



Review of the forming progress and challenges of carbon-resin composite bipolar plates and their flow field

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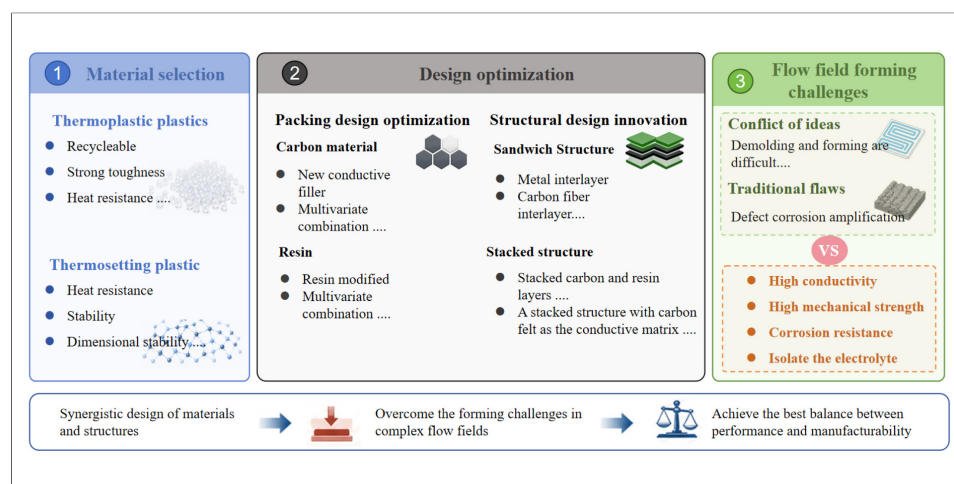
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Abstract

With the rapid development of large-scale energy storage technologies, redox flow batteries are considered a promising pathway for large-scale energy storage due to their advantages of decoupled energy and power, long cycle life, and high safety. As key components that affect battery efficiency and lifetime, bipolar plates not only serve as current collectors and structural supports but also enable electrolyte distribution via surface flow fields. Carbon-resin composite bipolar plates have become a research hotspot due to their outstanding compositional tunability and structural design flexibility. Adding a flow field to these bipolar plates can efficiently enhance battery efficiency without the need for additional material development. But as flow field structures become increasingly complex, carbon-resin composite bipolar plates face new manufacturing challenges during flow field forming. Unlike previous reviews that focus solely on the forming of bipolar plates while neglecting the additional challenges posed by flow fields, this review summarizes recent progress in material design optimization and structural innovation for carbon-resin composite bipolar plates. It analyzes the design characteristics of various flow field structures and their corresponding forming challenges. These insights provide a reference for further improvement and large-scale manufacturing of carbon-resin composite bipolar plates with integrated flow fields.



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INTRODUCTION

Since the first industrial revolution, fossil fuels have long dominated the global power supply. Their excessive use not only raises concerns about energy security but also leads to numerous severe environmental problems, including air pollution, greenhouse gas emissions, and acid rain^[1,2]. These challenges drive the urgent search for clean alternative energy sources. Renewable energy sources with extremely low greenhouse gas emissions, such as solar, wind, and tidal energy, have become important options for sustainable electricity generation^[3]. However, the inherent intermittency and unpredictability of these resources may cause fluctuations in the power grid and reduce the reliability of the electricity supply. Therefore, large-scale energy storage systems are urgently needed to smooth these fluctuations and stabilize the grid^[4,5].

Among various energy storage technologies, electrochemical energy storage systems have attracted significant attention due to their high efficiency, flexibility, and scalability. However, for large-scale energy storage technologies, high system power and capacity mean that safety incidents can cause severe damage and losses. Therefore, safety and reliability are the primary requirements for energy storage technologies^[6]. Carbon-based materials have broad application potential in electrochemistry due to their high electrical conductivity, high specific surface area, and chemical stability. Its unique properties stem from the precise atomic-scale structure, including the sp^2 -hybridized carbon-atom network and the delocalized π -electron system. In electrochemical applications, the design of carbon-based materials has emerged as a cutting-edge research frontier. Cutting-edge technologies focus on multiscale structural regulation and synergistic functional optimization to enhance catalyst performance and stability. These applications span multiple fields, including fuel cells, metal-air batteries, water electrolysis, carbon dioxide (CO_2) reduction, and sensors^[7,8]. Since its initial development by NASA in the 1970s^[9], redox flow battery (RFB) technology has undergone extensive exploration of various redox couples and continuous optimization of reaction structures^[10-13], gradually evolving from microgrid demonstrations toward large-scale grid applications^[14]. Owing to their intrinsic safety characteristics, RFBs have become one of the most promising and irreplaceable technologies for large-scale energy storage [Figure 1].

RFBs are a class of electrochemical energy storage systems that store and release energy through reversible redox reactions in liquid electrolytes^[15]. Taking the typical vanadium redox flow battery (VRFB) as an example, its basic configuration consists of a stack, electrolyte storage tanks, and circulation pumps^[16]. The active species are dissolved in the electrolyte, stored in separate tanks, and then pumped into the stack, where redox reactions occur within the reaction cells, thereby completing the charge and discharge processes. Unlike conventional lithium-ion batteries, the power of RFB systems is determined by stack size, whereas energy capacity is governed by electrolyte volume. This configuration enables independent control of power and energy^[17]. Although VRFBs exhibit significant advantages in system stability and cycle life, challenges remain regarding energy efficiency, volumetric power density, and cost control^[18].

As the core component of RFB systems, the overall performance of the stack largely depends on the integrated performance of several key materials^[19]. The bipolar plate is a core component of a flow battery, and its performance directly affects the battery stack's output power, service life, and cost. The bipolar plate plays multiple roles within the stack and accounts for 24%-38% of the total cost. In addition, the proportion of the bipolar plate and current collector that is in contact decreases with increasing numbers of battery cells, from 1%-22%. The bipolar plates perform the following critical functions: (1) Separation and sealing: Physically isolate the electrolyte between the positive and negative sides, preventing direct mixing of electrolytes that could pose hazards; (2) Current conduction: Act as a conductive bridge between the positive and negative electrodes, collecting and conducting electrons while connecting multiple individual cells in series; (3) Reduced pressure drop and optimized electrolyte distribution: The meticulously designed flow fields on the plate surface enable electrolyte transport without passing through the electrodes, significantly

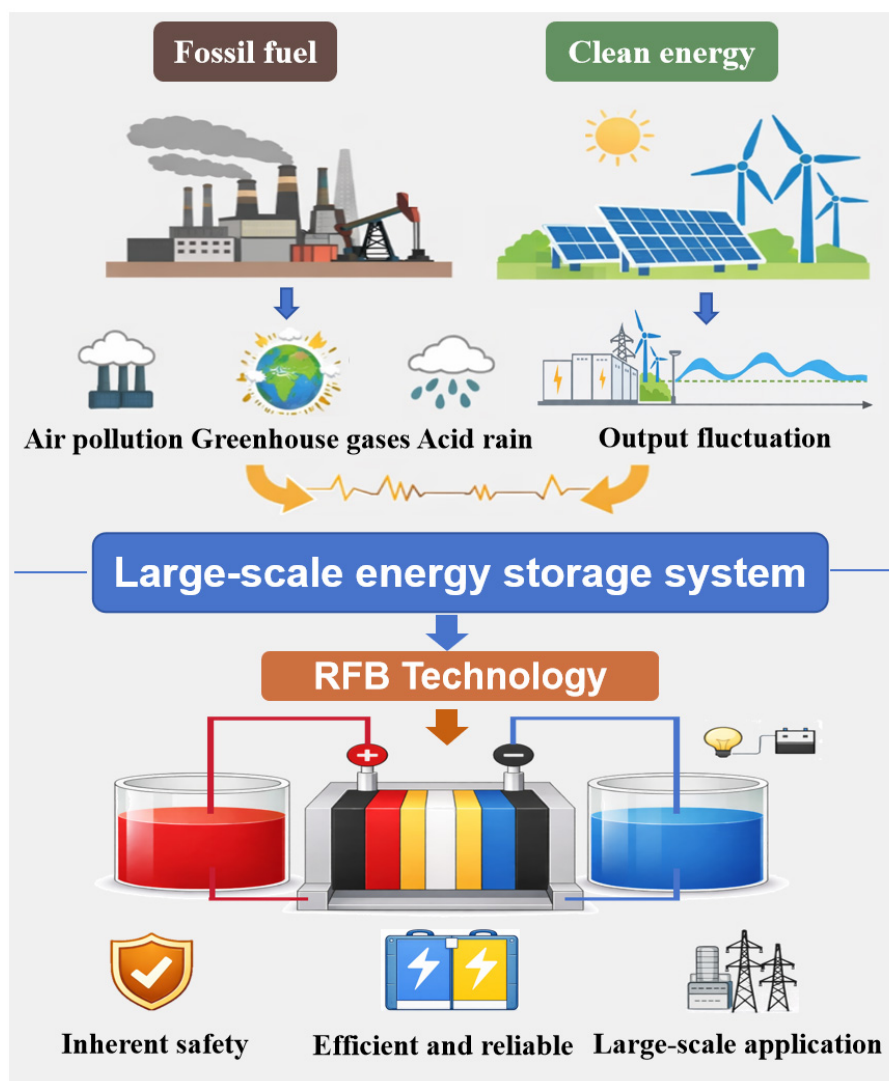


Figure 1. Environmental impacts of traditional energy industries and advantages of renewable energy. RFB: Redox flow battery.

enhancing delivery efficiency while minimizing pressure drop and ensuring efficient reaction progression; (4) Mechanical properties: Serve as a support structure for the battery stack^[20]. Therefore, the material selection and structural design of bipolar plates directly determine the stack's internal resistance and mechanical reliability. They also critically influence the battery system's long-term stability, ultimately determining its energy efficiency and cycle life. Meanwhile, the introduction of the flow field can enhance overall performance without increasing the cost of additional material research and development^[21].

Due to the extremely harsh operating environment of RFB systems, although bipolar plates play similar roles in many electrochemical energy storage devices, the material selection of BPs in RFBs is severely restricted^[22]. Therefore, despite their excellent electrical conductivity and mechanical strength, metallic bipolar plates without protective coatings are difficult to use in flow batteries with highly corrosive electrolytes^[23]. Even corrosion-resistant metals such as stainless steel and titanium alloys may suffer from pitting corrosion, crevice corrosion, or passive film failure during long-term operation. Once corrosion occurs, insulating corrosion products formed on the bipolar plate surface significantly increase contact resistance^[24]. In addition, dissolved metal ions may enter the electrolyte, disrupting its chemical stability^[25]. Currently, only a few studies attempt to unlock the potential of metallic bipolar plates through surface protection strategies^[26].

For example, Han *et al.* fabricated an electrocatalytically active bipolar plate by anodizing a titanium substrate to form a TiO_2 nanotube array. Subsequently, an IrO_x coating was deposited on the surface^[27]. Compared with graphite bipolar plates, the battery's voltage and energy efficiencies increase by 3%–4%. However, due to the relatively high density of metals, metallic bipolar plates are unfavorable for large-scale applications. Moreover, the use of noble metals or corrosion-resistant coatings leads to high costs and complex fabrication processes. On the other hand, non-porous graphite plates suffer from several drawbacks, including high brittleness, susceptibility to cracking, difficulties in machining, high cost, limited sealing performance, and relatively large weight. These limitations make it difficult to meet the requirements of flow batteries for large size, low cost, and high reliability^[28–30].

Overall, carbon-resin composite bipolar plates (CBPs) achieve good electrical conductivity while maintaining corrosion resistance by introducing a polymer resin matrix into conductive carbon materials. In addition, their relatively low density and formability via extrusion or compression molding make them suitable for mass production and the integrated manufacturing of complex flow fields. These advantages provide significant benefits for cost control and large-scale applications. CBPs not only effectively alleviate the brittleness and machining difficulties associated with graphite plates but also achieve a favorable balance among electrical conductivity, mechanical strength, corrosion resistance, and formability^[31]. However, this material-level balance does not directly translate into manufacturable performance when complex flow fields are introduced. It is fundamentally constrained by the coupling between material system selection (e.g., thermoplastic vs. thermosetting matrices, filler characteristics) and the geometric complexity and precision requirements of flow field structures, which together determine the flow field's formability.

A well-designed flow field can optimize the velocity distribution and the electrolyte concentration gradient on the electrode surface, thereby reducing concentration polarization and pressure-drop losses while improving the utilization of active species^[32,33]. Meanwhile, as flow field structures become increasingly complex and refined, the issue of forming precision for BPs becomes more prominent. Carbon-resin composites are typically fabricated through compression molding or extrusion processes^[34]. Their flow behavior, filler distribution, and shrinkage characteristics directly affect the dimensional precision (the degree of conformity between the actual and designed sizes) and surface quality (surface flatness or roughness, *etc.*) of microscale flow fields^[35]. Various forming defects may not only alter the actual fluid resistance and flow distribution but also influence electrode compaction and interfacial contact resistance^[36–38]. In addition, resin enrichment at the surfaces of the flow fields or uneven orientation of conductive carbon fillers may reduce local electrical conductivity and structural strength, thereby increasing the risk of deformation or leakage during long-term operation^[39,40]. Therefore, in CBP systems, material design and structural design can no longer be considered independent issues but rather a coupled process requiring coordinated optimization. Forming processes are required to ensure precise replication of flow field structures. How to achieve high-precision flow field replication and long-term structural stability while maintaining the formability of large-scale manufacturing has become a key scientific and technological challenge for the further engineering application of CBPs.

As shown in [Figure 2](#), this paper systematically reviews the development trajectory and recent progress in research on CBPs in RFBs. From multiple perspectives, including filler design, structural optimization, and flow field formation, the latest advances and representative achievements of CBPs for RFBs are summarized.

Particular attention is given to the potential influence of the current optimization strategies for thermoplastic and thermosetting CBPs on flow field forming. In addition, based on recent developments in flow field design, this paper systematically discusses the corresponding forming challenges. These analyses provide useful references for the development of RFBs with high performance, low cost, and long service life. They

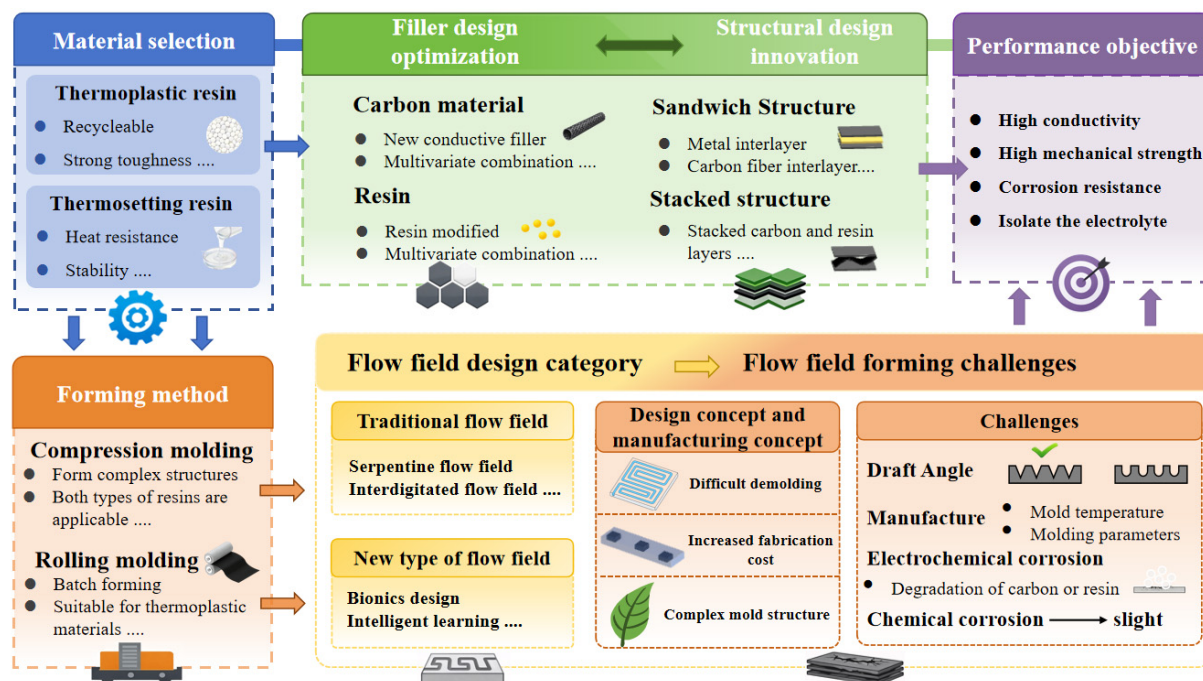


Figure 2. Innovative design strategies of carbon-resin composite bipolar plates and the challenges in flow field formation.

also establish a theoretical and engineering foundation for subsequent studies on material selection, structural and flow field optimization, and precision forming processes of CBPs.

CLASSIFICATIONS AND IMPROVEMENTS OF CBPS

CBPs are typically composed of conductive carbon materials (such as graphite, carbon black, and carbon fibers) and polymer matrices, including thermosetting and thermoplastic resins^[41,42]. The carbon components establish conductive pathways, whereas the polymer matrix offers structural robustness and processability. Importantly, the selection of a filler system not only determines the intrinsic properties of CBPs but also directly governs their formability (the material's ability to be shaped into a desired geometry) and manufacturability (the practical feasibility of producing the component at scale), especially for flow field structures. Through rational design, a balance between electrical conductivity and mechanical strength can be achieved.

Thermoplastic CBPs use thermoplastic polymers such as polypropylene (PP), polyethylene (PE), and polytetrafluoroethylene (PTFE) as the matrix^[43]. These materials soften upon heating and solidify upon cooling, exhibiting good processability and recyclability^[44]. Simultaneously, its ability to be processed by melting allows for the effective reproduction of flow field structures via continuous forming methods. Processes such as hot pressing, extrusion molding, and rolling allow rapid forming and large-area manufacturing, thereby significantly reducing production costs^[45,46]. However, a high content of conductive fillers markedly decreases melt flowability and weakens interfacial bonding strength. Meanwhile, thermoplastic resins generally possess relatively low thermal resistance and dimensional stability, making them susceptible to creep deformation under long-term compression or elevated operating temperatures^[47].

Thermosetting CBPs typically employ resins such as phenolic resin (PF) and epoxy resin (EP) as the matrix. During curing, these resins form highly crosslinked three-dimensional network structures. Such structures provide excellent dimensional stability and enable the accurate retention of molded flow field geometries.

Their main advantages are the dense structure formed after curing and superior thermal resistance, making them suitable for relatively harsh operating environments^[48]. From a manufacturing perspective, the irreversible curing process restricts post-forming adjustment and recycling, and introduces difficulties in achieving both high precision and in flow field fabrication. In addition, the curing process of thermosetting resins is irreversible, leading to long processing cycles and difficulty in recycling^[49].

In terms of forming processes, thermosetting resins are typically mixed and impregnated first, then compressed under heat and pressure to cure and shape^[50]. This approach is suitable for systems with high filler content and allows complex flow field structures to be formed in a single step. However, the irreversible curing process introduces challenges such as shrinkage stress and dimensional control. By contrast, thermoplastic resins rely on their melt-processable characteristics. Conductive fillers are usually dispersed through melt blending or extrusion mixing, followed by processes such as rolling, extrusion, or hot-press molding to construct plate structures and flow field geometries^[20,34,51]. The advantages of thermoplastic systems include reprocessability, high forming efficiency, and suitability for continuous production. Nevertheless, high filler loading significantly reduces melt flowability, making it more challenging to achieve replication accuracy and forming stability for complex micro-scale flow field structures. Recent research on CBPs has further extended into two major directions: filler design optimization and structural design innovation, both aimed at improving the overall performance of BPs. Optimization of filler design enhances conductive networks and interfacial bonding. This can be achieved by introducing novel carbon materials with different dimensional structures or by modifying existing resin systems. Meanwhile, innovations in structural design have become another important pathway for performance enhancement. Traditional homogeneous structures are increasingly unable to satisfy the requirements for high conductivity and corrosion resistance simultaneously. Consequently, researchers begin to explore multilayer, stacked, and multiscale structural design strategies. At the same time, different resin systems, combined with corresponding forming processes, exhibit distinct advantages across various aspects, offering diverse pathways for structural regulation and performance optimization of BPs.

THERMOPLASTIC CBPS

Filler design optimizations of thermoplastic CBPs

As a key component in RFBs, the BP primarily functions as a barrier separating the positive and negative electrolytes^[52]. Thermoplastic resins exhibit fluidity upon softening at elevated temperatures, allowing them to penetrate forming defects in the interior or on the surface of the BP, thereby reducing the risk of acidic electrolytes infiltrating the plate and causing internal swelling. At the same time, such flowability is essential for replicating flow field geometries but is highly sensitive to filler loading and dispersion.

Kim *et al.* spray thermoplastic PTFE in emulsion form onto expanded graphite powder^[53], as shown in [Figure 3](#). The mixture is first compression-molded into a preform and then processed through multi-step rolling for final shaping. BPs containing 6% or 10% PTFE exhibit almost no observable swelling after cycling compared with flexible graphite plates. This result indicates that the thermoplastic resin in conventional thermoplastic CBPs effectively suppresses swelling. In addition, Kang *et al.* use a similar fabrication route^[54], further confirming that PVDF, after hot pressing, effectively repairs the surface and cross-sectional microcracks in expanded graphite. It also suggests that appropriate resin distribution can improve structural integrity during forming, thereby helping maintain flow field stability.

Meanwhile, the electrical conductivity of CBPs does not increase linearly with increasing carbon content. Instead, when the content of conductive carbon materials reaches the percolation threshold, the electrical properties of the composite undergo a transition from an insulating to a conductive state. The percolation threshold of conductive fillers is strongly influenced by the particle size, morphology, and distribution of the

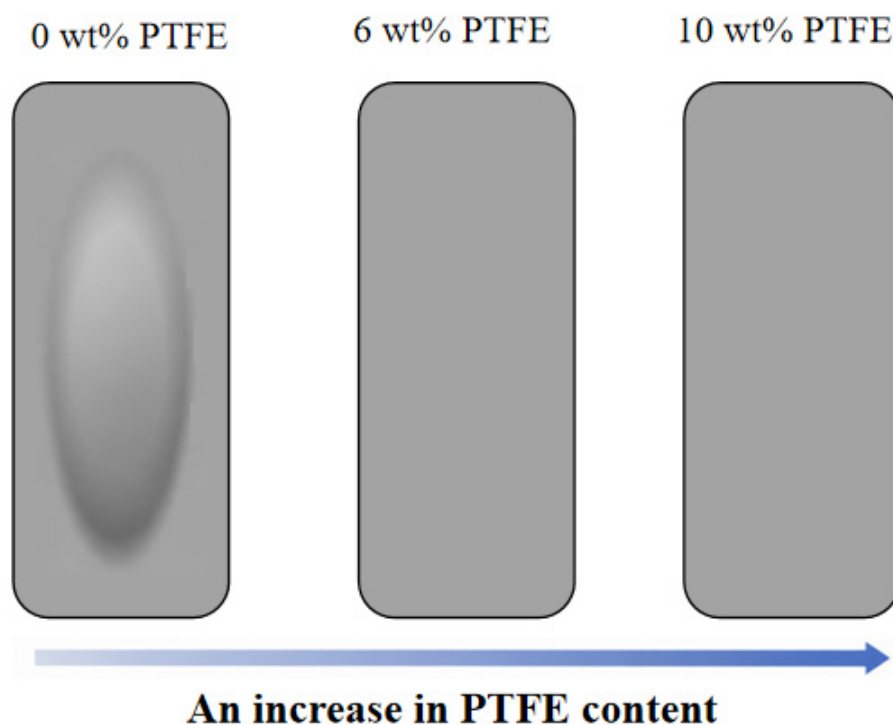


Figure 3. Surfaces of bipolar plates with different PTFE contents after single-cell cycling. PTFE: polytetrafluoroethylene.

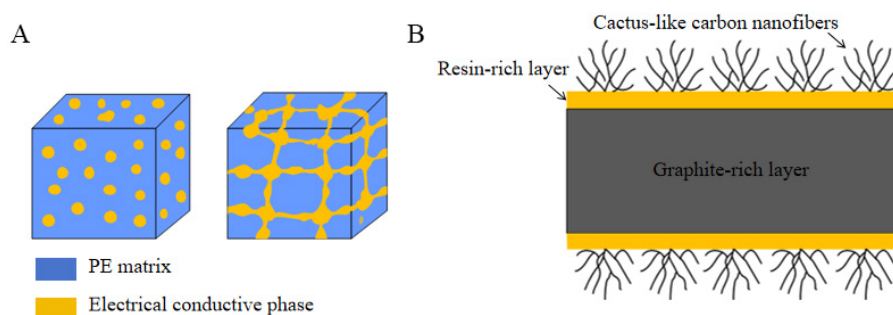


Figure 4. Schematic diagram of the conductive network and cactus-shaped carbon nanofibers (4): (A) Microstructural schematic of the highly efficient conductive network in the bipolar plate; and (B) Schematic diagram of the bipolar plate modified with C-CNF. PE: Polyethylene; C-CNF: cactus-like carbon nanofiber.

fillers within the polymer matrix^[55]. These parameters simultaneously affect rheological behavior, which directly determines the formability of flow field structures during processing. Many studies introduce a large amount of conductive filler to establish sufficient conductive pathways^[56]. However, excessive filler loading inevitably increases the risk of fracture in the BP. To address this issue, Liao *et al.* developed a ternary conductive system composed of graphene, graphite powder, and chopped carbon fibers, which forms an efficient conductive network at relatively low carbon content^[57]. At a carbon content of only 25 wt%, both the electrical and mechanical properties meet the 2020 Department of Energy (DOE)^[58] standards. Importantly, reducing filler content also helps retain sufficient flowability, which is beneficial for accurate flow field replication. Jiang *et al.* further designed cactus-like carbon nanofibers^[59]. In this structure, fibers radiate outward from a catalytic core, forming a three-dimensional clustered architecture. After graphitization at 2,800 °C, graphitized cactus-like carbon nanofibers (G-C-CNF) are obtained, which exhibit significantly improved graphitization and structural integrity. This architecture disrupts resin-rich surface layers, thereby improving both electrical contact and the effective exposure of flow field structures, as shown in Figure 4.

Table 1. Summary of main performance and conclusions of thermoplastic carbon-resin composite bipolar plate packing design

References	Main performance	Main conclusion
Kim <i>et al.</i> ^[52]	Specific through-plane resistivity (m Ω ·cm): 102.98 Single cell cyclic performance@100 mA/cm ² : 80.8%	Thermoplastic resins play a key role in inhibiting the expansion of graphite
Liao <i>et al.</i> ^[57]	ASR: 3.3 m Ω ·cm ² ; Flexural strength: 48.1 MPa; EE: 85.7% @100 mA cm ⁻²	Achieves high conductivity and strength at ultra-low carbon content via graphene bridging
Jiang <i>et al.</i> ^[59]	Conductivity: 198.7 S/cm; ASR: 25.4 m Ω ·cm ² ; EE: 86.28% @100 mA cm ⁻²	Surface CNF eliminates the resin-rich layer and enhances conductivity and durability
Qin <i>et al.</i> ^[60]	Conductivity: 103.43 S/cm; Flexural strength: 26.17 MPa; EE fluctuation: $\pm$ 1.5%	Multidimensional carbon network enables balanced performance at moderate filler content

ASR: Area-specific resistance; EE: energy efficiency; CNF: carbon nanofiber.

In addition, Qin *et al.* optimize both electrical and mechanical properties at low carbon content by incorporating multi-dimensional carbon materials^[60]. Zero-dimensional filler Ketjen black (KB), one-dimensional filler carbon nanotubes (CNTs), and two-dimensional filler flake graphite (FG) work synergistically to construct a three-dimensional continuous conductive network. Such a multi-dimensional filler design not only enhances conductivity but also improves dispersion uniformity, which is crucial for stable forming of intricate flow field geometries. Moreover, Zhang *et al.* introduce a new copolymer made from ethylene and propylene monomers^[61], known as polypropylene elastomer, which improves the processability of the composite material while maintaining excellent toughness. Table 1 is a comprehensive summary of the above-mentioned literature.

Structural design innovations of thermoplastic CBPs

The design of fillers is typically aimed at improving the performance of the BP by adjusting the ratio of carbon materials to resin. However, electrical conductivity and mechanical strength often exhibit a trade-off relationship^[62]. Therefore, simply adjusting the filler ratio cannot achieve a balance between electrical and mechanical properties. Such compositional tuning not only affects intrinsic properties but also directly influences the rheological behavior and forming capability of the composite during flow field fabrication. In addition, during the forming process, differences in flowability between the resin and fillers often lead to resin enrichment at the surface or interface. This phenomenon may interrupt conductive pathways and increase interfacial contact resistance. Filler design alone is therefore fundamentally insufficient to suppress such resin enrichment from a structural perspective.

To address these challenges in thermoplastic CBPs for VRFB, researchers have proposed a variety of structural design innovations. Onyu *et al.* develop a layered composite structure to achieve a synergistic performance enhancement^[63]. The structure adopts a stacked configuration consisting of a conductive composite layer [thermoplastic vulcanizates (TPV) combined with synthetic graphite], a woven carbon fiber fabric, and a pyrolytic graphite sheet. Such layer-wise functional separation enables local optimization of the forming process, thereby improving both structural integrity and the accuracy of flow field replication. As shown in Figure 5A, scanning electron microscopy (SEM) images reveal no obvious interfacial gaps between the layers, indicating strong interfacial bonding. Moreover, the layered structure BP has good thermal stability at high temperatures [Figure 5B]. Liu *et al.* replace powder-type conductive fillers with a carbon felt framework to construct a continuous conductive network^[39]. Thermoplastic polyvinyl fluoride (PVDF) forms a dense layer between carbon felt through solution impregnation followed by secondary hot pressing. In this design, the pre-constructed three-dimensional conductive framework reduces the dependence on high filler loading, thereby improving processability and enabling more stable formation of flow field structures. In addition, Pavel *et al.* use graphite foil as a conductive substrate and impregnate fluorinated polymers into the existing pores to construct a three-dimensional conductive pathway structure^[64]. After fluoropolymer impregnation, the graphite on the surface layer exhibits a certain tendency toward oriented distribution.

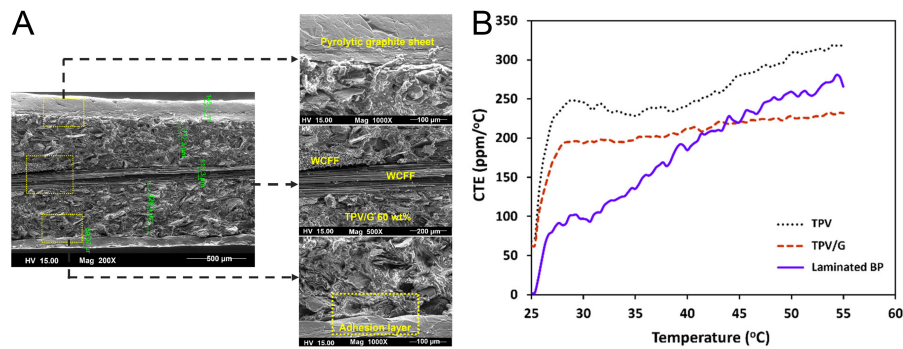


Figure 5. (A) SEM morphology of the laminated CBP; (B) The variation of the thermal expansion coefficients of TPV, TPV/G, and laminated BP with temperature. Reprinted from Ref.^[63], under CC BY 4.0 license. WCFF: Woven-carbon-fiber fabric; TPV: thermoplastic vulcanizates; CTE: coefficient of thermal expansion; SEM: scanning electron microscopy; CBP: composite bipolar plate.

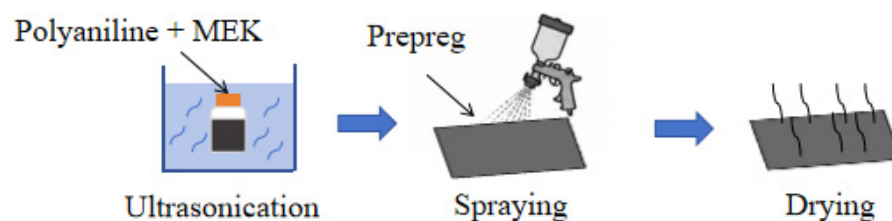


Figure 6. PANI spray preimpregnated material preparation process. MEK: Methyl ethyl ketone; PANI: polyaniline.

THERMOSETTING CBPS

Filler design optimizations of thermosetting CBPs

With increasing demands for the stability of CBPs, researchers have begun to refocus on CBPs based on thermosetting resin matrices. This shift is not only driven by performance considerations but also by the need for improved dimensional stability in flow field structures during long-term operation. Unlike thermoplastic resins, thermosetting systems form dense crosslinked networks during the curing process, which stabilize the distribution of conductive fillers even at relatively low resin content. Meanwhile, their relatively low thermal expansion coefficient and excellent structural rigidity enable superior dimensional stability and fatigue resistance during long-term operation. Such characteristics are particularly advantageous for preserving the geometric accuracy of pre-formed flow field structures under compression and thermal fluctuations. For example, Li *et al.* prepare phenolic-resin-based BPs by vacuum impregnation of expanded graphite (EG)^[65]. The uniform penetration of resin between graphite layers significantly enhances interlayer bonding strength and blocks pore fields, enabling the plate to maintain a continuous conductive network while exhibiting excellent flexural strength and gas tightness. In addition, Choe *et al.* propose a new strategy by incorporating polyaniline (PANI) conductive particles into epoxy resin^[66], as shown in Figure 6. PANI particles are sprayed onto the surface of the carbon fiber/epoxy composite system, forming localized conductive pathways within the resin matrix. The introduction of an appropriate amount of PANI significantly reduces contact resistance while maintaining good corrosion resistance and electrochemical stability. Such localized conductive design reduces the dependence on high overall filler loading, which is beneficial for maintaining processability during forming.

Structural design innovations of thermosetting CBPs

Component regulation alone cannot fully resolve issues such as the intrinsically low conductivity of the resin phase, interfacial stress concentration, and high surface resistance. More importantly, it cannot fundamentally address limitations in flow behavior and forming adaptability during flow field fabrication.

Therefore, researchers further shift their focus to structural design, aiming to achieve synergistic performance enhancement by optimizing both macroscopic structures and interfacial architectures.

In research about thermosetting composite BPs, the structural design consistently emphasizes interfacial bonding, electrical conductivity, and long-term stability. Kim *et al.* have conducted a series of studies in this field^[67]. To address crack issues in expanded graphite (EG) coatings, the team proposed a surface crack-closure method. After molding, compressive stress is applied to close microcracks in the graphite coating, thereby preventing penetration of acidic electrolyte. Such post-treatment improves structural integrity but also highlights the difficulty of controlling defects during the initial formation of flow field surfaces. In addition, Soohyun *et al.* first proposed integrating an E-glass/epoxy resin flow frame with a carbon fiber/epoxy resin matrix composite into a unified structure to eliminate the interface leakage inherent in traditional stacked components^[68]. However, the difference in thermal expansion coefficients between the two composite materials leads to severe residual curing stresses. Structural warpage and local buckling are effectively reduced by designing an intelligent curing cycle that carefully controls the curing temperature and cooling stages. Lee *et al.* proposed the soft-layer method^[69], in which a flexible release film is inserted between the prepreg and the mold during compression molding. Under pressure, the surface resin is squeezed out, exposing the conductive carbon fibers. This design significantly reduces area-specific resistance (ASR) without requiring additional graphite coating, while maintaining high mechanical strength and good gas tightness. It also establishes a processing foundation for subsequent multilayer composite structures. Based on the Soft Layer Method, the matrix is further expanded from conventional epoxy resin to a fluorinated elastomer system, while nano-carbon fillers are introduced to form a multiscale conductive network^[70]. The excellent acid-alkali resistance and flexibility of fluorinated elastomers enable the composite plate to maintain low contact resistance and excellent mechanical stability even in highly corrosive environments; their enhanced flexibility also improves deformation compatibility during forming, which is beneficial for reducing defects in complex flow field geometries. To further reduce manufacturing costs and expand application potential, the Soft Layer Method is also applied to a non-woven carbon felt/epoxy system^[71], enabling the fabrication of large-area BPs under low-pressure molding conditions. The 3D interconnected pore structure of carbon felt can form a stable vertical conductive path even under low pressure conditions, thereby reducing the sheet resistance to 22 mΩ·cm². Such low-pressure forming conditions are advantageous for scaling up manufacturing. However, they may also limit the replication accuracy of fine flow field structures due to insufficient compaction. In addition, Choe *et al.* evaluate the electrochemical corrosion durability of different graphite coatings through electrochemical aging tests^[72]. The results indicate that pyrolytic graphite, due to its highly oriented structure and stronger van der Waals bonding, exhibits significantly higher durability than conventional expanded flake graphite. Table 2 summarizes the main innovative points and conclusions of the above-mentioned achievements.

To further overcome the structural limitations of conventional stacks, many researchers propose innovative structural design strategies. These strategies aim not only to enhance conductivity and integration, but also to retain the formability required for reliable flow field fabrication. Choe *et al.* develop a CBP with an integrated current collector structure^[73], as shown in Figure 7. Through a co-curing process, a carbon fiber/epoxy prepreg and a metal current collector are simultaneously cured during a single hot-pressing step, forming a dense and pore-free continuous conductive network. This structure effectively eliminates the resistance increase associated with conventional bolted or conductive adhesive connections between the plate and the current collector, while minimizing interfacial contact resistance. At the same time, the integrated structure reduces interfacial discontinuities.

Subsequently, Choe *et al.* further construct a CBP with a “fiber spreading effect” using spread-tow fabric^[74]. Traditional one-way fabrics or thick woven fabrics frequently exhibit discontinuous in-plane conductive

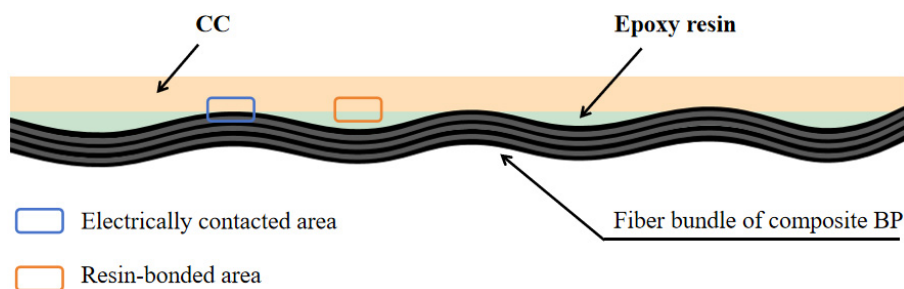


Figure 7. Schematic diagram of the cross-section of the composite structure. BP: Bipolar plate; CC: Current Collector.

Table 2. Main innovation points and conclusion summary

Reference	Key innovation	Main conclusions
Surface crack closure method	Crack closure for defect repair	Effectively improves gas-tightness and reduces interfacial contact resistance by repairing surface defects
Smart curing cycle	Optimized curing to reduce residual stress	Significantly alleviates thermal residual stress and enhances structural stability
Carbon fiber exposure method	Fiber exposure to enhance conductivity	Promotes conductive pathway continuity and lowers contact resistance
Nano-carbon/fluoroelastomer composite BP	Fluoroelastomer-based conductive composite	Achieves a balance of high mechanical strength, good conductivity, and excellent chemical stability
Nonwoven carbon felt + soft-layer method	Felt-based conductive network with soft-layer	Enables low-pressure fabrication while meeting conductivity requirements and maintaining acceptable mechanical properties
Graphite-coated durability study	Graphite coating with ASR-modulus model	Establishes a structure-property relationship and improves durability and electrochemical stability

BP: Bipolar plate; ASR: area-specific resistance.

paths due to fiber undulation and resin retention. Spread-tow prepreps with fiber bundle sizes of 10k and 20k are prepared by hand weaving, significantly reducing thickness undulation and resin-rich regions at fiber crossover points. Such structural uniformity improves local flow behavior during forming, which is essential for achieving high-precision flow field structures. Combined with the Soft Layer Method, excess resin is squeezed out during the compression molding process, thereby achieving complete exposure of carbon fibers while maintaining high. In addition, Jeong *et al.* propose a horizontally aligned carbon nanotube /epoxy nanocomposite BP (HACN-BP) structure^[75]. In this design [Figure 8], vertically aligned CNT arrays are rearranged via a “knocking-down” process, allowing the nanotubes to form a highly oriented, dense network in the in-plane direction, thereby establishing bidirectional conductive pathways. The CNT network significantly reduces electrolyte penetration and side reactions while maintaining high mechanical strength, demonstrating the great potential of controllable nanoscale conductive architectures in BP engineering.

Research trends indicate significant differences in the research focus between thermoplastic and thermosetting composite bipolar plates (CBPs). Studies on thermoplastic systems primarily concentrate on optimizing filler design, whereas those on thermosetting systems place greater emphasis on innovations in structural design. This difference primarily stems from the fundamentally distinct inherent properties, interfacial behaviors, and processing constraints of the two matrix materials. Thermoplastic and thermosetting composite materials exhibit essential differences in their processing behavior that directly influence the patterns of flow field formation. Thermoplastic resins soften and flow when heated, enabling optimal mold filling and high molding efficiency. This makes them particularly suitable for replicating complex flow field geometries and ideal for continuous manufacturing processes. However, a high filler

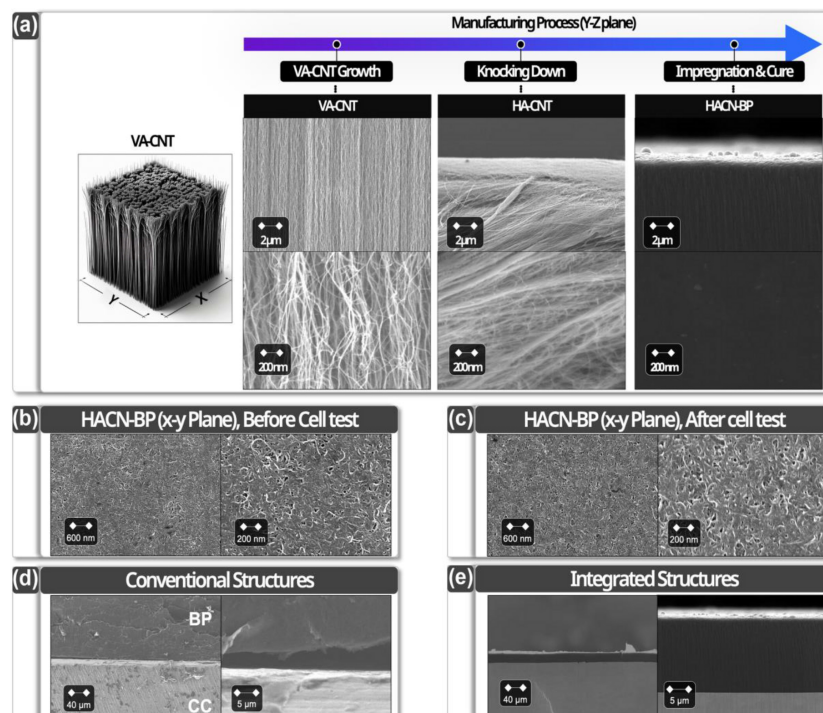


Figure 8. Surface morphology of the HACN-BP. Reprinted from Ref.^[75], under CC BY 4.0 license. VA-CNT: Vertically aligned carbon nanotube; HA-CNT: horizontally aligned carbon nanotube; HACN-BP: horizontally aligned carbon nanotube /epoxy nanocomposite bipolar plate; CC: Current Collector.

content significantly increases melt viscosity, thereby restricting fluidity and potentially leading to incomplete filling or reduced accuracy in fine flow field characteristics. In contrast, thermosetting resins undergo an irreversible curing process: their fluidity is limited during processing, but they exhibit excellent dimensional stability after curing, which helps maintain the geometric shape of the formed flow field. However, insufficient fluidity during the molding process makes precise replication of complex or micro-scale structures challenging; additionally, curing shrinkage and internal stresses may cause runner deformation or defect formation. Thermoplastic resins (such as polyvinylidene fluoride and polyetheretherketone) typically require elevated temperatures and pressures during molding, which can lead to uneven distribution of conductive fillers within the polymer melt, resulting in discontinuous conductive networks that reduce electrical conductivity and impair battery performance^[74-77]. Furthermore, a significant difference may exist between the thermal expansion coefficient of thermoplastic composites and that of carbon fillers, which can easily induce interfacial micro-cracks during operating temperature cycles, thereby increasing gas permeability. Weak interfacial adhesion is another common issue, leading to a marked reduction in mechanical strength during humidity cycling - for instance, tensile strength may decrease by more than 20%^[78,79]. Thermosetting resins (such as phenolic and epoxy resins) form cross-linked structures during curing, which may restrict the rearrangement and densification of conductive fillers, resulting in composite materials that still do not fully meet battery operating conductivity requirements. Although thermosetting resins generally exhibit good dimensional stability, filler orientation and segregation during injection molding can lead to anisotropic performance and batch-to-batch inconsistencies in composite bipolar plates, posing challenges to large-scale production and long-term operational reliability^[80,81]. Meanwhile, shrinkage during curing may generate stress at the interface, compromising both interfacial bond strength and the material's long-term durability. In a word, whether using thermoplastic or thermosetting resins as binders, carbon-resin composite bipolar plates face various challenges: discontinuous conductive networks, microcracks, increased gas permeability due to mismatched thermal expansion

Table 3. Comparison of formability of thermoplastic and thermosetting CBPs

Parameter	Thermoplastic CBPs	Thermosetting CBPs
Typical defects	Incomplete filling, filler agglomeration, and depression marks at channel corners ^[37,46]	Micro-pores and brittle micro-cracks at the root of ribs ^[36]
Dimensional tolerance	High-modulus materials exhibit less rebound, whereas low-modulus materials demonstrate greater rebound. During filling ^[82,83]	Susceptible to overall warpage induced by thermal residual stresses from curing-induced processes ^[68]
Scalability & cycle time	Excellent (second-to-minute level, highly compatible with continuous processes) ^[58,82]	Moderate (minutes to hours, typically involving batch compression molding) ^[20,34]

CBP: Composite bipolar plate.

coefficients, reduced mechanical strength due to weak interfacial adhesion, and filler segregation and anisotropy during molding. These issues collectively limit their widespread application in batteries. The following Table 3 presents a summary comparison of the processability of thermoplastic and thermosetting CBP.

Overall, thermoplastics are limited by flowability during forming, while thermosetting systems are constrained by curing behavior. Both impose inherent constraints on the formability and manufacturability of flow field structures. The performance charts for different single battery cells are listed below, as shown in Table 4.

Forming challenges of CBP with flow field

In RFBs, the flow field structure plays a critical role in regulating the distribution of the electrolyte within the porous electrode and the associated mass transport processes, thereby significantly influencing the battery's power density and overall system efficiency^[90]. With the increasing demand for high power density, low pressure drop, and high energy efficiency, flow field designs have gradually evolved from conventional simple serpentine or interdigitated fields toward more advanced architectures such as multi-level branching structures, biomimetic designs, and three-dimensional flow fields^[28]. These complex structures can significantly improve mass transport uniformity and reactant utilization. However, they also impose stricter requirements on the geometric precision and structural consistency of the flow fields. Small deviations in field width, depth, rib-to-field ratio, and corner transition morphology can alter the local flow velocity distribution, electrode compression state, and interfacial contact resistance, ultimately affecting the overall electrochemical performance of the battery^[91–93]. Therefore, the pursuit of higher performance has driven flow field structures toward increasing complexity, making high-precision forming an essential requirement. At the same time, the capabilities of manufacturing processes inherently constrain the achievable types and complexity of flow field architectures.

As structural complexity continues to increase, challenges related to forming consistency, dimensional control, interfacial integrity, and large-scale production stability become increasingly prominent. These issues pose significant barriers to the practical engineering application of CBP. Consequently, in the development of high-performance flow batteries, focusing solely on material properties or structural design is no longer sufficient. It is necessary to integrate flow field optimization with high-precision manufacturing technologies to achieve high-performance structures that are practically manufacturable.

Advances in flow field design: design ambition vs. forming reality

In conventional serpentine flow fields, insufficient convection and uneven species distribution often occur near the channel outlet and in the under-rib regions^[94,95]. Lu *et al.* introduce a blocking structure at the bends of the serpentine field^[96], thereby increasing the pressure difference beneath the ribs and promoting electrolyte penetration into the porous electrode, as shown in Figure 9.

Table 4. The efficiency of single cells in different batteries

No.	Literature	Electrolyte [L]	Cycles	T [°C]	Electrolyte	EE [%]	CE [%]	VE [%]	Charge/discharge voltage [V]	Cell-S	Current density [mA/cm ²]	Active area [cm ²]
1	Nam <i>et al.</i> ^[70]	0.05	20			84.3			1.2-1.6	1	60	4,900
		0.05	20			83.4			1.2-1.6	1	80	4,900
		0.05	20			80.4			1.2-1.6	1	100	4,900
2	Zhang <i>et al.</i> ^[84]	0.1	112	25	1.5M V ⁿ⁺ and 2M sulfate	82	96	85		1	70	28
		16.5	2300			75	93	80		5	50	2,000
3	Choe <i>et al.</i> ^[85]	0.05			1.6M vanadium ion	~ 82			1.2-1.6	1	100	
		0.05			1.6M vanadium ion	~ 71			1.0-1.7		200	
4	Lim and Lee ^[86]		100			84	~ 96	~ 98		1		
5	Choe <i>et al.</i> ^[72]					80						
6	Liao <i>et al.</i> ^[87]	0.07			1.5M V ²⁺ in 3.0M H ₂ SO ₄ , 1.5M VO ₂ ⁺ in 3.0M H ₂ SO ₄	85.7	96.7	88.6	0.8-1.65		100(37.5,140)	40
7	Liao <i>et al.</i> ^[57]	0.07			VO ₂ ²⁺ in 3.0M H ₂ SO ₄ , 1.5M V ²⁺ in 3.0 M H ₂ SO ₄ , 1.5M VO ₂ ⁺ in 3.0 M H ₂ SO ₄	85.9	97.6	88.0	0.8-1.65	1	100(37.5,140)	40
8	Liu <i>et al.</i> ^[37]	0.15	4		1.5M vanadium sulfide in 1.5M H ₂ SO ₄		~ 72 -79	> 80	1-1.55	1	40	24
9	Yang <i>et al.</i> ^[88]		18			81.61	96.45	84.61	1-1.7	1	80(120,160)	
10	Dongjiang <i>et al.</i> ^[89]	0.05	> 100		1.5M V ⁴⁺ in 3M H ₂ SO ₄ , 1.5M V ³⁺ in 3M H ₂ SO ₄	~ 80		~ 84	0.8-1.75	1	50	10

However, interdigitated flow fields are highly sensitive to pumping power and, in large-scale applications, also face a trade-off between energy consumption and structural complexity. Chai *et al.* introduce a parallel interdigitated flow field with a higher aspect ratio structure^[91]. The parallel interdigitated structures [PIFF (T2) and PIFF (T3)] effectively increase the flow velocity beneath the ribs, thereby enhancing mass transfer between branch channels and adjacent side channels, as shown in Figure 10. These designs highlight another important trend: the transition from planar structures to more three-dimensional (3D) flow field architectures with variable rib heights and complex channel networks. However, such 3D features introduce significant challenges in pressure transfer and material flow during molding.

Although the above-modified flow fields make remarkable progress in boosting mass transfer and enhancing performance, they still face a series of challenges in forming and processing in practical engineering applications and large-scale manufacturing. The increase in the number of flow field corners and variations in rib height introduce complex geometrical features that significantly increase the processing difficulty of the plates, placing higher demands on mold precision and

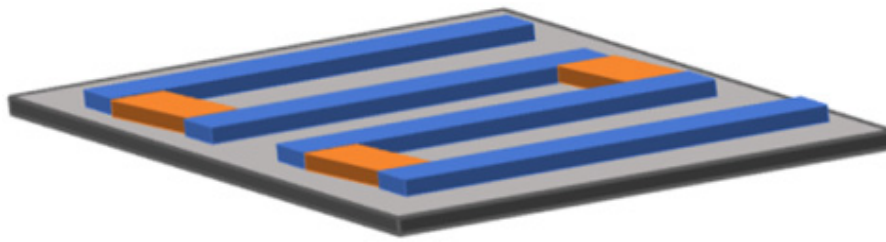


Figure 9. Illustration of the blocked serpentine flow field.

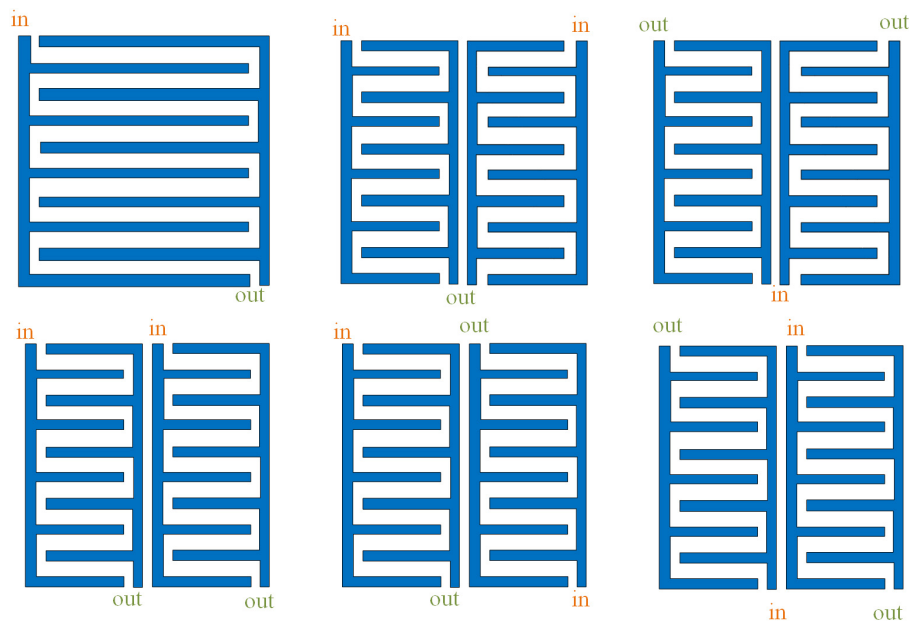


Figure 10. Schematic diagrams of different flow fields.

manufacturing consistency. For CBPs, the increasing complexity of rib width and rib height structures often leads to local stress concentration and uneven resin flow during hot pressing^[97]. In addition, although parallel or bifurcated structural designs are beneficial for regulating pressure drop distribution, the fine structural features also pose challenges to mold lifetime and manufacturing cost. Meanwhile, in order to further strengthen mass transfer and control pumping power, researchers have proposed new complex flow field designs that combine obstruction structures with simulation-based optimization. For example, biomimetic flow fields inspired by plant leaf venation incorporate obstacles of different shapes (circular, diamond, and triangular)^[98,99]. Others, inspired by fuel cell architectures and natural transport networks, introduce spiral or nonlinear flow paths^[100,101]. These biomimetic designs represent the highest level of structural sophistication, enabling precise control over local mass transport behavior. However, they also impose the most stringent requirements on manufacturability. The presence of multi-scale features and complex curvature significantly increases the difficulty of melt filling and, more critically, mold release. In particular, undercuts, sharp angles, and intricate internal geometries can cause severe demolding resistance, leading to surface damage or structural defects during part removal. In addition, as shown in [Tables 5-7](#), we summarized the specific flow field parameters of thermoplastic and thermosetting bipolar plates used in RFBs and Proton Exchange Membrane Fuel Cells (PEMFCs) to enable a more intuitive comparison of the challenges in flow field fabrication.

Table 5. Flow field parameters of BPs based on thermoplastic resins

Flow field parameters of BPs based on thermoplastic resins
Graphite/polypropylene surface layer with a flow field depth of 1 mm; the flow field width is not specified ^[102]
A polypropylene-based BP for PEMFCs with flow field dimensions of 1.5 mm in width and 0.5 mm in depth ^[103]
Different ratios of flow field width, rib width, and flow field depth were investigated, with the optimal flow field configuration identified as (5, 2, 3), applicable to VRFBs of various scales, including 416 cm ² , 918 cm ² , and 1,495 cm ² ^[104]
A flow field bipolar plate for redox flow batteries was fabricated using polyvinyl chloride, with a channel cross-sectional area of 4 × 1.59 mm ² and a flow field pitch of 7.5 mm ^[105]
A lung-inspired biomimetic structure was fabricated using 3D printing technology, with a constant flow field depth of 0.5 mm and flow field widths varying across hierarchical levels. (1.1 mm), (1.2 mm–0.7 mm), (1.1 mm–0.7 mm–0.45 mm) ^[106]

BP: Bipolar plate; PEMFC: Proton Exchange Membrane Fuel Cell; VRFB: vanadium redox flow battery

Table 6. Flow field parameters of BPs based on thermosetting resins

Flow field parameters of BPs based on thermosetting resins
A commercial flat-plate PEMFC bipolar plate with a designed thickness of 1.8 mm, featuring a gas flow field structure with a depth of 0.65 mm and a width of 0.5 mm ^[36]
A benzoxazine resin-based bipolar plate for PEMFC with a flow field width of 1.5 mm ^[107]
An epoxy resin-based bipolar plate for fuel cells with flow field dimensions of 1.5 mm in width and 0.3 mm in depth ^[108]
Flow fields measuring 1.1 mm × 1.8 mm were formed on a metal plate, followed by encapsulation with a carbon-polymer composite material ^[109]
An epoxy resin-based serpentine flow field bipolar plate for PEMFC with a thickness of 0.6 mm and a field depth of 1 mm ^[110]

BP: Bipolar plate; PEMFC: Proton Exchange Membrane Fuel Cell.

Table 7. Flow field parameters of VRFB BPs

Flow field width	Flow field depth	Rib width	Flow field types	Reference
2mm	2mm	2mm	Serpentine flow field	[111]
1mm	4mm	5mm	Interdigitated flow field	[112]
1.5mm	1.5mm	2mm	Interdigitated /Serpentine flow field	[113]
2mm	2mm	2mm	Serpentine flow field	[114]
1mm	N/A	1mm	Interdigitated /Serpentine flow field	[115]
2mm	1.4mm	N/A	Distributive interdigitated flow field	[116]
2mm	1.5mm	2mm	Serpentine flow field	[117]
4mm		4mm	Scaled-up serpentine flow field	[118]
2mm–Main flow field 0.5mm–Secondary flow field		N/A	Vein-like flow field	[70]
3mm	2mm	3mm		[119]

VRFB: Vanadium redox flow battery; BP: bipolar plate; N/A: not available.

Flow field forming challenges

The fundamental challenge in forming flow fields in VRFB BPs is the need to simultaneously satisfy multiple functions under harsh electrochemical environments, including fluid distribution, electron conduction, and mechanical support. At present, the fabrication of flow fields in BPs mainly relies on machining and compression molding^[119–121]. Machining methods typically use graphite or dense composite plates as substrates, in which the desired flow field structures are directly produced by milling or engraving. However, when fabricating fine field features in graphite materials, cutting parameters such as feed rate significantly affect surface quality and can induce surface damage. Due to the intrinsic brittleness of graphite, crack propagation and fracture are prone to occur during machining. In addition, tool deflection during micro-milling further reduces dimensional and form accuracy, leading to structural defects in fine features^[103,122,123].

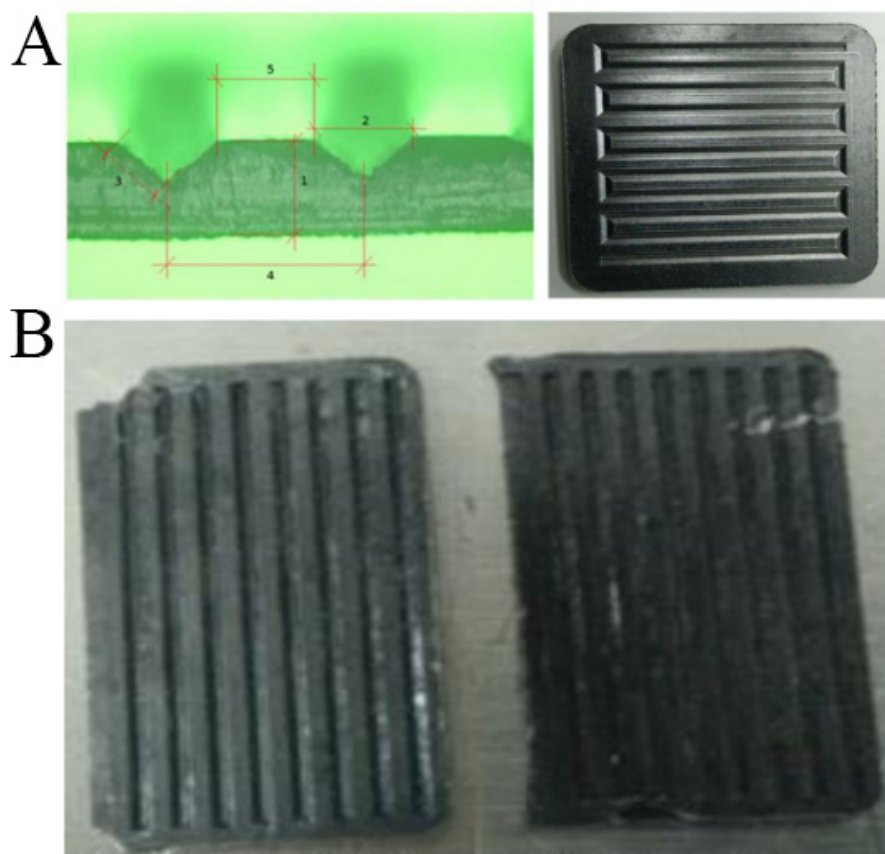


Figure 11. (A) Dimensional schematic of the V-shaped demolding design and the corresponding fabricated BP; (B) fracture of the BP sample. Reprinted from Ref.^[119], under CC BY 4.0 license. BP: Bipolar plate.

In contrast, compression molding integrates the flow field structure concurrently during the forming process. This approach offers potential advantages such as simplified processing steps and is therefore widely regarded as an ideal route for the large-scale manufacturing of CBPs^[34].

Forming defects

Existing studies indicate that during compression molding, the material exhibits complex and constrained flow behavior due to its rheological characteristics and fiber interactions. Meanwhile, the pressure distribution within the mold cavity is often non-uniform and evolves, which can lead to defects such as voids, insufficient impregnation, and structural inhomogeneity^[124,125]. More importantly, such defects act as preferential initiation sites for electrolyte penetration and localized electrochemical reactions. As a result, microcracks and interfacial gaps facilitate the ingress of acidic electrolyte, while filler agglomeration and resin-deficient regions lead to uneven current distribution.

Although fuel cells operate under relatively milder conditions and therefore face fewer challenges in flow field forming, they still encounter issues related to forming defects. Understanding these issues provides valuable insights into flow field fabrication in flow batteries. During the hot-press molding of CBPs, defects such as incomplete filling and demolding damage often occur due to restricted material flow and insufficient pressure transfer. As a result, the geometric design of flow fields must consider formability. In particular, the draft angle not only affects demolding efficiency but may also influence BP performance. Yusuf *et al.* report^[119] that V-shaped flow fields exhibit higher forming accuracy than U-shaped flow fields with a zero draft angle [Figure 11A]. U-shaped fields require an appropriate draft angle to avoid sample fracture [Figure 11B]. It should be noted that although a larger draft angle facilitates demolding, it also tends to produce a rougher surface on the formed sample.

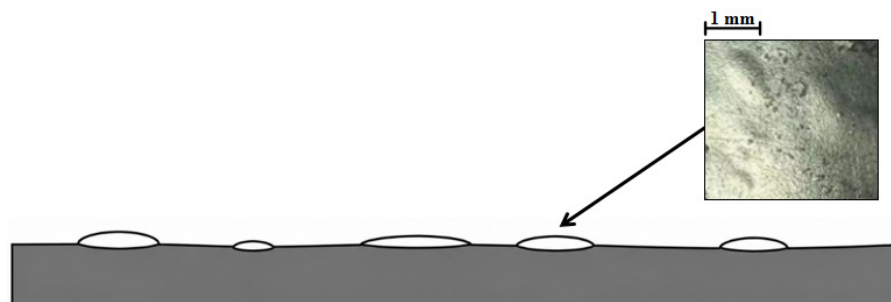


Figure 12. Surface bubble leakage caused by inappropriate molding methods.

Table 8. Surface roughness of the flow field under different resin contents^[120]

Resin content	Surface roughness Ra (μm)	Differences from molds
10%	2.411	Maximum, approximately $+1.3 \mu\text{m}$
10/20/10%	1.582	Low, approximately $+0.48 \mu\text{m}$
20%	1.536	Approximately $+0.43 \mu\text{m}$
30%	1.849	Approximately $+0.74 \mu\text{m}$

Simaafrookhteh *et al.* point out that for thermosetting CBPs, the crosslinking reaction during hot pressing can generate water vapor or ammonia^[36]. Therefore, implementing an appropriate degassing step is critical to ensuring optimal performance. In addition, the mold's average surface temperature, surface roughness, and even the filler feeding method can influence the plate's surface quality and the accuracy of the flow field's forming. Furthermore, Boyacı *et al.* find that improper molding pressure may cause adhesion between the plate and the mold surface^[41], resulting in visible pores on the BP surface. Such pores act as defect sites that can facilitate electrolyte penetration and initiate localized corrosion, as shown in Figure 12.

Under optimal pressure and temperature conditions, extending the molding time can effectively reduce the surface roughness. Zhang *et al.* fabricate CBPs with high flow field forming accuracy and low surface roughness through a three-layer structural design^[120]. Owing to the plasticity of expanded graphite, the difference between the formed field depth and the mold field depth is only $\pm 4 \mu\text{m}$. The specific parameters of surface roughness are shown in Table 8. Meanwhile, Zhu *et al.* report that the impregnating agent is primarily distributed between graphite layers and that when the plate is subjected to bending loads, stress tends to concentrate in the inclined regions of the flow field^[97].

Therefore, the interfacial bonding between the resin and graphite layers, as well as the uniformity and degree of crosslinking in the impregnated resin distribution, are key factors determining the compressive performance of flow field-containing BPs. Poor interfacial bonding or non-uniform resin distribution can lead to microcrack initiation in flow field regions. These defects may propagate under cyclic loading and electrolyte exposure, thereby accelerating localized corrosion and structural degradation. Table 9 lists the main challenges in forming flow fields.

For CBPs with flow fields attached on both sides, the fabrication process also faces significant challenges. To address this issue, Brent proposes two manufacturing approaches^[126]. The flow fields are first fabricated separately^[34], after which the mold is rotated by 90° . The two halves of the BP are then heated and fused to form the final plate. In the second method, one side of the plate is first molded. The half plate is then flipped, and the flow field is molded on the other side to produce the final BP. The manufacturing process is shown in Figure 13.

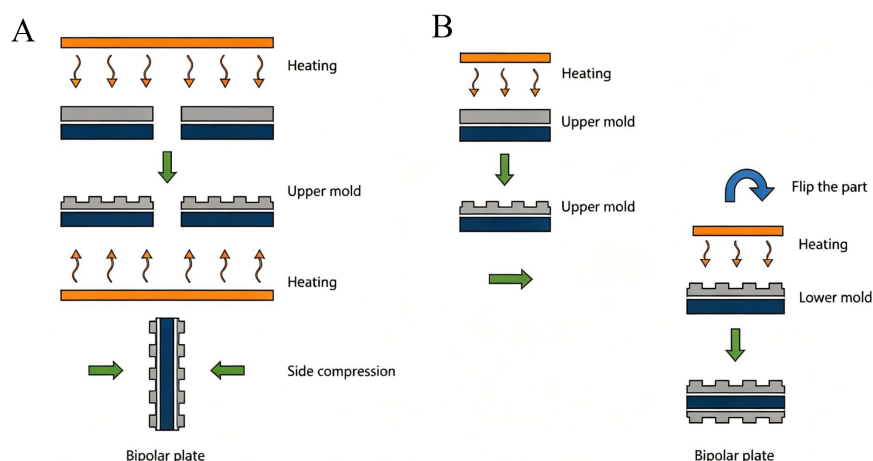


Figure 13. Schematic diagram of flow field bipolar plate formation (A) Both parts of the BP are formed simultaneously; (B) The two parts of the BP are formed sequentially. BP: Bipolar plate.

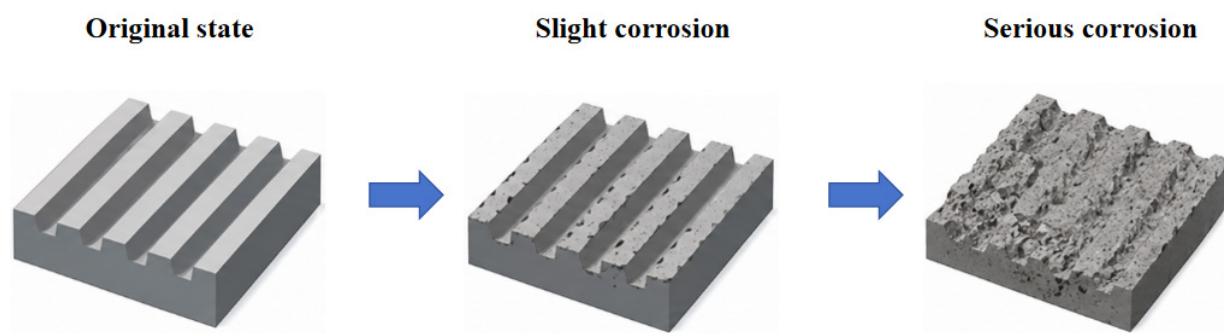


Figure 14. Corrosion morphology characteristics of bipolar plates with flow fields after a certain number of cycles.

Table 9. Summary of the main challenges in runner forming

Reference	Key innovation	Main conclusions
Sepehr <i>et al.</i> ^[36]	Multi-filler thermoset composite BP; improved conductivity (~ 38 S/cm) and strength (47 MPa); defect mitigation strategy	Molding defects are critical; precise fields (0.5 mm × 0.65 mm) are achievable only with defect control
Zhu <i>et al.</i> ^[97]	Ultra-thin flexible BP (0.775 mm); wettability regulation for enhanced performance	Field wettability dominates water management and mass transport behavior
Yusuf <i>et al.</i> ^[119]	Direct flow-field fabrication via hot compression; optimized V-shaped field	Dimensional precision deviation (~ -0.118% to 0.27%); geometry affects demolding and manufacturability

BP: Bipolar plate.

Accurately evaluating the severity of forming defects is essential. The conventional performance targets for bipolar plates require an area-specific resistance (ASR) < 0.4 Ω·cm² and a flexural strength > 40 MPa. The critical defect size threshold determines the plate's feasibility. Sietmann *et al.* indicate that the presence of the flow field structure itself increases the resistance of the BP by approximately 19% compared with that of a solid bulk material. In contrast, internal defects increase the overall resistance by only about 1%–4%^[37]. However, macroscopic defects (> 0.5 mm), such as incomplete rib filling, can significantly impair mechanical integrity and alter local pressure drop^[127]. More critically, surface cracks wider than 50 μm or sharp corners formed during defect formation can serve as pathways for acidic electrolyte penetration, thereby greatly accelerating galvanostatic corrosion and active-species degradation at defect sites^[128–130]. The characteristics of the corrosion morphology are shown in Figure 14.

Therefore, quality control in flow field fabrication must strictly limit surface cracks to $< 50\ \mu\text{m}$ and suppress internal pore agglomeration to maintain flexural strength and electrochemical stability^[72,131] simultaneously.

The effect of small random particles is almost negligible. Therefore, from the perspective of electrical performance, the geometry of the flow fields has a much greater impact on resistance than internal micro-defects. Nevertheless, for structural reliability and long-term operational stability, greater attention should be paid to large defects such as cracks, bubbles, and pore agglomerations. In terms of quality control, millimeter-scale defects can be identified through Computed Tomography (CT) inspection, without excessive concern about the influence of micron-scale dispersed particles on electrical conductivity^[37].

Electrochemical corrosion and chemical corrosion

As mentioned above, BPs used in flow batteries must operate in strongly acidic and highly oxidative environments. Therefore, the fabrication of flow fields must not only consider the impact of forming defects but also account for their long-term stability in harsh corrosive environments. During corrosion, both the stability and electrical conductivity of the BP may deteriorate. In addition, parasitic reactions that consume electrons during corrosion can reduce battery efficiency and capacity. The corrosion of CBPs in VRFBs can generally be classified into two types: electrochemical corrosion and chemical corrosion^[20,132].

Fundamentally, both originate from carbon oxidation driven by the combined effects of high potential on the positive electrode and a strongly acidic vanadium electrolyte. Electrochemical corrosion is the most common corrosion mechanism. However, the standard potential for carbon corrosion is 0.207 V, which is lower than the anode potential of VRFBs; therefore, the BP on the cathode side usually exhibits relatively high stability^[51,129]. During the corrosion process, carbon-oxygen-containing functional groups such as C-O, C=O, and O-C-O are formed^[130] rather than being released directly as gases. These oxygen-containing functional groups increase surface hydrophilicity. They also facilitate the penetration of electrolytes into internal defects of the plate. Because the diffusion of reactive ions within cracks and pores is limited, a higher overpotential is required, which accelerates the conversion of these oxygen-containing functional groups into CO or CO₂^[133]. Continuous penetration and corrosion may subsequently lead to plate cracking and even cause internal short circuits in the battery. For CBPs with flow fields, the fields and their adjacent regions are prone to local potentials significantly higher than the average. After 120 charge-discharge cycles, additional active sites tend to form at the edges and corners of the flow fields, where oxidation reactions lead to further loss of carbon atoms^[131]. In addition, the degradation of the ribs in the flow field may also intensify the non-uniform distribution of potential, resulting in locally elevated potentials that further accelerate the electrochemical oxidation process. Clearly shows the cross-sectional morphology of the corroded region^[128]. The bright corroded areas exhibit a more open structure, which increases the likelihood of electrolyte penetrating through the plate. Moreover, obvious carbon black agglomerations can be observed in the non-corroded regions (yellow arrow areas), whereas no identifiable carbon black is found in the corroded regions. This suggests that carbon black particles may participate in the corrosion reaction more actively than graphite. These findings indicate that although the geometry of the flow fields accounts for a major portion of the resistance in BPs, unthinkingly reducing resistance by adding more conductive particles may instead increase the risk of corrosion.

The chemical corrosion of bipolar plates in flow batteries primarily results from direct chemical attack by active substances in the electrolyte on the plate materials. For example, in vanadium redox flow batteries (VRFBs), the high-concentration sulfuric acid electrolyte serves as the primary corrosive agent^[134]. The strongly acidic environment of sulfuric acid solution can directly attack the carbon materials on the bipolar plate surface, leading to the oxidation of C-C and C=C bonds within the carbon framework. Furthermore,

the active vanadium ions in the electrolyte, particularly in highly oxidized states [such as vanadium(V)], exhibit strong oxidizing properties that can chemically react directly with the carbon materials of bipolar plates, leading to oxidative degradation. In composite bipolar plates, the interface between the polymer matrix (e.g., phenolic resin, polyanthraquinone) and the conductive fillers (e.g., graphite, carbon fiber) represents a vulnerable site for chemical corrosion^[81]. The electrolyte may penetrate these interfaces, attacking the polymer matrix or fillers, thereby reducing interfacial adhesion and compromising the material's structural integrity. Prolonged immersion in corrosive electrolytes may also cause swelling, dissolution, or degradation of the polymer matrix, adversely affecting its mechanical properties and dimensional stability. Compared with electrochemical corrosion, this type of corrosion is significantly milder^[134]. Even after 190 days of immersion in a fully charged electrolyte (100% state of charge), scanning electron microscopy revealed no observable changes in the composite bipolar plate. However, if a metal is inserted between the bipolar plates, surface corrosion may subsequently lead to electrochemical corrosion of the metal^[135].

Outlook on flow field forming challenges

In recent years, numerous novel flow field structures have been proposed using computational fluid dynamics (CFD), topology optimization, and data-driven design methods^[111,114,136]. These designs often demonstrate significantly improved uniformity of electrolyte distribution and mass-transfer performance in simulations. However, they face considerable challenges in practical fabrication. First, complex flow fields typically exhibit highly differentiated geometric features, whereas compression molding relies on the restricted flow of materials under high temperature and pressure. In composite systems with high filler content, it is difficult for the material to fill fine grooves and intricate structures fully. Second, complex flow fields often lack properly designed draft angles, making it inevitable for the demolding process to introduce edge damage and microcracks. As a result, the development of new fabrication approaches is urgently required to accommodate the increasingly sophisticated flow field structures.

CONCLUSION AND OUTLOOK

CBPs are formed by combining conductive carbon materials with a polymer matrix. They achieve a good balance among electrical conductivity, corrosion resistance, mechanical strength, and processability. Therefore, they have become an important research focus for flow battery BPs in recent years. The incorporation of flow fields enables significant performance enhancement of RFB stacks at relatively low cost. However, the continuous increase in flow field complexity inevitably exacerbates the manufacturing challenges of BPs with integrated flow fields.

Meanwhile, the performance requirements for redox flow batteries (RFBs) continue to rise. Consequently, flow field structure design has emerged as a key strategy for enhancing battery stack performance. However, while complex flow field configurations improve battery performance, they also impose higher demands on the molding process of CBPs (composite bipolar plates). In practical manufacturing and operation, these plates face dual challenges of molding accuracy and long-term corrosion resistance. Different resin systems and molding parameters significantly affect the molding accuracy of the flow field; during compression molding, the normal stress on the flow field ribs is much lower than the shear stress generated by friction, resulting in a substantially lower filler density in the ribs compared to the ridges. Moreover, the ribs are frequently subjected to electrolyte erosion during battery operation, necessitating higher material density and lower defect density. Furthermore, compared to flow-field-free bipolar plates, the ridges of flow-field bipolar plates also serve an electron exchange function. This enables higher current density to be achieved within a smaller area, but it readily leads to localized excessive overpotential, resulting in corrosion and failure of the conductive filler. In summary, ensuring precise distribution of fillers and pressure to the rib ridges during the molding process remains a key focus for future research. CBP materials must operate continuously in highly

acidic electrolytes; damage to the flow field regions along the ribs or planar surfaces increases the risk of battery stack failure. Thermosetting resins undergo three-dimensional cross-linking and curing reactions during compression molding, enabling high-precision replication of complex flow fields while maintaining excellent dimensional stability. In contrast, although thermoplastic CBP offers higher processing efficiency, the high filler loading significantly reduces melt fluidity. It limits the material's ability to conform to flow patterns at the microscopic scale, making it more suitable for relatively simple flow configurations or large-scale sheet production. Looking forward, three critical forming challenges will dominate future research in CBPs with integrated flow fields:

(1) Defect mitigation: Suppressing voids, resin-rich regions, and fiber/filler segregation during molding remains essential to ensure both mechanical reliability and corrosion resistance.

(2) Precision scale-up: Achieving uniform, high-resolution replication of complex flow fields over large-area plates is a key barrier to industrialization, requiring advances in mold design, pressure distribution control and process stability.

(3) Material flow modeling: Developing accurate multi-scale models that capture the rheological behavior of highly filled composites during molding is crucial for predicting flow, optimizing process parameters and guiding material design.

These challenges are strongly coupled with material choices and structural design strategies. Therefore, future progress will rely on the co-optimization of materials, flow field design, and forming processes, rather than isolated improvements in a single dimension.

DECLARATIONS

Authors' contributions

Methodology, software, investigation, writing original draft: Guo, Q.

Validation, formal analysis, visualization: Sun, H.

Conceptualization, writing review and data curation: Li, J.

Writing review, editing and supervision: Wang, H.

Writing review, discussion, project administration and resources: Ma, X.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

During the preparation of this manuscript, the AI tool Gemini 3.5 Flash (version 3.5 Flash, released 2026-05-19) was used solely for language editing. The tool did not influence the study design, data collection, analysis, interpretation, or the scientific content of the work. All authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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