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Room-temperature fluoride-ion batteries: an emerging electrochemical system for the post-lithium era

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The rapid rise of emerging pillar industries such as intelligent robotics, electric vehicles, aerospace, and the low-altitude economy has placed new demands on the flexibility, safety, and energy density of energy systems. The energy density of conventional lithium-ion batteries is approaching its theoretical limit, making it difficult to meet the ever-growing need for higher energy densities, thereby posing a significant challenge to existing battery technologies. Therefore, achieving further improvements in battery energy density requires conceptual breakthroughs in battery materials and battery chemistry.

Fluoride-ion batteries (FIBs), which operate via anion shuttling between the cathode and anode, represent a "new concept" battery system and an important technological direction for the post-lithium era. They not only leverage the abundance of fluorine resources but also eliminate the safety hazards (e.g., dendrite growth caused by metal deposition during cycling) inherent in metal-ion batteries. Nobel laureate Robert Grubbs (2005) has described FIBs as a "disruptive" battery technology. Since the concept was first proposed in 1974, FIBs have evolved from high-temperature (150 °C) solid-state configurations to liquid-based and, more recently, room-temperature solid-state designs. In 2011, Reddy et al. reported a rechargeable FIB[1]. In 2018, Davis *et al.* developed a rechargeable fluoride-ion battery capable of operating at room temperature[2]. Since 2015, our group has pioneered FIB research in China, developing $BaSnF_4$-based solid electrolytes via doping strategies and demonstrating functional solid-state FIBs with promising performance[3].

As a promising new battery system, room-temperature solid-state fluoride-ion batteries are still in their "infancy." Compared with liquid-based lithium-ion and solid-state lithium batteries, they remain at the critical transition stage from laboratory proof-of-concept to materials engineering. Key challenges involve the twin bottlenecks of sluggish bulk ion transport and high interfacial impedance, which must be addressed synergistically through combined bulk defect engineering and

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atomic-scale interface design. Current research focuses on two main fronts: (i) moving beyond traditional limitations of high-temperature operation and low ionic conductivity, and (ii) engineering stable electrode/electrolyte interfaces to mitigate poor solid-solid contact, limited electrochemical stability, and the resulting high interfacial resistance. Additionally, overcoming the extremely low room-temperature ionic conductivity (< 10^{-10} S/cm) and high migration barriers in conventional fluoride-ion conductors remain major hurdles. Researchers are employing lattice-activation strategies to create continuous "fluoride-ion defect highways" within the solid-electrolyte lattice, thereby enhancing ionic conductivity through aliovalent doping and structural disorder. By leveraging reversible fluoride-ion migration and interface-adaptive mechanisms, simultaneous achievement of high energy density, intrinsic safety, and long cycle life at room temperature is being pursued.

For electrode materials, conversion-type metal fluorides currently offer high theoretical capacities but undergo large volume changes during cycling, whereas intercalation-type materials exhibit better cycling stability but have limited specific capacity[4].

Although FIB is regarded as a promising next-generation battery system, it is still in its infancy. Future research will focus on enhancing cycle life, reducing large volume expansion of cathode materials, understanding electrode reaction mechanisms, and improving the room-temperature ionic conductivity of the solid electrolyte. Cycle life can be improved by constructing a stable SEI, applying carbon coatings, and using materials with low volume change. Cathode expansion can be mitigated by nano-structuring and alloying. The reaction mechanism can be clarified by combining high-resolution characterization with theoretical simulations. The room-temperature ionic conductivity of solid electrolytes can be improved by aliovalent ion doping and solid-solution design. Greater efforts in designing high-performance electrodes, developing room-temperature electrolytes with wide electrochemical stability windows, and optimizing interface engineering will be essential to advance FIBs toward practical application.

DECLARATIONS

Authors' contributions

Writing - original draft: Wang, L. Q.
Investigation: Zhou, S.
Writing - review & editing: Wang, X.

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Not applicable.

AI and AI-assisted tools statement

Not applicable.

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Conflicts of interest

Wang, X. is an International Advisory Editorial Board Member of the journal *Energy Z*, but was not involved in any steps of editorial processing, notably including manuscript handling, and decision making, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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