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Review

Engineering aspects of the design, construction and performance of modular redox flow batteries for energy storage

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A B S T R A C T

Despite many studies and several extensive reviews of redox flow batteries (RFBs) over the last three decades, information on engineering aspects is scarce, which hinders progress with scale-up and implementation of this energy storage technology. This review summarises cell design requirements then critically considers design, construction and cell features together with their benefits and problems, leading to good practice through improved cell performance, knowledge and experience. Techniques for the characterisation of the reaction environment are illustrated by measurements of mass transport to (and from) electrode surfaces as a function of flow conditions, as well as pressure drop and electrolyte flow dispersion. The influence of design features on performance is illustrated by the effect of process conditions on the components of cell potential. Adequate attention to engineering aspects is seen to be critical to the effective performance of RFBs, particularly during scale-up and long-term operation. Techniques for the characterisation of reaction environment are summarised and a list of essential design and construction factors is provided. Finally, critical areas needing research and development are highlighted.

Contents

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1. Introduction

Interest in redox flow batteries (RFBs) has grown considerably due to the increasing demand for static energy storage and the shortage of possible devices. The major drivers for this trend are the rapid growth market for intermittent solar, wind and tidal power and the promise of highly efficient power grids based on extended and versatile load-levelling capacity [1]. After decades of fundamental research and pilot-scale developments, medium and large-scale installations are being commercialized, creating an incipient and active RFB industry [2]. The development of practical RFBs has been slow and difficult. Many engineering challenges remain, even for successful systems, including the need to decrease capital costs, lower running costs and extend battery lifetime. Meanwhile, several promising systems have made only partial scale-up progress. The authors consider that this is partly due to inadequate consideration of engineering aspects of cell design, construction and performance, which has resulted in limited confidence in the technology.

RFB development has achieved important progress in electrolyte, electrode and membrane choice as well as the proposal, and reintroduction, of alternative chemistries. However, the academic field has largely evolved in an empirical fashion around the electrochemistry of established redox species while, in contrast to fields such as electrolysers and fuel cell design [3], little consideration has been given to the accepted principles of electrochemical engineering. More attention needs to be paid to the principles of green energy storage, for instance, the limitation of degradation or the minimization of critical materials [4]. Problems caused by this restricted approach include unsuccessful scale-up, poor maintenance, costly manufacture, low efficiency and limited life-time. In particular, the majority of publications have been restricted to short term studies of small electrodes in the laboratory; very few contributions have considered pilot-scale devices and the effect of cell design, electrode structure, reaction environment and operational conditions on performance.

In view of the demands of RFB technology, an increased focus is needed on engineering aspects, cell and stack design, reliable comparison figures of merit, monitoring, and modelling. RFBs are reversible electrochemical reactors, but many workers seem unaware of the established literature on electrochemical engineering and figures of merit describing their quantitative performance. Several leading books exist in the field [5–11] and useful theory for RFBs and their design can be found in well-established literature on filter-press cells and electrolysers. A sufficient knowledge of electrochemical engineering is essential to appreciate the critical features of cell design and operating conditions together with an ability to compare results from RFBs operated at different scales or predict performance under different operational conditions.

The present review aims to direct attention to the engineering aspects of RFBs, as this is a major present challenge to their extended commercial implementation. An electrochemical engineering approach to RFB design and scale-up is strongly encouraged and we also attempt to reduce the gap in technological and research awareness between the academic literature and the industry. This review is in line with the principles proposed by Arbabzadeh et al. [4] to direct research in energy storage, which highlight the need for: a) improved maintenance and operation and b) focus on the design of energy storage systems.

Numerous reviews have been published on RFBs, especially over the past decade; indeed, the authors are aware of more than 30 literature reviews since 1980. General reviews consider the main types of RFB and some performance figures, fundamental theory and main design considerations [12–15]. Several reviews describe the various RFB systems [16–20]. There are also more specialised reviews on RFBs, including: an early historical overview [21]; the perspective of other energy storage technologies [22,23]; membranes [24,25]; VRFB policy and funding [26]; non-aqueous systems and their membranes [27]; carbon-based electrodes [28]; an overview of selected engineering aspects [29]; regenerative fuel-cells [30]; challenges in the Zn-Ce RFB [31]; electrode materials and reaction mechanisms for the VRFB [32]; advances in VRFBs [33–35]; chemical characteristics of the redox species for RFBs [36,37]; H_2-halogen systems [38]; vanadium electrolytes [39]; and recent organic RFBs [40]. Perceived technical challenges and research needs for RFBs were summarised by a group of experts for the U.S. Department of Energy [41]. Recent books and monograph chapters have also assessed the state of RFB technology. For instance, summaries on the development,