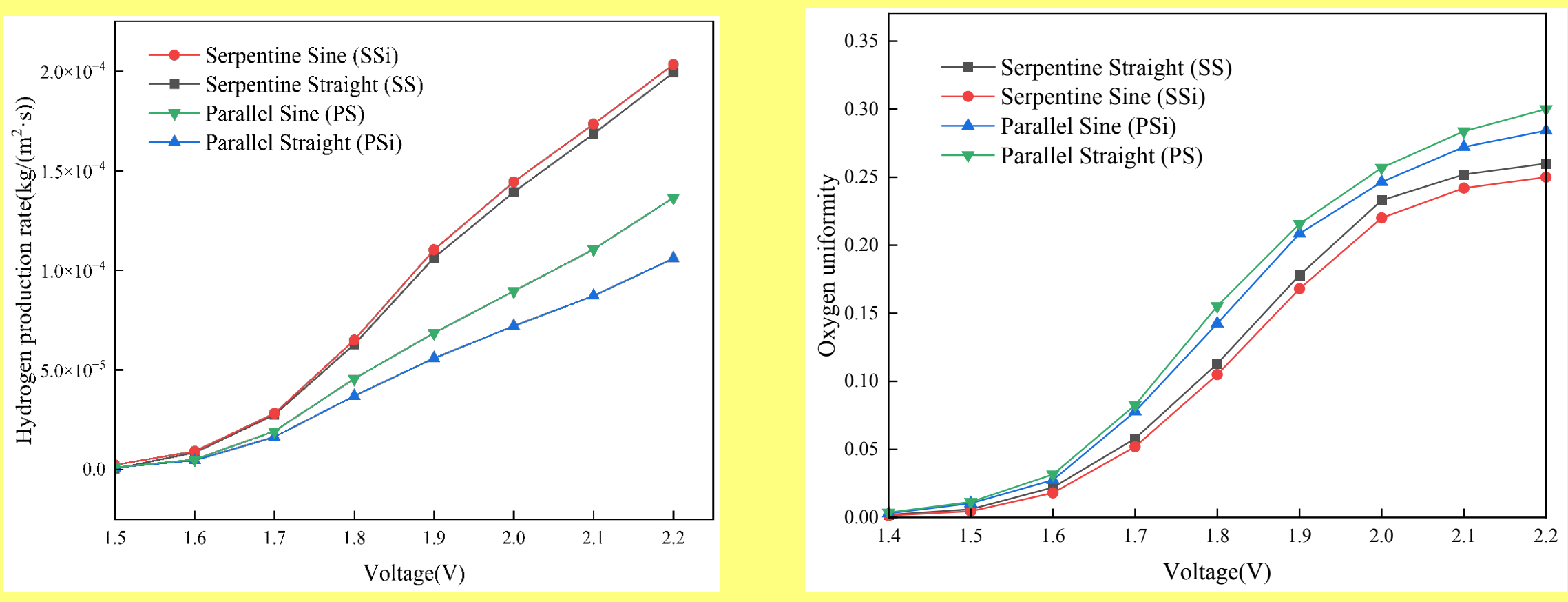
Fig.3. Polarization curves under different flow channel.

As shown in Fig. 4, the sinusoidal design significantly improves performance across multiple metrics. Compared with SS, SSi enhances velocity uniformity by 7.2% and ESSR by 31.8% at 2.2 V under τ_{crit} = 0.02 Pa, and by 72.5% under τ_{crit} = 0.03 Pa, demonstrating superior bubble detachment and mass transport stability at high loads. Meanwhile, SSi achieves a 7.92% higher hydrogen production rate and a 5.58% improvement in anode oxygen uniformity over SS. The sinusoidal design also benefits parallel channels, boosting PSi's hydrogen production rate by 28.8% over PS. These results confirm that the sinusoidal structure effectively mitigates flow stagnation and gas accumulation, delivering robust performance improvements under both moderate and extreme operating conditions.



(a) Uniformity of velocity under different voltages

(b) The proportion of the effective scouring area of sinusoidal and straight flow



(c) Hydrogen production rate

(d) Oxygen uniformity

Fig. 4. Multi-performance comparison of four flow channel configurations

Based on the verified superior performance of SSi, we further optimized the amplitude parameter k. Fig. 5 presents polarization curves at various k. In the activation-controlled region, curves overlap nearly completely. When exceeding 1.8 V, current density rises nonlinearly with k. At 2.2 V, k=0.3 reaches 2.0252 A/cm², 1.6% higher than k=0.4; k=0.5 yields 2.2148 A/cm², 16.4% higher than k=0.1. A moderate k=0.3 balances mass transport and flow uniformity, while an overlarge k degrades performance.

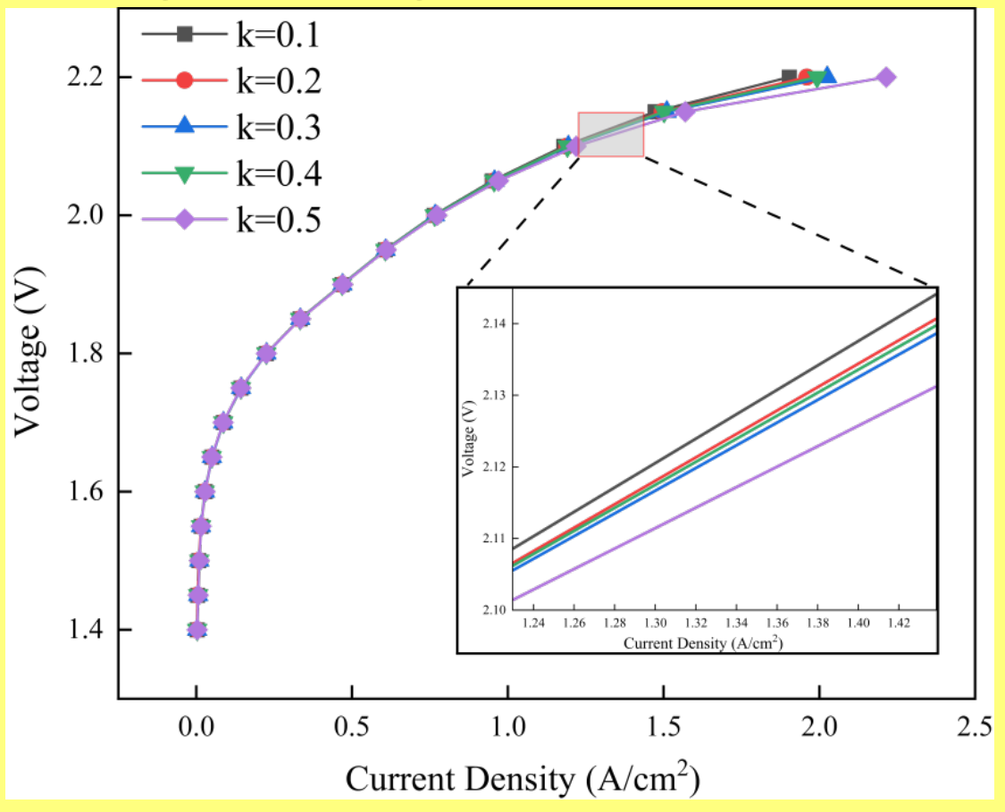


Fig.5. Polarization curves under different parameters k.

Fig. 6 shows the multi-dimensional performance variation with amplitude k . Pressure drop rises nearly linearly with k , while current uniformity presents a U-shaped trend and peaks at k =0.3. Compared with the original SSi channel, the optimized structure improves current uniformity by 21.0% and overall performance by 12.8%, with only a 7.9% rise in pressure drop and negligible change in hydrogen production. At k =0.5, hydrogen production slightly increases by 0.86%, yet pressure drop rises by 16.0% and current uniformity drops by 47.1%, bringing potential electrode degradation risks. Moderate perturbation at k =0.3 achieves the best balance between mass transfer and flow resistance, regarded as the global optimal solution.

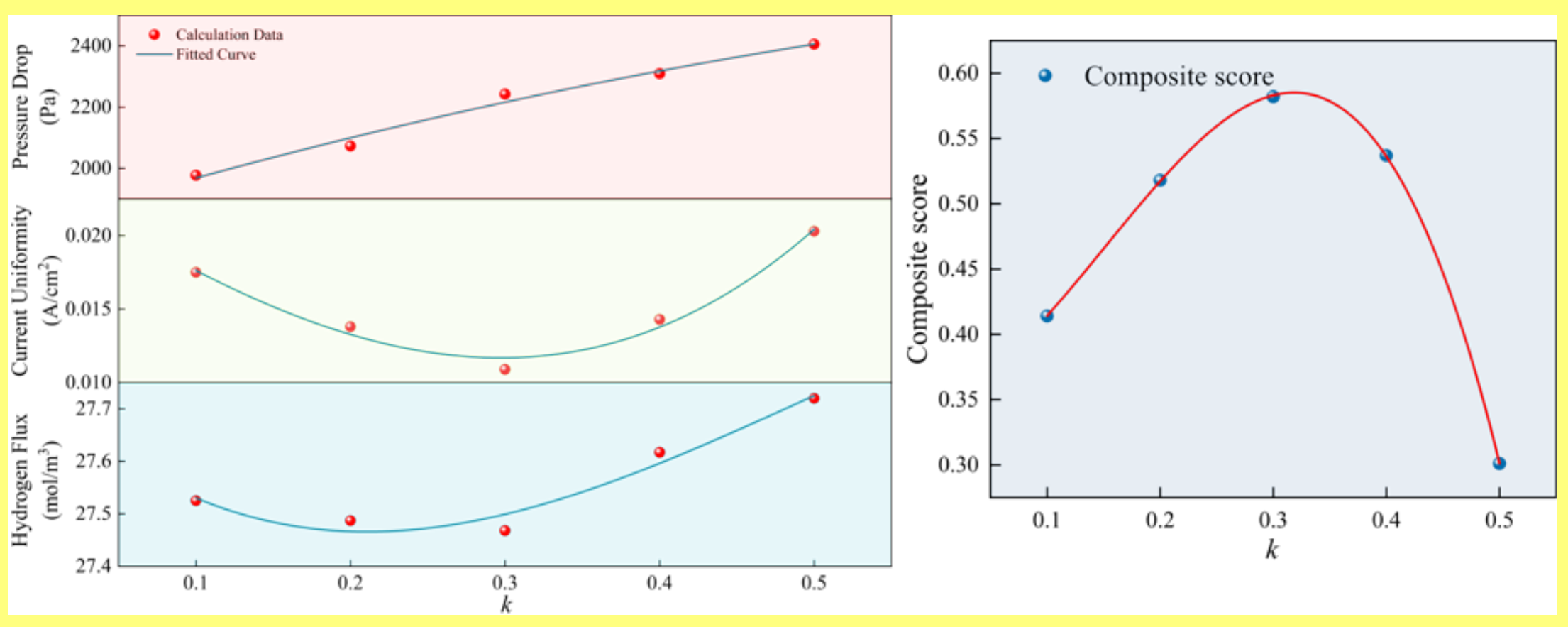


Fig.6. Effects of amplitude *k* on performance and multi-objective evaluation

Conclusions

This work presents a sinusoidal serpentine flow channel to mitigate mass transfer and thermal bottlenecks in high-power PEMWE via secondary flow regulation. Four channel configurations are compared numerically, and TOPSIS verifies the superiority of the SSi design. The amplitude parameter k is further optimized to balance hydrogen production, uniformity and flow resistance. Main conclusions are summarized as follows:

1. SSi achieves the optimal performance. At 2.2 V, its current density is 12.9% and 5.0% higher than PS and SS; it increases hydrogen production rate by 7.92% with only a 2% rise in pressure drop.
2. SSi raises the minimum shear stress by 40%, and its ESSR is enhanced by 31.8% and 72.5% at 2.2 V, presenting excellent bubble removal capacity.
3. The TOPSIS score of SSi reaches 0.748, which is 8.9% and 52.6% higher than SS and parallel configurations.
4. The optimal amplitude is k=0.3, improving current uniformity and overall performance by 21.0% and 12.8%. At k=0.5, hydrogen production only rises by 0.86%, while pressure drop increases by 16.0% and uniformity drops by 47.1%

References

[1] C. Li, B. Wang, M. Xu, J. Li, G. Liu. Enhancing PEM electrolyzer efficiency through sinusoidal flow channel architecture design. Electrochimica Acta. 550 (2026) 147990.https://doi.org/10.1016/j.electacta.2025.147990