

Synergistic Optimization of Bi@NSC Electrode and Wavy-Shaped Channel for Enhanced Flow-Electrode Capacitive Deionization

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Research Article

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Abstract

Flow-electrode capacitive deionization (FCDI) enables continuous desalination, but its performance is often constrained by the limited charge-storage capability of carbon-based flow electrodes and inefficient slurry transport. Herein, a material–flow-field synergistic strategy was developed by coupling spherical bismuth nanoparticles confined within N/S co-doped carbon (Bi@NSC) flow-electrode particles with a wavy-shaped channel (WSC). The Bi@NSC composite combines the Faradaic redox activity of Bi with the capacitive charge storage of the heteroatom-doped carbon framework, delivering a specific capacitance of 352 F g^{-1} at 5 mV s^{-1} . Under optimized operating conditions, the Bi@NSC-WSC FCDI system achieved a NaCl removal efficiency of 50.0% and a salt adsorption capacity of 10.0 mg g^{-1} . Computational fluid dynamics simulations using COMSOL further indicated that the WSC reduced low-velocity regions, improved slurry distribution, and mitigated local particle accumulation, providing a hydrodynamic explanation for the improved desalination performance. These results demonstrate that the coordinated optimization of flow electrode materials and channel architecture offers an effective strategy for improving FCDI desalination.

1. Introduction

The increasing scarcity of global freshwater and growing demand for saline water treatment have stimulated the development of efficient low-energy desalination technologies. Conventional desalination technologies, such as reverse osmosis (RO)[1] and electrodialysis (ED)[2, 3], have been widely implemented for water purification; however, their practical applications are often restricted by high energy consumption, membrane fouling, and challenges in concentrate management. Therefore, the development of sustainable desalination technologies with low energy requirements, high operational flexibility, and environmental compatibility is highly desirable.

Capacitive deionization (CDI) is an electrochemically driven desalination technology that has attracted increasing attention owing to its low energy consumption, facile operation, and potential compatibility with renewable energy sources[4]. In conventional CDI systems, salt ions are primarily removed through electric double-layer (EDL) adsorption within porous carbon electrodes. However, the limited charge storage capacity, finite active sites, and electrode saturation during continuous operation significantly restrict the long-term desalination capability of fixed-electrode CDI[5, 6]. Flow-electrode capacitive deionization (FCDI) has emerged as an advanced CDI configuration that replaces stationary electrodes with continuously circulating slurry electrodes, enabling continuous operation and theoretically unlimited desalination capacity[7–9]. During FCDI operation, charged flow electrode particles participate in ion migration through ion-exchange membranes and store the removed ions through electrochemical processes. Consequently, electrical conductivity, ionic transport behavior, particle dispersion, and dynamic interactions between particles and current collectors are critical factors governing FCDI performance.

Carbon-based materials, including activated carbon (AC)[10], carbon black[7], and graphene derivatives[11], remain the most commonly used flow electrode materials owing to their large surface areas, abundant porous structures, and chemical stability. Nevertheless, their desalination mechanism is primarily dominated by EDL adsorption, which intrinsically limits charge-storage capability and salt removal efficiency. Moreover, insufficient electrical connectivity among carbon particles can increase internal charge-transfer resistance and reduce effective electrode utilization during continuous circulation[12, 13]. To overcome these limitations, the introduction of Faradaic-active components into carbon frameworks has been considered an effective strategy for constructing hybrid flow electrodes with coupled capacitive/Faradaic charge-storage mechanisms. Compared with conventional carbon materials, Faradaic materials can provide additional redox-active sites and enhance ion storage capability[14, 15]. However, the practical application of Faradaic materials in flow electrodes remains challenging owing to poor intrinsic electrical conductivity, active-site accessibility limitations, particle aggregation, and structural instability during long-term operation.

Among various Faradaic materials, bismuth (Bi)-based materials have attracted considerable interest owing to their reversible redox activity, high theoretical charge-storage capability, and favorable electrochemical stability[16–19]. Incorporating Bi species into conductive carbon frameworks provides additional Faradaic storage sites beyond conventional EDL adsorption, offering new opportunities to improve FCDI performance. However, the direct utilization of Bi nanoparticles is hindered by severe aggregation, limited electron transport pathways, and insufficient utilization of active sites. Constructing carbon-confined Bi nanostructures with heteroatom-doped conductive networks is therefore an effective approach to integrate the electrochemical activity of Bi with enhanced electrical conductivity and structural stability[20]. Furthermore, besides electrode composition, the flow-field architecture plays an equally important role in FCDI performance. As flow electrodes rely on continuous particle transport, channel geometry directly affects slurry dispersion, particle–collector interactions, and interfacial mass transfer.[21] Nevertheless, current studies have mainly focused on developing advanced electrode materials, while the synergistic optimization of flow-electrode composition and flow-channel architecture remains insufficiently explored.

Herein, we propose a synergistic optimization strategy integrating a Bi@NSC flow electrode with a wavy-shaped channel (WSC) for enhanced FCDI desalination. Bi nanoparticles were confined within an N/S co-doped carbon framework to construct a composite flow electrode with coupled capacitive/Faradaic charge-storage capability. The Bi nanoparticles provide redox-active sites, whereas the NS-doped carbon matrix facilitates electron transport and suppresses the aggregation of active components. Meanwhile, the WSC architecture was introduced to regulate the flow electrode transport behavior, and computational fluid dynamics (COMSOL Multiphysics) simulations were employed to analyze the flow distribution, velocity variation, and interfacial mass-transfer characteristics under different channel configurations, thereby elucidating the influence of channel geometry on particle transport and electrode utilization. This work provides a material–flow-field synergistic strategy for the rational design of high-performance flow electrodes and optimized FCDI reactors.

2. Experimental section

2.1. Synthesis of Bi@NSC

The Bi@NSC composite was synthesized via a one-step pyrolysis method using bismuth citrate and MES potassium salt as precursors. Briefly, bismuth citrate and MES potassium salt were mixed at a mass ratio of 1:5 (w/w) and thoroughly ground to obtain a homogeneous precursor mixture. The resulting mixture was transferred into a ceramic boat and placed in a tubular furnace for further processing. After purging with high-purity Ar to establish an inert atmosphere, the sample was heated from room temperature to 900°C at a slow heating rate of 2°C min⁻¹ and maintained at 900°C for 120 min. The furnace was then allowed to cool naturally to room temperature under continuous Ar protection. The obtained carbonized product was washed several times with ultrapure water to remove residual soluble potassium-containing species and other impurities. Finally, the product was dried to obtain the N,S-doped carbon-confined Bi composite, which was denoted as Bi@NSC.

2.2. Configuration of the FCDI Cell

A laboratory-scale FCDI cell was assembled using ion exchange membranes (AEM/CEM), graphite current collectors, flow channels, and sealing gaskets[22]. Three graphite flow-field configurations, including straight-turning-shaped channel (STSC), arc-shaped channel (ASC), and wavy-shaped channel (WSC), were fabricated with identical hydraulic dimensions (Scheme. 1).. The flow channels were designed with a uniform width of 3 mm, and the WSC was constructed using periodic elliptical units with an aspect ratio (a/b) of 5 to regulate flow distribution. The Bi@NSC slurry was circulated through the flow channels, while the feed solution passed through the desalination chamber. Under an applied voltage, ions migrated across the ion exchange membranes and were stored by the Bi@NSC flow electrodes through coupled capacitive/Faradaic processes.

2.3. Computational fluid dynamics simulation of flow-field distribution

The flow behavior of Bi@NSC slurry within the STSC, ASC, and WSC configurations was simulated using the Laminar Flow module of COMSOL Multiphysics 6.2. Three-dimensional geometrical models were constructed according to the experimentally fabricated channel dimensions, while maintaining identical hydraulic dimensions among different channels to systematically evaluate the effect of channel geometry on flow-field distribution. The Bi@NSC slurry was assumed to be an incompressible Newtonian fluid, and its flow behavior was described using the continuity equation and Navier–Stokes equations[23, 24]. The inlet boundary condition was defined by the average velocity corresponding to the experimental flow rate of 20 mL min⁻¹, while the outlet was set as zero gauge pressure. A no-slip boundary condition was applied to the channel walls. The physical parameters of the slurry were defined as follows: density of 1050 kg m⁻³, dynamic viscosity of 3.5 × 10⁻³ Pa·s, and operating temperature of 298 K. A tetrahedral mesh was generated for model discretization, with local refinement applied in curved and contraction–

expansion regions to accurately capture velocity gradients. Mesh independence analysis was performed to determine the appropriate mesh density and ensure simulation reliability. The velocity distribution, streamline profiles, and local flow disturbance characteristics were extracted to elucidate the influence of channel geometry on Bi@NSC slurry transport, particle renewal behavior, and interfacial mass-transfer processes.

3. Results and discussion

3.1. Rational design of Bi@NSC flow electrode for enhanced FCDI desalination

The rational design of the Bi@NSC composite flow electrode is shown in Scheme 1. In conventional activated carbon (AC)-based flow electrodes (Scheme 1a), salt removal mainly relies on ion adsorption within the electric double layer (EDL) formed at the carbon/electrolyte interface. Although porous carbon materials provide abundant adsorption sites, their charge storage capability is intrinsically limited by the non-Faradaic nature of EDL adsorption[25, 26]. In contrast, the Bi@NSC flow electrode (Scheme 1b) introduces electrochemically active Bi nanoparticles into an N/S co-doped carbon framework, enabling coupled capacitive and Faradaic charge-storage processes. The confined Bi nanoparticles serve as additional redox-active sites for Faradaic charge storage, while the NS-doped carbon matrix provides a conductive network for rapid electron transport and suppresses Bi nanoparticle aggregation[27]. Therefore, compared with conventional AC flow electrodes, the Bi@NSC architecture integrates EDL-based capacitive storage with Faradaic reactions, providing enhanced charge-storage capability and improved electrode utilization[28]. Furthermore, the spherical morphology of Bi@NSC particles is favorable for slurry dispersion and flow stability, facilitating particle transport and dynamic particle-collector interactions during FCDI operation[29]. This rational combination of faradaic-active Bi nanoparticles and conductive carbon framework provides a promising strategy for improving charge transfer, ion transport, and desalination performance in flow-electrode systems.

3.2. Materials characterization

The structural and morphological features of the Bi@NSC composite were systematically investigated by XRD, SEM, STEM, and EDS elemental mapping. As shown in Fig. 1a, all diffraction peaks of Bi@NSC can be indexed to metallic Bi (PDF#85-1330), while no obvious impurity peaks are detected, confirming the successful formation of crystalline Bi nanoparticles within the carbon matrix[30]. The incorporation of Bi nanoparticles is expected to introduce additional electrochemically active sites, providing potential charge-storage capability for the subsequent flow-electrode desalination process.

SEM images reveal that Bi@NSC exhibits a uniform spherical morphology (Fig. 1b). The enlarged SEM image (Fig. 1c) shows that the particle surface is composed of abundant nanoscale features, generating a hierarchical rough structure. Such a surface architecture can increase the accessible interface between the electrode material and electrolyte, shorten ion diffusion pathways, and facilitate ion

transport under dynamic flow conditions. Moreover, the spherical morphology is beneficial for slurry transport by reducing flow resistance and promoting homogeneous dispersion of Bi@NSC particles, which is critical for stable operation of flow-electrode systems.

TEM characterization further confirms the internal structure of Bi@NSC (Fig. 1d). Numerous uniformly distributed dark nanoparticles are observed within the carbon framework, indicating that Bi nanoparticles are effectively confined within the carbon matrix without severe aggregation. STEM image and corresponding EDS elemental mappings (Fig. 1e–i) demonstrate that C forms the continuous backbone, while Bi nanoparticles are homogeneously dispersed throughout the carbon structure. Meanwhile, N and S elements are uniformly distributed, confirming the successful construction of NS-doped carbon layers. The uniform confinement of Bi nanoparticles prevents particle aggregation-induced electron transport limitations, whereas heteroatom doping can modulate the electronic structure of carbon frameworks and improve interfacial interactions.

Overall, the Bi@NSC composite integrates three structural advantages: Bi nanoparticles as electrochemically active centers, NS-doped carbon as a conductive framework, and spherical morphology for favorable flow behavior[31]. This unique architecture simultaneously addresses the requirements of electron transport, ion diffusion, and slurry stability, providing a structural foundation for enhanced charge transfer, efficient salt migration, and improved electrode utilization in the Bi@NSC-based FCDI system.

3.3. Electrochemical performance

The electrochemical charge-storage behavior of the Bi@NSC electrode was investigated by cyclic voltammetry (CV) measurements at different scan rates. As shown in Fig. 3a, increasing the scan rate from 5 to 100 mV s^{-1} enlarged the CV curves while maintaining distinct redox peaks, indicating the coexistence of electric double-layer capacitive and Faradaic charge-storage processes. A high specific capacitance of 352 F g^{-1} at 5 mV s^{-1} was achieved, demonstrating the enhanced charge-storage capability of the Bi@NSC electrode. This improvement can be attributed to the incorporation of Bi nanoparticles, which provide additional Faradaic active sites beyond conventional carbon-based electrodes dominated by electrostatic ion adsorption.

The redox kinetics were further evaluated according to the relationship between peak current and scan rate: $i = av^b$. As shown in Fig. 3b, the calculated b -values for the two redox peaks were 0.50 and 0.51, respectively, suggesting that the charge-storage process is predominantly governed by diffusion-controlled processes[32]. Meanwhile, the retained redox response at high scan rates indicates that the NS-doped carbon framework facilitates electron transport and maintains efficient electrochemical accessibility of Bi active sites.

To quantitatively distinguish the capacitive and diffusion-controlled contributions, the current response was further separated at different scan rates (Fig. 3c). The contribution from pseudocapacitive storage

increased continuously with increasing scan rate, from 14.85% at 5 mV s^{-1} to 75.32% at 100 mV s^{-1} , indicating accelerated surface-controlled charge storage under rapid electrochemical operation. At 30 mV s^{-1} , the pseudocapacitive contribution reached 36.59% (Fig. 3d), confirming the significant contribution of fast surface-controlled processes.

Overall, Bi@NSC integrates Faradaic-active Bi nanoparticles with an NS-doped conductive carbon framework, enabling synergistic capacitive and Faradaic charge storage. Such a hybrid charge-storage mechanism provides an electrochemical basis for enhanced charge utilization and rapid salt removal in the subsequent Bi@NSC-based FCDI system.

3.4. FCDI performance

The influence of flow-field configuration on the desalination performance of the Bi@NSC flow-electrode system was investigated under identical operating conditions. As shown in Fig. 4a, b, all three flow channels (STSC, ASC, and WSC) exhibited continuous decreases in conductivity and C_t/C_0 , confirming the effective removal of NaCl from the feed solution. The corresponding NaCl concentrations were calculated based on the conductivity–concentration calibration curve (Fig. S1). Distinct differences in desalination kinetics were observed among the three channel configurations. After 1800 s of operation, the WSC configuration reduced the NaCl concentration to 500 mg L^{-1} , corresponding to a removal efficiency of 50.0% and a salt adsorption capacity (SAC) of 10.0 mg g^{-1} . In comparison, the ASC and STSC configurations achieved removal efficiencies of 46.0% and 41.0%, with corresponding SAC values of 9.2 and 8.2 mg g^{-1} , respectively. These results indicate that the WSC configuration provides a more favorable flow environment for Bi@NSC slurry transport, thereby improving desalination performance.

As shown in Fig. S2, EIS analysis further demonstrated distinct resistive responses among the three flow-field configurations. The fitted R_s values of STSC, ASC, and WSC were 23.7, 18.5, and 20.1Ω , respectively, with ASC exhibiting the lowest R_s , suggesting reduced overall ohmic losses associated with its smoother flow path. In contrast, the corresponding R_{ct} values were 1.68, 2.11, and 1.23Ω , with WSC showing the lowest value, 26.8% and 41.7% lower than those of STSC and ASC, respectively. The difference between the R_s and R_{ct} trends indicates that bulk transport and interfacial charge transfer are affected differently by channel geometry. The periodic undulation of WSC promotes continuous slurry redistribution and particle renewal, which favors dynamic particle–current-collector contact and consequently lowers the interfacial charge-transfer resistance. This electrochemical response is consistent with the superior desalination performance observed for the WSC configuration.

After identifying WSC as the optimal flow-field configuration, the effect of flow-electrode rate on desalination performance was further evaluated (Fig. 4c). Increasing the flow-electrode rate from 5 to 20 mL min^{-1} accelerated the conductivity decay, indicating enhanced NaCl removal kinetics at higher slurry circulation rates. This improvement is mainly associated with the accelerated renewal and redistribution of Bi@NSC particles, which increases particle–particle interactions and particle–current collector contact frequency. In addition, the enhanced hydrodynamic disturbance reduces the diffusion boundary

layer around the particles, thereby facilitating ion transport and charge transfer processes. However, the improvement became less pronounced at higher flow rates, suggesting that the desalination process gradually shifted from external mass-transfer limitation toward limitations associated with particle charging and interfacial electrochemical processes. Therefore, an appropriate flow-electrode rate is required to balance particle transport, effective charging time, and energy consumption.

The influence of Bi@NSC concentration on desalination performance was subsequently investigated (Fig. 4d). Increasing the Bi@NSC concentration from 1 to 10 wt% resulted in improved desalination kinetics, which can be attributed to the increased number of electrochemically active particles and enhanced conductive network within the flow electrode. The higher particle concentration provides more available pathways for electron transport and more active interfaces for salt storage, thereby improving electrode utilization. However, further increasing the Bi@NSC concentration to 20 wt% led to a slight decline in desalination performance, likely due to the increased slurry viscosity and reduced particle mobility. Excessive solid loading may hinder effective particle dispersion and weaken the dynamic contact between particles and the current collector. These results indicate that an optimal Bi@NSC concentration should be achieved by balancing electrochemical activity and flowability of the slurry electrode.

The effect of applied voltage on the desalination performance was further examined (Fig. 4e). Increasing the applied voltage from 0.8 to 1.8 V continuously enhanced the conductivity decay, owing to the strengthened electric-field driving force for ion migration and improved charging of the Bi@NSC flow electrode. A significant improvement was observed when the voltage increased from 0.8 to 1.5 V, whereas further increase to 1.8 V resulted in only limited enhancement. This phenomenon suggests that the desalination process gradually becomes constrained by ion transport and interfacial charge-transfer kinetics rather than the applied electrical driving force. Therefore, although higher voltage promotes desalination, an appropriate operating voltage is essential to achieve a balance between desalination efficiency and energy consumption.

Finally, the desalination performance under different initial NaCl concentrations was evaluated to assess the applicability of the Bi@NSC-FCDI system under various salt-loading conditions (Fig. 4f). The system maintained continuous NaCl removal over the investigated concentration range (500–2000 mg L⁻¹), demonstrating good adaptability toward different saline conditions. However, the conductivity decay rate decreased with increasing initial NaCl concentration, which can be attributed to enhanced concentration polarization and increased ion transport resistance under higher salt loading. Despite this limitation, the Bi@NSC flow electrode maintained stable desalination behavior, highlighting its potential for treating low-salinity and brackish water streams.

3.5. Effect of flow-field architecture on Bi@NSC slurry transport behavior

To elucidate the underlying mechanism of the enhanced desalination performance induced by flow-field regulation, the velocity distribution and particle transport behavior of Bi@NSC slurry in different channels were investigated by COMSOL Multiphysics simulation[33, 34]. As shown in Fig. 5a–c, all three channels exhibited typical laminar flow characteristics; however, significant differences in local velocity distribution were observed due to the distinct channel geometries. In the STSC configuration (Fig. 5a), abrupt changes in flow direction at the turning regions generated pronounced velocity gradients, accompanied by obvious low-velocity zones near the inner corners and channel walls. The enlarged local velocity profile further confirmed the formation of non-uniform flow regions caused by flow separation and insufficient momentum transfer. In comparison, the ASC structure with smoother curvature alleviated the local flow disturbance and reduced velocity fluctuation (Fig. 5b). However, the limited curvature regulation still resulted in uneven velocity distribution at the bending regions. Notably, the WSC configuration exhibited a more homogeneous velocity field with reduced velocity gradients throughout the channel (Fig. 5c). The periodic wavy structure continuously disturbed the slurry flow and promoted redistribution of fluid velocity, thereby minimizing stagnant regions and improving the dynamic transport environment of Bi@NSC particles.

The corresponding particle distribution simulations further revealed the influence of flow-field architecture on slurry dispersion and particle utilization (Fig. 5d–f). In the STSC channel (Fig. 5d), Bi@NSC particles tended to accumulate near sharp turns and low-velocity regions, indicating insufficient particle renewal during continuous circulation. Such particle aggregation may reduce the effective contact between Bi@NSC particles and the electrolyte, thereby limiting ion transfer and active-site accessibility. The ASC channel exhibited improved particle dispersion due to the smoother flow pathway (Fig. 5e); however, localized particle enrichment was still observed near curved regions. In contrast, the WSC channel maintained a more uniform particle distribution with significantly reduced aggregation behavior (Fig. 5f). The periodic contraction–expansion units generated continuous hydrodynamic perturbation, facilitating particle migration and enhancing particle–collector interactions. Previous two-phase CFD studies have similarly demonstrated that improved spatial distribution of conductive particles favors the formation of effective charge-percolation pathways and consequently promotes charge transfer within flow electrodes [35, 36].

The improved slurry transport behavior in the WSC channel provides a favorable hydrodynamic environment for the Bi@NSC flow electrode. The reduced low-velocity regions and enhanced particle dispersion can promote continuous exposure of electroactive Bi sites, accelerate ion transport across the electrode/electrolyte interface, and improve the utilization efficiency of the composite flow electrode[36, 37]. Therefore, the superior NaCl desalination performance observed in the Bi@NSC-WSC FCDI system can be attributed not only to the enhanced capacitive/Faradaic charge-storage capability of Bi@NSC, but also to the optimized flow-field regulation provided by the WSC architecture. These results demonstrate that coupling advanced flow-electrode materials with rational flow-channel engineering is an effective strategy for improving the practical performance of FCDI systems.

4. Conclusion

In summary, a Bi@NSC composite flow electrode coupled with a wavy-shaped channel was developed for enhanced FCDI desalination through the synergistic regulation of electrode composition and flow-field structure. The Bi@NSC electrode integrated capacitive and Faradaic charge-storage mechanisms, where Bi nanoparticles provided additional redox-active sites and the N/S co-doped carbon framework facilitated electron transport. Under identical operating conditions, the Bi@NSC-WSC FCDI system achieved a NaCl removal efficiency of 50.0% and a salt adsorption capacity of 10.0 mg g^{-1} , which were higher than those of the STSC (41.0%, 8.2 mg g^{-1}) and ASC (46.0%, 9.2 mg g^{-1}) configurations. Furthermore, COMSOL simulations indicated that the WSC architecture reduced low-velocity regions and improved the flow-field distribution, which may facilitate Bi@NSC slurry transport and mitigate particle accumulation during operation. These findings suggest that the integration of Faradaic-active flow electrodes with optimized flow-channel architectures provides an effective approach for improving FCDI desalination performance.

Declarations

CRedit authorship contribution statement

Lijun Zhang original draft, Methodology, Investigation, Funding acquisition, Conceptualization, Formal analysis. **Xiaoshi Yi**: Visualization, Formal analysis, Writing. **Yarui Song**: Writing – review & editing, Supervision, Resources, Validation. **Baochuan Qi**: Writing – review & editing, Funding acquisition, Formal analysis, Data curation, Visualization.

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.

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Schemes

Scheme 1 is available in the Supplementary Files section

Figures

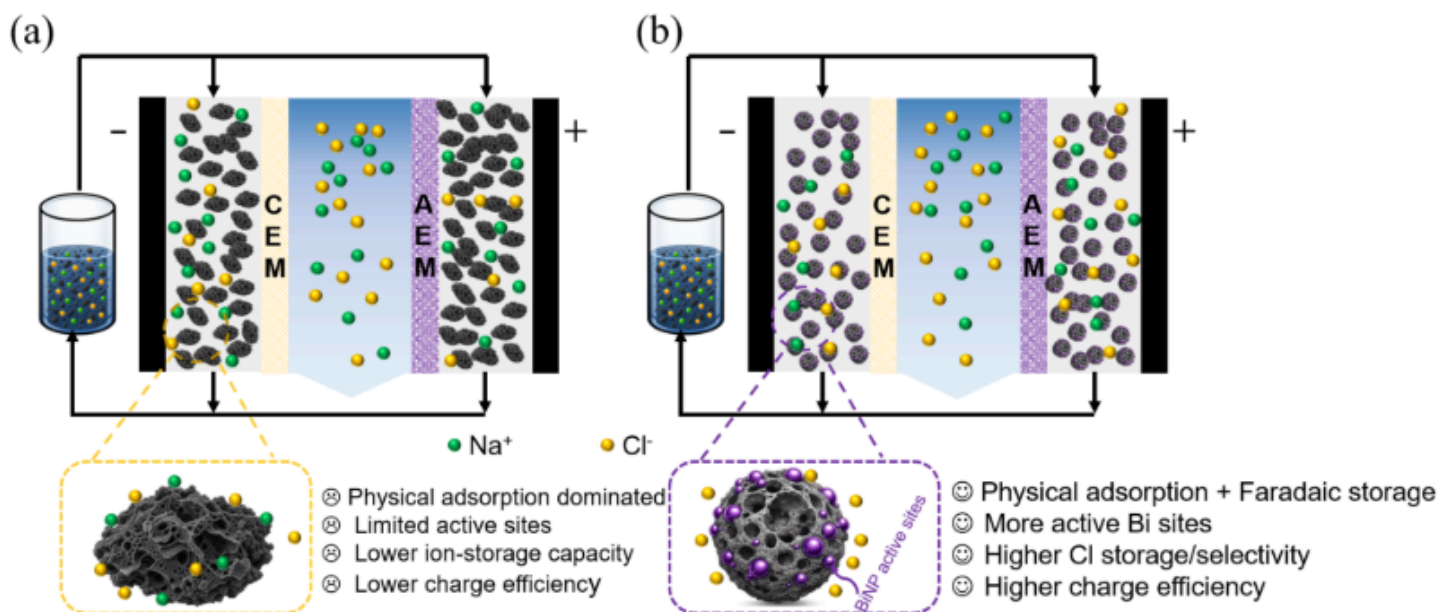


Figure 1

Design strategy of Bi@NSC composite flow electrode for enhanced FCDI desalination. Schematic illustration of (a) conventional carbon-based flow electrode relying mainly on capacitive charge storage and (b) Bi@NSC flow electrode integrating coupled capacitive and Faradaic charge storage.

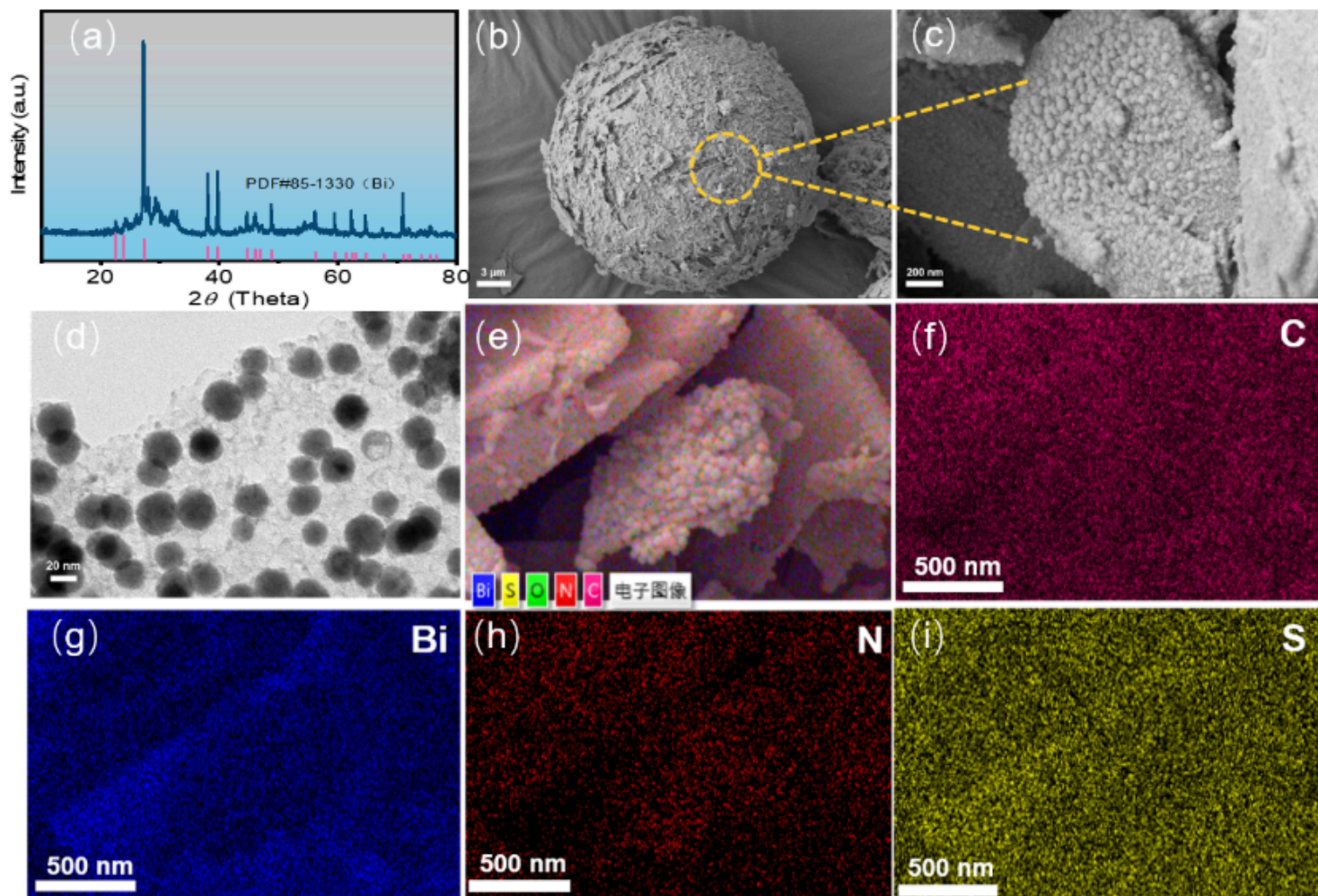


Figure 2

Structural and morphological characterization of Bi@NSC. (a) XRD pattern; (b, c) SEM images at different magnifications; (d) TEM image; (e) STEM image of the selected region for elemental mapping; and (f–i) corresponding EDS elemental mappings of C, Bi, N, and S, respectively.

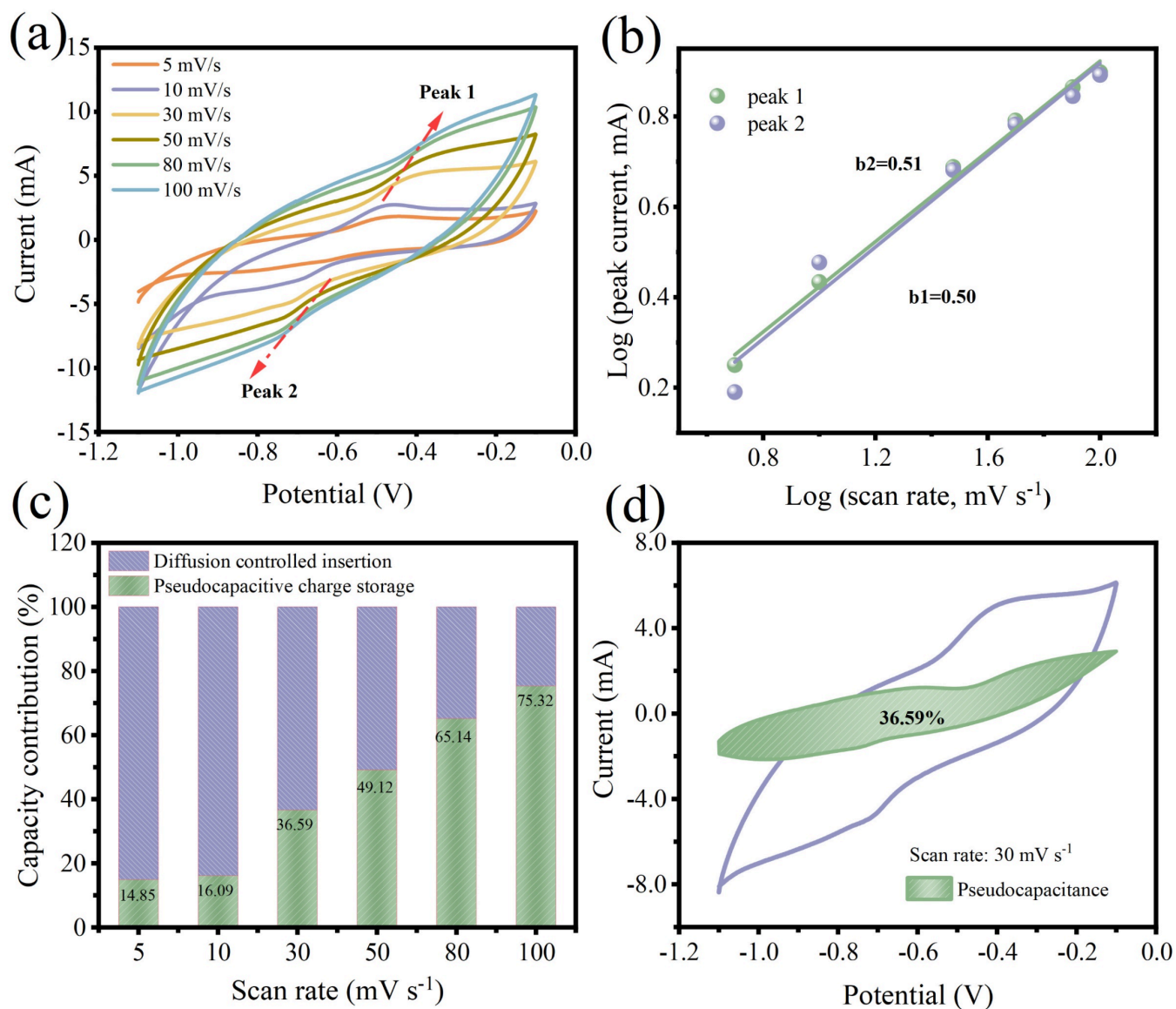


Figure 3

Electrochemical charge-storage behavior and pseudocapacitive contribution of Bi@NSC electrode: (a) CV curves at different scan rates; (b) relationship between peak current and scan rate; (c) capacitive and diffusion-controlled charge contributions at different scan rates; and (d) representative separation of pseudocapacitive contribution at 30 mV s^{-1} .

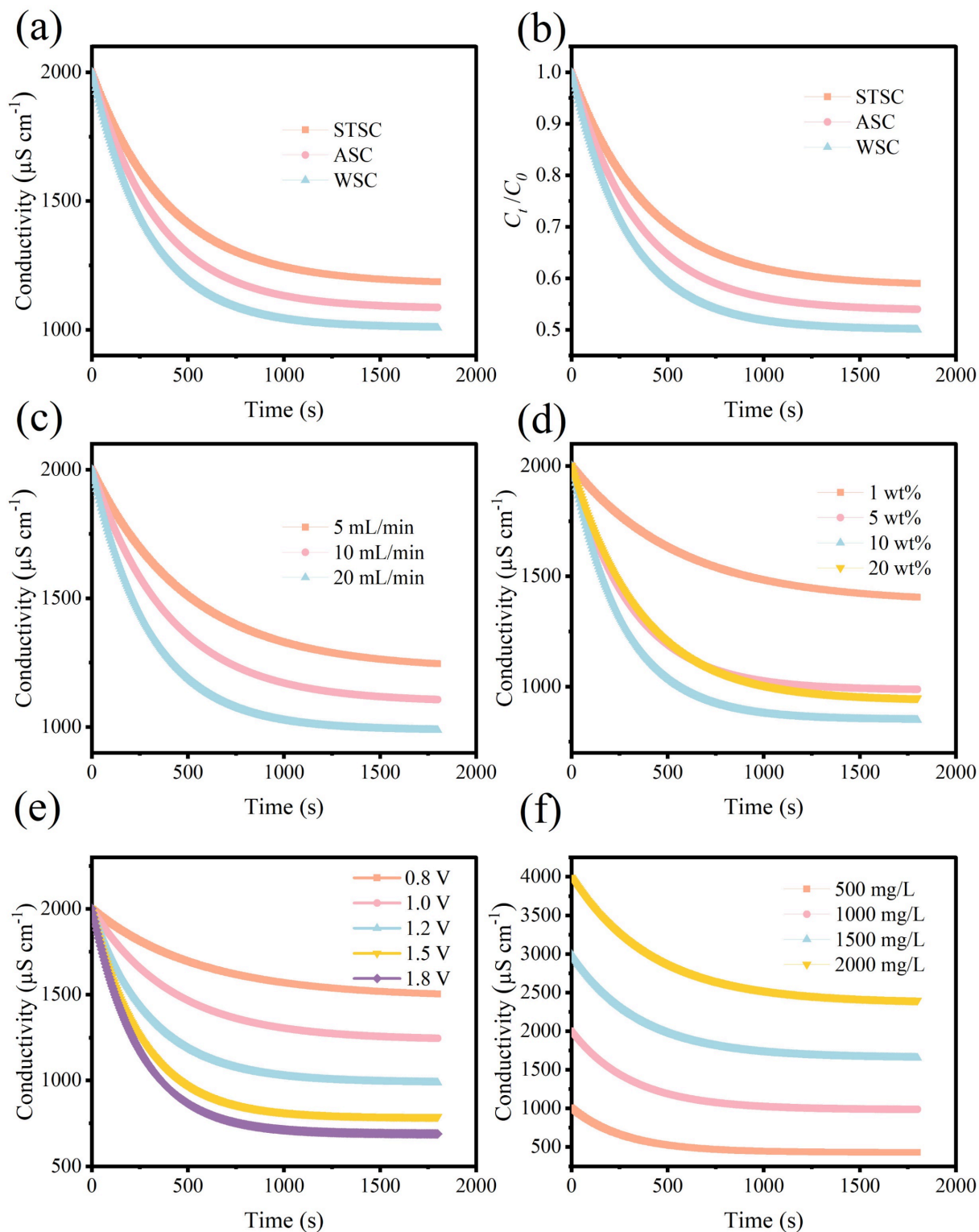


Figure 4

Effects of flow-field configurations and operating parameters on the NaCl desalination performance of Bi@NSC-FCDI system: (a,b) Time-dependent conductivity and normalized salt concentration (C_t/C_0) profiles under different flow-field configurations (STSC, ASC, and WSC). Experimental conditions: Bi@NSC concentration of 5 wt%, flow-electrode rate of 20 mL min⁻¹, applied voltage of 1.2 V, and initial NaCl concentration of 1000 mg L⁻¹. (c) Effect of flow electrode rate on desalination performance.

Experimental conditions: WSC flow channel, Bi@NSC concentration of 5 wt%, applied voltage of 1.2 V, initial NaCl concentration of 1000 mg L⁻¹, and flow-electrode rates of 5, 10, and 20 mL min⁻¹. (d) Effect of Bi@NSC concentration on desalination performance. Experimental conditions: WSC flow channel, flow-electrode rate of 20 mL min⁻¹, applied voltage of 1.2 V, initial NaCl concentration of 1000 mg L⁻¹ and Bi@NSC concentrations of 1, 5, 10, and 20 wt%. (e) Effect of applied voltage on desalination performance. Experimental conditions: WSC flow channel, Bi@NSC concentration of 5 wt%, flow-electrode rate of 20 mL min⁻¹, initial NaCl concentration of 1000 mg L⁻¹, and applied voltages of 0.8, 1.0, 1.2, 1.5, and 1.8 V. (f) Effect of initial NaCl concentration on desalination performance. Experimental conditions: WSC flow channel, Bi@NSC concentration of 5 wt%, flow-electrode rate of 20 mL min⁻¹, applied voltage of 1.2 V, and initial NaCl concentrations of 500, 1000, 1500, and 2000 mg L⁻¹.

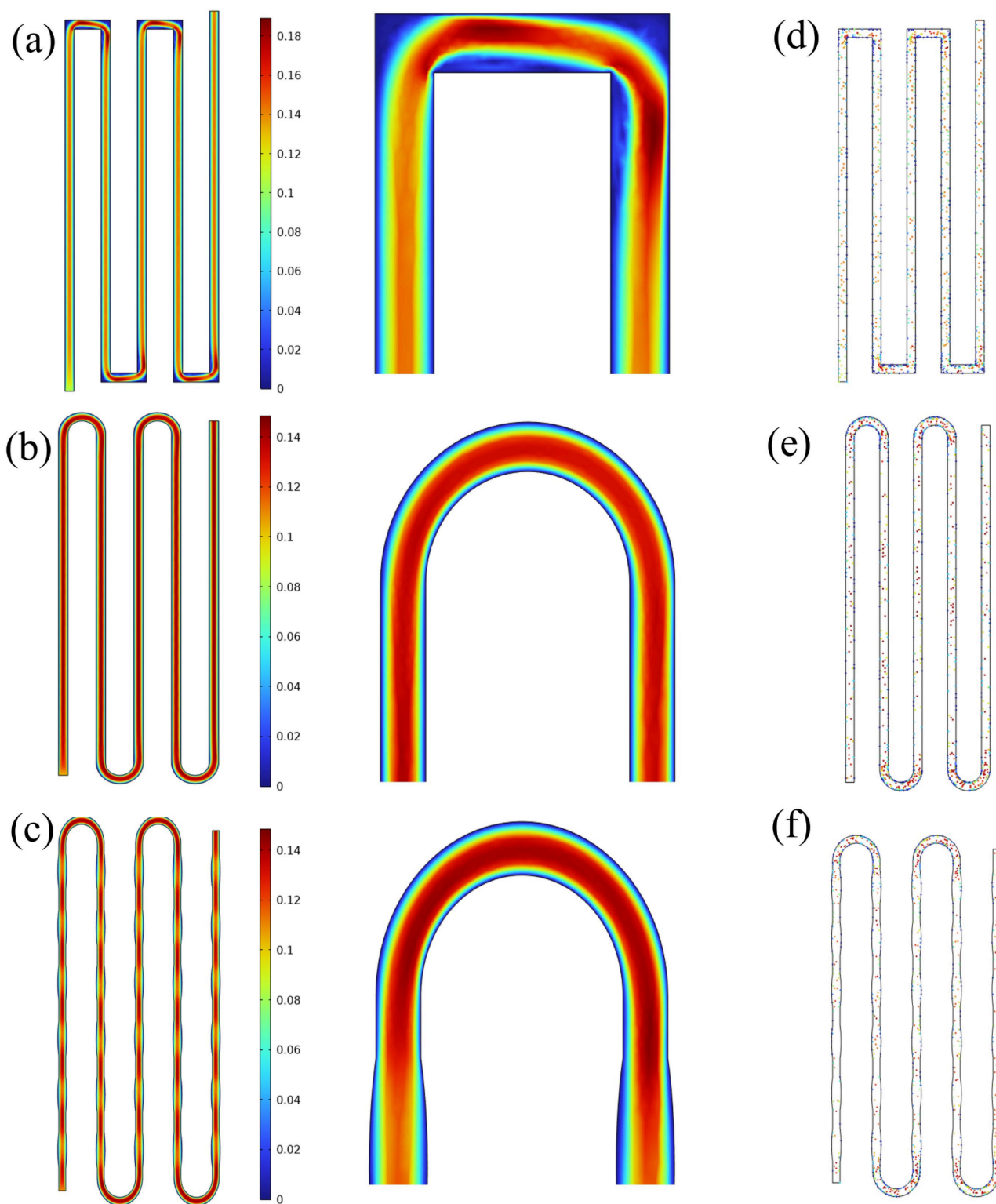


Figure 5

Hydrodynamic regulation of Bi@NSC flow electrode by different channel architectures: (a–c) Simulated velocity distributions and local magnified flow fields; (d–f) simulated Bi@NSC particle distributions in STSC, ASC, and WSC channels.

Supplementary Files

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