

Development Overview and Perspective of Semi-Solid Flow Batteries

Junjie Zheng,^[a] Qinpeng Zhu,^[a] Jinglin Xian,^[a] Kang Liu,^{*,[a]} and Peihua Yang^{*,[a]}

The development of efficient and cost-effective grid energy storage devices is crucial for advancing the future of renewable energy. Semi-solid flow batteries, as an emerging energy storage technology, offer significantly higher energy density and lower costs compared to traditional liquid flow batteries. However, the complex interplay between rheology and electrochemistry poses challenges for in-depth investigation. With a sketch of historical development of semi-solid flow batteries,

this minireview summarizes several key issues, including particle interactions, electron transport, and the sustainability of electrochemical reactions in slurry electrodes. By tracing the technological evolution of semi-solid flow batteries, we provide a forward-looking perspective on their potential applications in future large-scale energy storage systems, highlighting their promising role in addressing the challenges of energy transition.

1. Introduction

The ongoing exploitation of fossil energy and the worsening environmental issues underscore the urgent global need for advanced, high-efficiency and eco-friendly energy storage technologies to facilitate the energy transition.^[1,2] As the demand for renewable energies, such as solar and wind power, continues to rise, there is a crucial need for safe and reliable energy storage solutions to address their variability and intermittency.^[3] Electrochemical secondary batteries, particularly lithium-ion batteries, have shown significant progress in portable energy storage systems due to their outstanding voltage window and high energy density.^[4,5] However, their deployment in large-scale energy storage is severely restricted by the expensive cost of lithium resources and the flammable nature of organic electrolytes.^[5–8] Therefore, there is a pressing need for energy storage systems that are safe, cost-effective, and capable of long-term operation to meet large-scale storage demand.^[9–11]

Among various energy storage systems, flow batteries, utilizing highly safe liquid electrolytes stored in external tanks, offer ease of scalability and remarkable long-term cycling stability, positioning them as strong contenders for large-scale energy storage applications. A flow battery consists of positive and negative electrolyte tanks containing active materials that undergo redox reactions (Figure 1a). These active materials include a range of metal ions, such as vanadium,^[12–15] zinc,^[16,17] iron,^[18,19] nickel,^[20,21] in different oxidation states, as well as various conductive polymers, such as quinone molecules,^[22] 2,2,6,6-tetramethylpiperidinoxy,^[23] pyridine derivatives,^[24] phenazine^[25] and azobenzene molecules.^[26] Electrode materials with outstanding conductivity, chemical stability, and catalytic

activity (such as graphite felt) are used.^[27,28] An ion-selective membrane separates the positive and negative reaction chambers to prevent electrolytes mixing and facilitate selective ion migration, which is essential for targeted ion transport while blocking others.^[29,30] Pumps and a circulation system are necessary to circulate electrolytes from the storage tanks into the positive and negative reaction chambers, ensuring complete redox reactions.

However, flow batteries face significant challenges including high costs and limited energy density, which restrict their widespread application.^[31] Firstly, meeting the electrochemical reaction requirements necessitates costly components such as graphite felt and ion-selective membranes.^[28] Secondly, the low solubility of electrode materials in aqueous solutions restricts improvements in energy density. Although additives can enhance solubility, they complicate the solvent system and accelerate the degradation of ion-selective membranes,^[32,33] thereby escalating costs. Therefore, exploring more cost-effective and higher-performance energy storage technologies is crucial to address these issues.^[34]

Semi-solid flow batteries (SSFBs) represent an innovative approach that combines the strengths of solid-state electrodes with conventional flow battery technology.^[35] In SSFBs, solid active particles and conductive agents are suspended within an electrolyte to form semi-solid electrodes, reducing the need for high solubility. The use of solid active particles allows SSFBs to achieve higher concentrations of active materials compared to liquid electrolytes. This capability leads to enhanced energy density, enabling SSFBs to store more energy per unit volume or weight. Moreover, the simplified solvent system and reduced reliance on complex additives can potentially lower manufacturing and operational costs associated with ion-selective membranes and solvent additives. The positive and negative electrolyte tanks in SSFBs store positive and negative slurries, respectively (Figure 1b). This design prevents the occurrence of side reactions caused by the contact between positive and negative slurries, thereby eliminating the need for ion-selective membranes. These slurries consist of active material particles

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capable of reversible redox reactions and conductive agents (such as acetylene black, Ketjen black, carbon nanotubes, carbon fibers) dispersed in the electrolyte.^[36] The conductive particles form a network in the suspension, significantly improving the electron transport efficiency within the electrode. This network promotes rapid electrochemical reactions and helps maintain stable dispersion of the slurry, preventing settling.

During the reaction process, economical microporous membranes can replace expensive ion-selective membranes to separate the positive and negative reaction chambers within the SSFBs.^[37] Peristaltic pumps and sealed pipelines ensure continuous flow of the slurry between the storage tanks and reaction chambers, enabling long cycling and sustainable operation of the battery. This semi-solid flow electrode retains the fluidity of a flow battery while combining the superior energy density of a solid electrode. By circumventing the solubility limitations, this design can significantly enhance the energy density, offering an efficient, safe, and cost-effective solution for large-scale energy storage needs.

Advancements in electrochemical energy storage technology typically follow a bottom-up approach: starting from the exploration of chemical mechanisms, progressing to rational module design, and culminating in scaled-up applications. Despite over a decade of development, SSFBs have demonstrated technological feasibility. However, the complex coupling between rheology and electrochemistry as well as issues related to suspension stability and rational flow channel design remain challenges. This review systematically introduces SSFBs by tracing their development over the past decade. It further analyzes the suspension stability issues that currently limit the progress of SSFBs research, the rheological and electrochemical challenges during the flow process, and the relevant model theoretical analysis and characterization methods. Finally, we put forward our insights and prospective for future development.

2. Progress and Development of SSFBs

In recent years, the development of SSFBs has advanced significantly (Figure 2). In 2011, Chiang et al. first introduced a novel energy storage device, the semi-solid rechargeable lithium flow battery, which combines the high energy density of solid-state electrodes with the scalable structure of fuel cells

and flow batteries.^[35] They demonstrated an emerging energy storage technology where energy is stored in a suspension of solid particles and transferred through conductive network for charge transport. Theoretical energy densities for suspensions containing 40 vol% active materials such as $\text{Li}_4\text{Ti}_5\text{O}_{12}$ - LiCoO_2 were reported as 397 Wh L^{-1} (168 Wh kg^{-1}), $\text{Li}_4\text{Ti}_5\text{O}_{12}$ - $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ as 353 Wh L^{-1} (150 Wh kg^{-1}), and graphite- LiCoO_2 as 615 Wh L^{-1} (309 Wh kg^{-1}). Subsequently, they developed a three-dimensional mathematical model integrating fluid dynamics and electrochemistry to study the impact of changes in the equilibrium potential of the intercalation material on the performance of the flow battery. The study showed that choosing a potential change with a relatively flat voltage-capacity curve at low flow rates can maximize battery efficiency.^[38] Furthermore, they explored the feasibility of SSFBs in aqueous electrolyte systems, proposing the use of $\text{LiTi}_2(\text{PO}_4)_3$ - LiFePO_4 .^[39] The use of aqueous electrolytes significantly reduces costs and further validates that high concentration semi-solid fluids can substantially enhance electrode energy density. However, despite these advancements, SSFBs struggle to maintain superior performance over long cycling processes, primarily due to the instability of suspended electrodes.

For aqueous SSFBs, Gogotsi et al. used manganese oxide (MnO_2) as the active material, based on theoretical models and experiments, to prove the universality of semi-solid flow electrodes, which also have broad application prospects in other electrode materials.^[40] The importance of analyzing the rheology and electrochemical mechanism of electrodes for designing efficient systems is emphasized for the application of semi-solid suspended electrodes in supercapacitors.^[41] As research on SSFBs deepens, balancing the viscosity and conductivity of suspended electrodes has become the biggest obstacle to device development. The suspended electrode is prepared by suspending the active material and the conductive carbon material in the electrolyte. To achieve higher energy density, more active materials and conductive carbon particles are needed, which drastically increases the viscosity of the suspension, thereby reducing its flow efficiency.

In 2021, Wu et al. introduced an innovative single-component lithium-ion semi-solid flow battery technology, utilizing carbon fiber materials (such as carbon paper or carbon felt) directly as 3D current collectors for the fluid, without adding additional carbon particles.^[42] This design overcomes the high viscosity problem caused by carbon particles in traditional SSFBs, thereby addressing the challenges of active material



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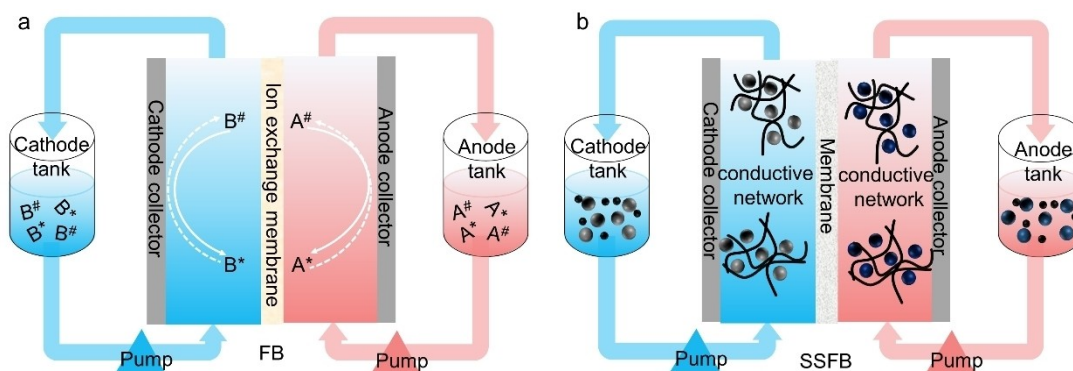


Figure 1. Schematics of (a) FB and (b) SSFB. Electrolytes of a FB are homogeneous solutions, while that of a SSFB are uniform slurries.

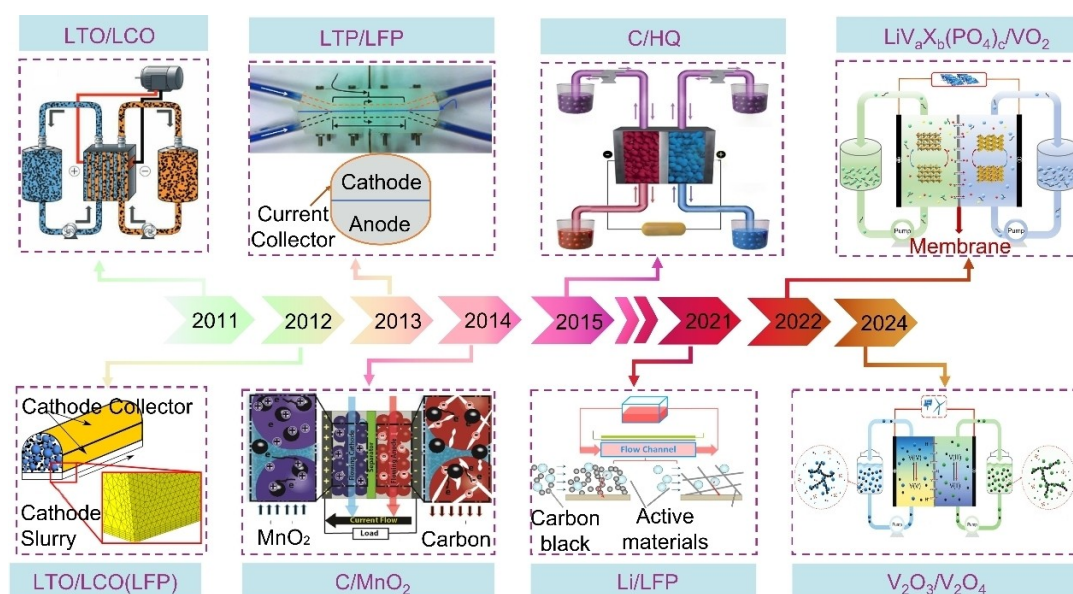


Figure 2. Development history of semi-solid flow batteries. Reproduced with permission from Ref. [35, 38–44].

filling and energy density. However, the lack of additional conductivity provided by carbon particles limits the current density range of this system to 0.05 C–0.2 C. Based on the “salt-in-water” strategy, a stable aqueous lithium battery system was prepared using $\text{LiV}_x\text{X}_b(\text{PO}_4)_c$ and VO_2 suspensions of positive and negative active particles in a high-concentration LiTFSI electrolyte.^[43] Although the battery operated stably, the high concentration of salt introduces severe viscosity limitations, allowing only 1 M of active material, resulting in an overall energy density of only $\sim 15 \text{ Wh L}^{-1}$. To overcome such drawbacks, they combined a multivalent vanadium-based colloidal suspension with traditional vanadium electrolyte, achieving an energy density of up to 48 Wh L^{-1} .^[44] The presence of conductive carbon particles was found to significantly reduce resistance and increase capacity, highlighting the importance of balancing the ratio of conductive carbon particles and active materials in improving SSFBs performance. Therefore, the development of SSFBs necessitates a focus on the preparation of uniformly dispersed and stable semi-solid suspension slurry

electrodes, to overcome existing challenges and realize their full potential for large-scale energy storage.

3. Microscopic Insights of SSFBs

3.1. Particle Interactions

In SSFBs, electroactive particles must be suspended in the electrolyte, necessitating their even dispersion and minimal size to prevent rapid settling. The incorporation of nanostructured materials, such as nanoparticles, into the base fluid creates a nanofluid state, which is advantageous for renewable energy applications. To analyze nanoparticles stability and aggregation behavior in solution, an energy-distance curve can be obtained by superimposing molecular and surface forces. This curve illustrates the total interaction potential between nanoparticles as their distance changes,^[45] reflecting the combined impacts of all attractive and repulsive forces (Figure 3a). Key attractive forces include van der Waals forces and dipole attraction.^[46] Van

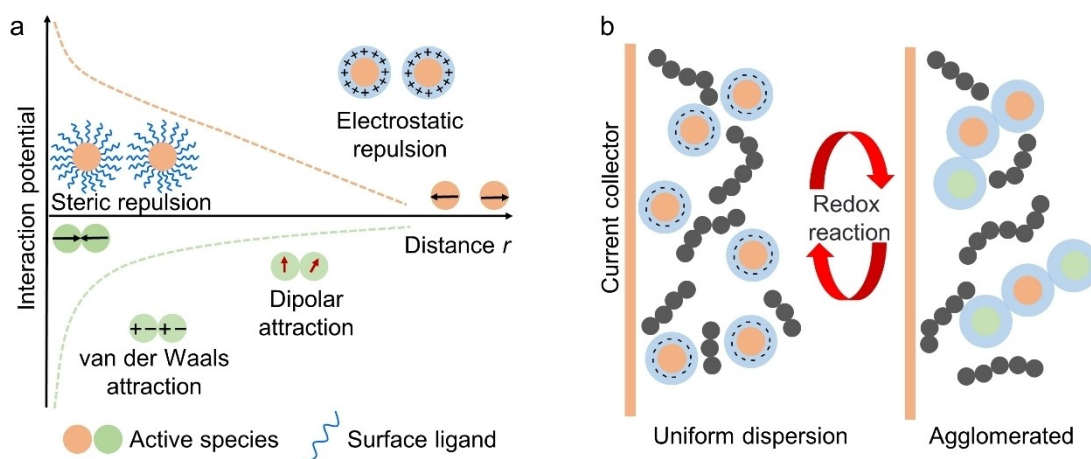


Figure 3. Nanoparticles interaction in suspensions. (a) The interaction between attractive and repulsive forces. (b) Particle aggregation caused by electrostatic shielding.

der Waals forces, arising from the formation of instantaneous dipoles, exert a weak mutual attraction even between non-polar particles at short ranges. Dipole attraction is more pronounced between polar particles or those with permanent dipoles.^[47] When a particle has a charge distribution, it attracts particles with opposite charge distribution, forming a stronger attraction. Repulsive forces mainly involve steric repulsion and electrostatic repulsion. Steric repulsion arises from the physical size and shape of particles, when particles get too close, their surface ligands clash, creating a force that prevents further proximity. Electrostatic repulsion, based on surface charge state, causes like-charged particles to repel each other per Coulomb's law, maintaining dispersion.^[48]

When external conditions (such as pH value, salt concentration, and temperature) change, the electrostatic repulsion between particles will weaken, causing the particles to aggregate more easily.^[49–51] Increasing salt concentration in a semi-flow battery can diminish electrostatic repulsion among particles, which may promote particle aggregation. However, it can also weaken the repulsive force barrier, leading to irreversible aggregation. Conversely, decreasing the salt concentration or increasing the thermal motion energy of the particles tends to maintain particles in a stable dispersed state by enhancing their kinetic energy to overcome repulsive forces. To achieve precise control over the behavior of nanoparticles in solution, both chemical and physical properties of particles and the surrounding medium must be finely adjusted, considering external stimuli and thermal motion on particle interactions. Recent advancements in evaluation methods, particularly the xDLVO theory,^[52] provides an analytical framework for understanding and predicting the stability and aggregation tendency of nanoparticles.^[48]

Nanoparticles in liquids typically carry positive or negative charges due to charge carriers or surface functional groups adsorbed onto their surfaces,^[53] creating a double-layer structure.^[54,55] This charged layer plays a critical role in the dispersion stability. Electrostatic repulsion between like-charged particles is the primary force maintaining their dispersed state.

However, ion distribution is influenced by thermal motion leads to Debye-Hückel screening,^[56,57] diminishing direct charge interactions and reducing electrostatic repulsion effectiveness. During the charging and discharging processes, nanoparticles undergo redox reactions that alter their surface charge states (Figure 3b). Changes in the electronic state of the particle surface can increase or decrease its surface charge.^[58,59] When the surface charge decreases, electrostatic repulsion weakens, increasing the likelihood of particle aggregation. Combined with the perturbation of ion distribution due to thermal motion, this significantly reduces electrostatic repulsion between initially dispersed particles of the same charge, leading to instability and eventual agglomeration.

Achieving stable dispersion of particles in liquid media requires careful consideration of several factors: the charge state of the particle surface, ion distribution in the solution, and the influence of external variables such as temperature and pH.^[45] Precise control of these parameters is essential to optimize particle dispersion and prevent agglomeration. For instance, adjusting the ionic strength of the solution allows for modulation of the Debye length, thereby controlling the electrostatic shielding impacts between particles.^[60] Selecting appropriate surface modifiers like polymers or surfactants enhances the charge stability and mechanical resilience of the particle surface, further bolstering dispersion stability. In essence, the stability of nanoparticles in solution and their aggregation behavior results from the interplay of various interaction forces. By finely tuning the balance of these forces, it becomes possible to achieve either stable dispersion or controlled aggregation of particles. This capability is critical for advancing applications such as high-performance nanofluids and SSFBs.

3.2. Electron Transport

During electrochemical processes, the transfer of electrons and ions is fundamental to the charge and discharge mechanisms in

batteries. In SSFBs, ion transport occurs through electrolyte transfer, while electron transport requires a conductive network, typically composed of conductive carbon particles (Figure 4a). When the suspension concentration is appropriate, these particles form a continuous network structure, allowing electrons to transfer between particles via hopping mechanisms or tunneling impacts.^[61]

The hopping mechanism involves charge carriers, such as electrons, jumping between surfaces of particles. In a suspension system, particles often form an incomplete and non-continuous network where direct connections between particles may not always exist. Electrons must jump from one particle surface to another. The efficiency and distance of these jumps depend on several factors, including particle spacing, surface properties, particle size, and interparticle interactions. Therefore, an adequate amount of conductive carbon particles is essential in SSFBs to establish a stable pathway for electron transport. Tunneling, a quantum mechanical phenomenon, allows electrons to cross potential barriers despite insufficient classical energy.^[62] When particles are very close, the probability of electrons tunneling from the Fermi level of one particle to another particle increases, enabling long-range charge transport.

In electroactive suspension systems, hopping and tunneling mechanism often occur simultaneously and contribute to the transport of electrons.^[63] At lower particle concentrations, electrons transport predominantly occurs through the hopping mechanism due to the larger particles distance and lower tunneling probabilities. However, as the particle concentration increases, the distance between particles decreases, making the tunneling more significant and sometimes dominant. This explains why electron transport capacity in electroactive

suspension systems exhibits a non-monotonic trend with the change in particle concentration, often forming a bell-shaped curve.^[64]

Shear rate also significantly impacts electron transport. At low shear rates, the particle network remains relatively stable, facilitating effective electrons transport through hopping. Increased shear rates can disrupt the particle network, reducing hopping efficiency. However, further increased shear rates decrease particle clusters size, enhancing the tunneling probability and potentially restoring electron transport capacity.^[65] Nonetheless, high shear rates can lead to increased power consumption and overheating, which needs to be carefully considered.

3.3. Electrochemical Reactions

In solid-state electrodes, the solid electrolyte interphase (SEI) is a critical protective layer for electrodes, formed by the reduction of electrolyte components on the electrode surface. The SEI hinders further electrolyte decomposition, reduces side reactions, and protects the electrode material, while allowing selective ion transmission and blocking electron and solvent molecules penetration. This greatly improves the cycle stability and extend battery life.

In SSFBs, SEI formation differs significantly from conventional batteries. The electrode material is suspended in the electrolyte, unlike the fixed electrode material in traditional batteries. SEI forms not only on the electrode material but also at the contact point between the electrode material particles and the current collector, complicating and reducing the electron transfer path. Since SEI film is electrically insulating, it

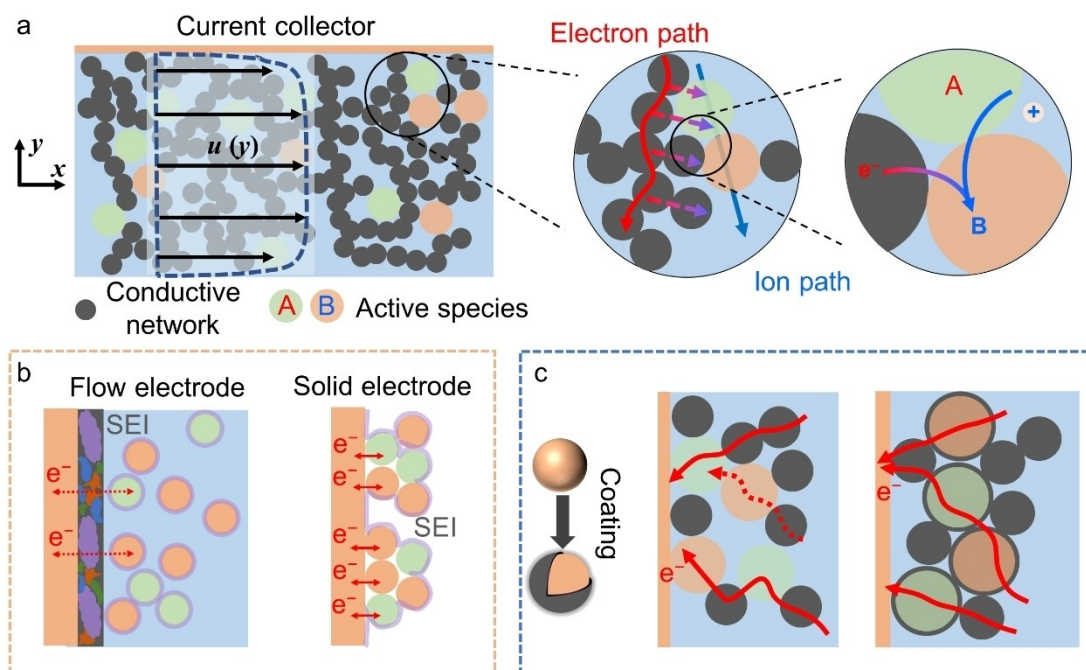


Figure 4. Interaction between charge carriers and active materials in SSFBs. (a) Electron and ion transport paths. (b) SEI comparison between the semi-solid flow electrode and solid-state electrode. (c) Facilitated charge transport by surface coating of active species.

hinders electron transfer from suspended electrode material particles to the current collector, thereby affecting the electrochemical reaction (Figure 4b). The formation of SEI also increases the interfacial impedance of ions transmission, leading to higher overpotential and reduced battery efficiency and cycle performance. In addition, the circulating flow process in SSFBs causes continuous fragmentation and reformation of the fragile SEI on particle surfaces, increasing internal resistance and disrupting internal dynamic stability.^[66]

Building on insights from solid-state electrodes, coating the surface of active particles or adding dispersants to the suspension are feasible strategies for ensuring the stable operation of SSFBs. Typically, a substantial amount of conductive carbon particles is added to the suspension to create a stable conductive network, which resists disruption under continuous flow conditions.^[67] However, this approach sharply increase the viscosity of the suspension, making the flow more difficult and prone to clogging.^[68]

Surface coating of active particles, a method widely used in conventional batteries to improve the electronic conductivity, can be applied to SSFBs. By coating carbon on the surface of active particles, additional electron conduction paths are created during the flow process,^[69] reducing contact resistance between particles and promoting the formation of a more uniform and stable SEI film (Figure 4c). This not only reduces the SEI film impedance but also increases the mechanical strength of the active particles, maintaining their structural integrity during continuous flow and collision in SSFBs. Consequently, the contact between active materials and the current collector is enhanced, thereby improving the charge transfer efficiency.

Electrolyte additives, particularly dispersants, play a key role in maintaining the dispersibility and stability of active particles in the suspension.^[70–72] Employing suitable surface modifiers like polymers or surfactants, can enhance the charge stability and mechanical toughness of the particle surfaces, thereby preventing agglomeration and precipitation. This ensures that the suspension remains stable. This uniform distribution maximizes contact areas, which is conducive to rapid ion diffusion of efficient electrochemical reaction. Furthermore, dispersants adjust the viscosity of the suspension, making it difficult to precipitate and easy to pump, and improve the viscosity and rheological properties of the suspension, which is of great help to the stable operation of SSFBs.

4. Theoretical Models of SSFBs

To deepen our understanding of the internal mechanism of SSFBs and elucidate the interplay between rheology and electrochemistry, it is essential to employ theoretical models for simulation and prediction. A three-dimensional kinetic Monte Carlo model (KMC) based on the variable step size method (VSSM) effectively described the electrochemical discharge process.^[73] This model accounts for the Brownian motion of particles, volume expansion of electrode materials during ion insertion, and the formation and destruction of conductive

carbon networks. The Stokes-Einstein Equation is used to determine particle diffusion coefficient, incorporating slurry viscosity and particle radius, which are estimated by the Thomas expression based on the solid volume fraction. This comprehensive model enables the prediction and evaluation of electroactive suspensions in SSFBs.^[74,75]

Franco et al. specified a reference system at a specific current density (C/20) and interface depth (1 μm),^[76] varying the carbon ratio from 3 vol% to 17 vol% to observe its impact on the specific capacity (Figure 5a). The three-dimensional visualization model reveals the evolution of the carbon network as the carbon ratio increases, depicting the distribution of electroactive carbon (yellow), non-electroactive carbon (red) and silicon particles (blue). When the carbon content is low, an effective conductive network between the carbon particles cannot be established, leading to low conductivity and consequently low capacity and energy density. As the carbon content increases, a continuous network begins to form, facilitating electron transport and improving conductivity. This improvement positively impacts the battery stability by optimizing active material utilization and ensuring charge-discharge cycling. However, beyond 11 vol% carbon, further conductivity gains are negligible, as the network reaches sufficient density. Excessive carbon increases the suspension viscosity, which adversely affects the fluidity and pumpability. Moreover, the additional carbon displaces active material, ultimately decreasing the overall energy density of the battery. This analysis identifies the optimal carbon content range for effective charge transfer paths, crucial for optimizing battery formulations to improve the performance and energy density.

For rheological influence mechanism, a comprehensive three-dimensional multi-physics coupling model can be constructed to optimize SSFBs channel configuration.^[77,78] This model integrates fluid dynamics, electrochemical reactions, ion transport within particles, and mass balance in the tank. It compares the performance impact of different flow channel designs (e.g., parallel vs. serpentine channels) and flow rate, revealing that parallel channels offer more uniform velocity distribution and piston-like flow characteristics conducive to uniform electrochemical reactions. It also evaluates changes and distribution of electrode potential and state of charge changes with the flow of slurry.^[79,80]

In SSFBs, the redox reaction process generally refers to the insertion process of ions (Figure 5b). During the discharge process, edge slurry retention leads to higher active materials concentration at the edge of serpentine flow channel, especially the curved part.^[82,83] This results in uneven electrochemical reactions and excessive local concentration. Increasing flow rate reduces edge slurry content, enhancing the reaction uniformity (Figure 5c). Through reasonable channel design and adjustment, the electrochemical performance and energy efficiency of the battery can be significantly improved. In advancing SSFBs, it is necessary to integrate innovative battery structure design with theoretical simulation and electrochemical testing to comprehensively study kinetic process and performance influencing factors. Analyzing multi-physical field coupling within the battery will reveal the structure-activity relationship,

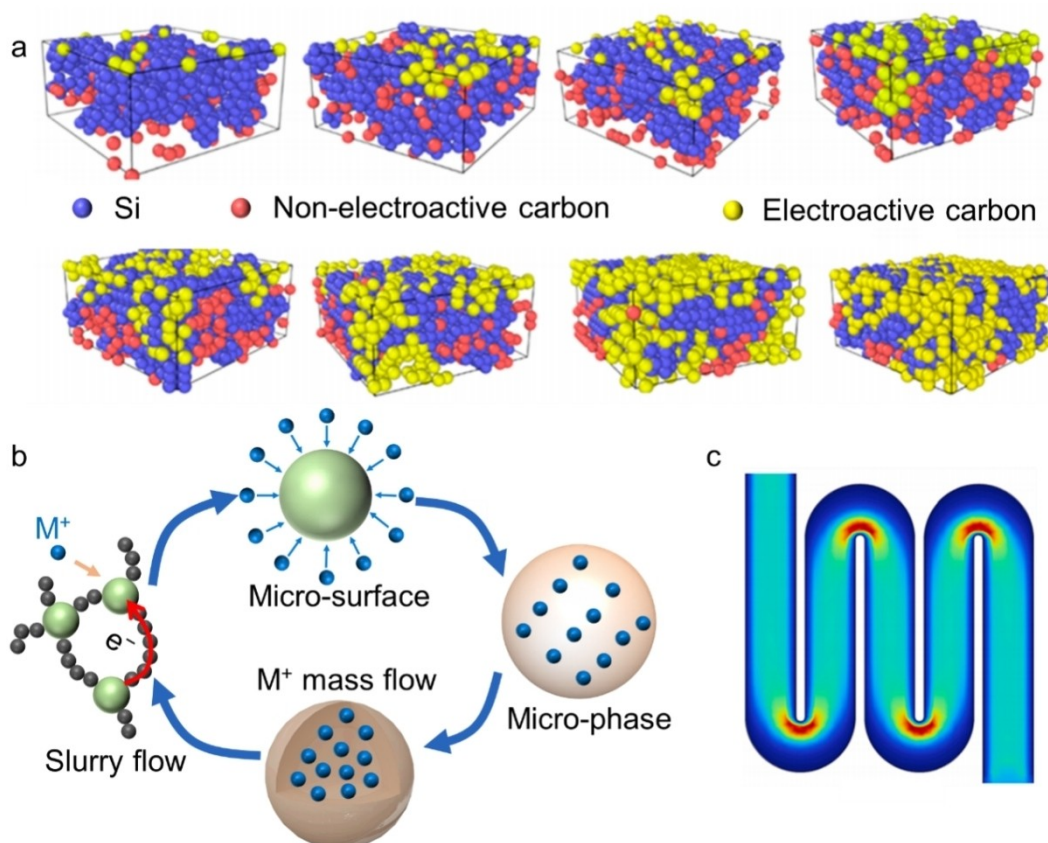


Figure 5. Modeling of SSFBs. (a) Three-dimensional visualization model of different carbon ratios. Reproduced with permission from Ref. [76]. (b) Ion intercalation reaction. (c) Distribution of active substance concentration in serpentine flow channel. Reproduced with permission from Ref. [81].

providing a theoretical foundation and key technologies for the high performance SSFBs.

5. Advanced Characterizations of SSFBs

To achieve further advancements in SSFBs, it is essential to understand the internal rheological mechanisms and clarify the electrochemical changes of active particles. This requires appropriate characterization techniques to in-situ analyze the redox state of active materials during the charge and discharge processes, monitor changes in electrolyte composition, and identify potential operational issues. This is crucial for developing high-performance SSFBs.

In situ Raman spectroscopy is a valuable tool for real-time monitoring of SSFBs,^[84–87] enabling observation of the state and structural changes of active materials during electrochemical reactions (Figure 6a). By tracking the intensity and position shifts of the Raman peaks, the state transition of active material particles during the redox process can be inferred. Additional Raman peaks observed during the reaction can indicate the formation of reaction intermediates. For example, in semi-solid electrolytes containing transition metal oxides, Raman spectroscopy can reveal the changes in the valence state of the metal centers, providing insights into the electrochemical mechanism of the battery. Moreover, Raman peak changes after different

cycles helps evaluate the redox reversibility and stability of the active materials.

Similarly, in-situ nuclear magnetic resonance (NMR) technology complements Raman spectroscopy (Figure 6b), offering precise characterization of electrolyte changes in slurry electrode, including water decomposition and the effects of electrolyte additives and dispersants.^[88,89] This comprehensive analysis is vital for understanding the specific reaction mechanisms in the flow process of SSFBs.

Electrochemical impedance spectroscopy can further elucidate the kinetic parameters such as charge transfer resistance, double-layer capacitance, and diffusion impedance within SSFBs. Electrochemical impedance studies the impact of the conductive network on battery performance. For example, when the shear rate suddenly increases, the shear force exceeds the mutual attraction between the particles, forcing conductive particles to rearrange and separate contact points. This transition from an aggregated to a more dispersed state interrupts electron transmission paths, significantly increasing impedance and reducing conductivity.

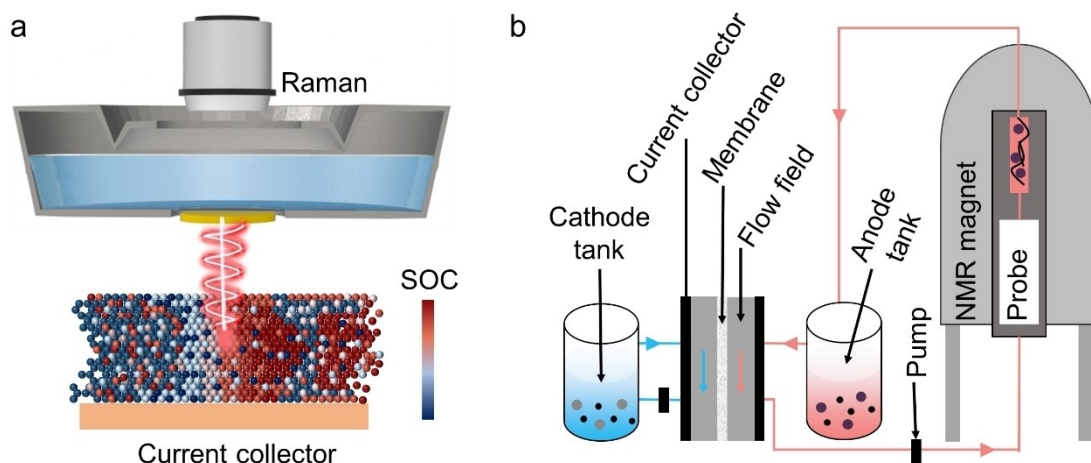


Figure 6. In-situ characterization of SSFBs. (a) Raman monitoring. (b) NMR monitoring.

6. Conclusions and Outlook

6.1. Battery Pack

SSFBs represent a cutting-edge technology in energy storage, offering a novel approach to addressing current system challenges. The advantages and disadvantages of SSFBs in single battery packs and large-scale energy storage systems are systematically discussed in Table 1. A primary advantage of SSFBs is their significantly improved energy density. By suspending solid active material particles in the electrolyte to form a semi-solid slurry with electronic conductivity, this design allows the battery to accommodate more active materials per unit volume, thereby substantially improving the energy storage capacity. This technology holds considerable promise for backup power supplies and scalable energy storage systems, which demand high safety and adequate energy density. Furthermore, since the slurry electrodes are usually stored in a storage tank, self-discharge is minimal, effectively increasing the energy storage efficiency.

However, SSFBs face significant challenges. One major issue is the cycle life. Due to the degradation and agglomeration of active particles during the charge and discharge process, along with the possible side reactions in the electrolyte, the battery performance gradually declines over time. Another challenge is rate performance. The low conductivity of the semi-solid slurry limits rapid charging and discharging capabilities, especially in high-power demand scenarios. Reducing internal resistance and

increasing power output through improved flow field design and material dispersion are crucial technical difficulties that need urgent resolution.

6.2. Energy System

In large-scale energy storage systems, the scalability and cost-effectiveness of SSFBs become their biggest highlights. The energy storage scale can be easily adjusted by adding a storage tank for the slurry without changing the basic structure of the battery stack. This modular and scalable feature is very suitable for large-scale grid energy storage applications, especially for flexible response to fluctuating power generation from renewable energies. In addition, by reducing dependence on expensive ion exchange membranes and optimizing material use, SSFBs systems theoretically offer significant cost savings, which could promote widespread adoption in the energy market.

SSFBs also encounter several challenges in the application of energy systems. The complexity of flow field design is an inevitable issue. Ensuring that the semi-solid slurry flows evenly and efficiently in the battery stack, while reducing fluid resistance and improving energy conversion efficiency requires a deep understanding of fluid mechanics and precise design. Material compatibility and stability are also important considerations. In high-concentration electrolyte environments, interactions between active materials, electrolytes and additives become critical. How to ensure the stability and electrochemical performance of materials in long-term operation is the key to improving the overall reliability and efficiency of the system.

6.3. Conclusions

A comprehensive analysis of performance optimization in SSFBs highlights the critical role of conductivity, which directly influences the charge-discharge rate, energy efficiency and cycle stability. Both electronic or ionic conductivity are key

Table 1. Summary of advantages and limitations of semi-solid flow batteries.

	Advantage	Limitation
Battery pack	Energy density	Cycle life
	Low self-discharge	Rate performance
Energy system	Scalability	Complex flow field
	Low cost	Material compatibility

indicators, with higher conductivity facilitating more efficient charge transfer, thereby enhancing power density and energy density. The use of nanoparticles presents a promising approach to enhancing conductivity, with their type, size, concentration, and functionalization playing significant roles in influencing battery performance.

Surface modifications, such as polymer or nanocoating, can improve material stability and reduce degradation, thus extending battery cycle life. Moreover, incorporating conductive nanomaterials improves slurry conductivity and supports advanced electrode designs, which collectively enhance rate performance and overall system efficiency. Conductivity is also temperature-dependent, with variations in temperature directly affecting the ionic conductivity of the electrolyte and, consequently, the overall battery performance. In the complex SSFBs system, conductivity arises from the interplay of multiple physical fields, including electric, fluidic, and thermal field.

Fluid dynamics, including Brownian motion, shear thickening/shear thinning phenomena, and flow field design, play a pivotal role in distributing charge carriers uniformly, preventing particle precipitation, and optimizing electrode utilization. The dispersibility of nanoparticles can be enhanced through surfactants and functional additives, which prevent aggregation, and improve compatibility with current collectors. The interactions of these materials can be revealed by dynamic light scattering and Zeta potential evaluation. During the flow mode, real-time dynamic particle behavior can be monitored by in-situ spectroscopies techniques (such as electrochemical impedance microscopy, X-ray photoelectron spectroscopy, and Raman spectroscopy).

Understanding these interactions is of great significance for designing high-performance SSFBs. The integration of theoret-

ical models with experimental validation offers predictive insights into flow channel design and battery performance across various parameters, providing a powerful tool for optimizing battery structure and functionality. Achieving the optimization of SSFBs requires a holistic approach that encompasses material selection, preparation processes, structure design and operational conditions. The comprehensive regulation of these factors will improve conductivity and battery performance, laying a solid foundation for the continued development and application of SSFB technology.

6.4. Outlook

From a large-scale energy storage perspective, SSFBs' outstanding energy storage characteristics and portability suggest their important role in diversified energy systems such as wind, hydro, thermal and solar power generation. SSFBs can bridge the gap between intermittent energy supply and demand, ensure smooth power output, stabilize grid operation, and assist in peak load shifting and valley filling, thereby improving energy utilization efficiency. The slurry storage tank design of SSFBs offers unparalleled portability, enabling potential in energy transportation and distribution (Figure 7).

SSFBs, akin to "nano-electric fuel", are easy to store and transport, meeting immediate electricity needs of across various industries. Their recyclability, rechargeability and potential for reuse distinguish SSFBs from traditional fuels. The regeneration process allows the electrode material to return to its original state, greatly reducing energy loss, minimizing environmental pollution, and aligning with sustainable development goals. SSFBs effectively address current energy transition challenges

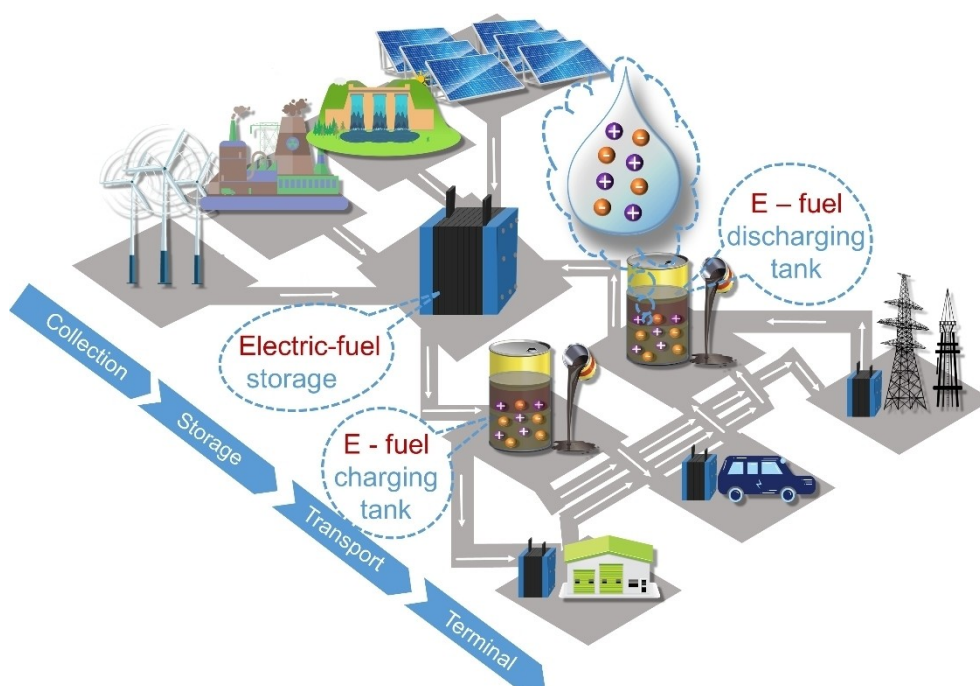


Figure 7. SSFBs offer versatile solutions for advancing energy storage and renewables utilization.

and provide a robust support for a clean, efficient and intelligent energy system. With the ongoing technological advancements and cost reductions, SSFBs are expected to become a key component in the future energy system, promoting low-carbon and eco-friendly economic development.

In summary, SSFBs are emerging as an ideal link between clean energy sources and end-user demands, leveraging their distinctive advantages in energy storage, portable transportation, and rechargeability. Their widespread applications in diverse power generation sectors and innovative role as “nano-electro fuel” highlight their immense potential to drive energy transition and green economic development. As technology advances and markets expand, SSFBs are poised to lead a new era of energy utilization, steering human society towards a cleaner, smarter, and more sustainable future.

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Conflict of Interests

The authors declare no conflict of interest.

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