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Membrane-Less Redox Flow Batteries: Efficiency and Design Cold Plate Thermal Designs for EV Battery Systems

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ABSTRACT

The efficiency of the membrane-less redox flow batteries or ML-RFBs and their incorporation with compact thermal control systems for the operation of the EV batteries are analyzed in this paper. A sustainable energy storage system is attained since ML-RFBs use low-cost iron and modified carbon porous electrodes. The role of heat control in the context of improving battery characteristics is described in the work, and specific new structures of the cooling plate, for example, convex-porous structures, are considered. Also, the paper presents innovations in electrode structure, numerical simulations, and sensitivity calculations for tapping enhanced scalability, stability, and durability. The work presented here underscores the need of advancement for it to find application in commercialization of EV systems.

Keyword: Membrane-less redox flow batteries, Energy storage, Thermal management, Electric vehicle batteries, Carbon porous electrodes, Cooling plate designs, Computational modeling

INTRODUCTION

The future of both electrical and renewable energy and the popularization of electric automobiles has boosted the need for effective energy storage solutions. Membrane-less redox flow batteries have recently attracted much attention as a promising candidate for electrodeposition due to potential benefits as follows; scalability, low-cost materials and relatively simple design compared to the conventional membrane-based systems. However, achieving improvements in their energy efficiency and operational stability still poses significant issues for practical development, especially for EVs, where miniaturization and high reliability are highly desirable. Effective thermal management has become a critical function in achieving high performance and safety of batteries for EV systems. Some high-level cold plates are most preferred due to their higher ability to dissipate heat with equal distribution of temperatures. This paper focuses on the correlation between improvements in ML-RFBs efficiency and advanced cold plate thermal designs, which lay essential design aspects for the advanced energy storage of future generation EVs.

LITERATURE REVIEW

Membrane-less redox flow battery efficiency

According to Marma et al. 2019, this work presented a new class of membrane-less hydrogen-iron redox flow battery (RFB) system to reduce costs and issues associated with membrane-based RFB systems. Substituting the expensive membrane for a solid material, the system employs low-cost iron materials for the carbon porous electrode (CPE) with optimized pore structure to minimize Teflon impregnation for the control of crossover.

Cell testing and one dimensional modeling showed that the membrane-less system was as effective as other traditional systems and that the Ohmic properties of the cell did not degrade or increase due to numerous contaminants (Marma et al. 2019). The impact of Teflon on kinetic and Ohmic losses in the larger aperture was slightly worse while crossover effects were negligible. This work expounds on the capability of the membrane-less H2- Iron RFB as an optimal energy storage technology.

Redox flow battery thermal management designs

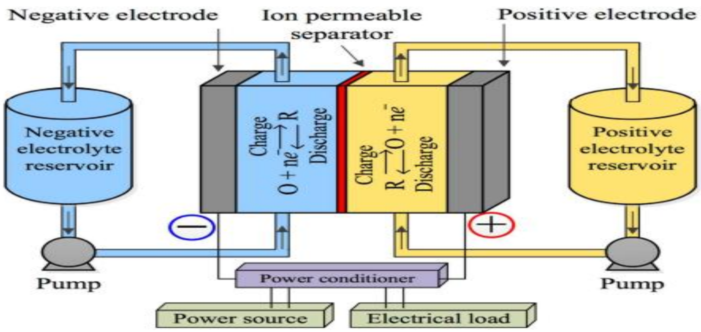

Figure 1: A classical RFB system, showing a divided cell, electrolyte recirculation

(Source: https://www.sciencedirect.com/science/article/pii/S2352152X16301736)
According to Arenas et al. 2017, Major studies of redox flow batteries or RFBs occurred for the past three decades, but a dearth of attention on engineering limitations impedes their scale up and commercial application. This review focuses on important cell design needs and assesses construction attributes, advantages, and issues to improve and understand cell efficiency for practice. This also discusses methods of examining the reaction surroundings from the standpoint of mass transport kinetics, pressure drop assessment, and electrolyte flow spot distribution while under different flow regimes (Arenas et al. 2017). This review also looks at means and ways that execution design influences the performance of the battery by process conditions for cell potential. Stressing on engineering aspects as critical to scalability and robustness, it presents design parameters and defines directions for research and development.

Cold plate systems for EV batteries

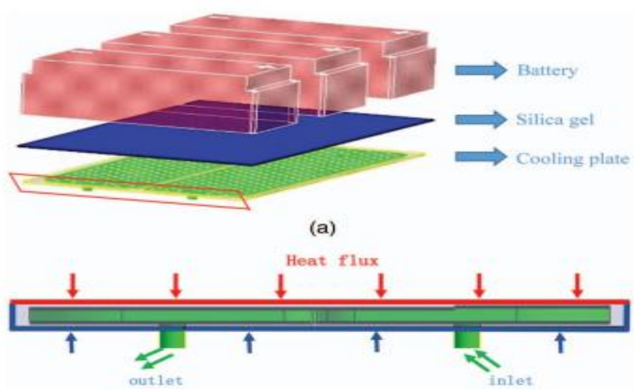

Figure 2: (Color) Boundaries of the cooling plate

(Source: https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29EY.1943-7897.0000648)
According to Li et al. 2020, Electric vehicle (EVs) energy storage devices, lithium-ion batteries, are sensitive to temperature, which requires a control system, battery thermal management system (BTMS), for the safety of the battery and enhanced cycle life. In order to determine what cooling plate structure provides the greatest area for cooling rectangular batteries, CFD modeling of four different and typical cooling plate structures was conducted. Regarding the designs of the cooling plate, the cooling plate with the convex structure achieved the highest cooling performance (Li et al. 2020). Obtained results also depicted how much the variations in mass flow rate affected the rating on heat transfer efficiency within the designs. As a result, a convex-structured cooling plate is determined to be the best solution for improving thermal performance of EV batteries.

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EV battery thermal optimization techniques research

According to Zhu et al. 2020, Battery packs are of paramount importance in electric vehicles (EVs) to cut short the environmental pollution; their safety, aging, and life are known to be strongly correlated with thermal behavior. In this research, thermal management and thermal performance enhancement of an EV battery pack will be discussed for real world scenarios. In order to validate the model, a heat generation model of Bernardi', with taking into account reversible heat, tests and consequently simulations are conducted (Zhu et al. 2020). Concerning the thermal behavior of such a battery pack with an underside cooling system, numerical investigations are conducted at extreme operational conditions, and the findings are compared with test data where good agreement is achieved. In sensitivity analysis inlet temperature and flow inlet rate found to be significant. Optimization predicts the values of inlet parameters, enhances the battery pack thermal characteristics for practical use.

METHODS

Secondary techniques concerning the enhancement of the efficiency and thermal characteristics of the membrane-less redox flow batteries or ML-RFBs integrated with the electric vehicle or EV battery systems can be found in the literature that are focused on the factors for the improvement.

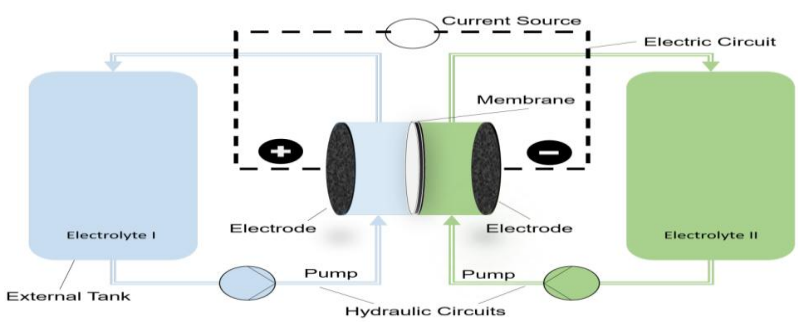
Thermal Management Techniques: Articles on thermal regulation in batteries for electric vehicles discuss the cooling methods that include; liquid cooling, air cooling and types of cold plates. When these techniques are incorporated in ML-RFBs, they can help minimise over-heating and optimise the efficiency of the electric system (Akinyele et al. 2020). Literature review has revealed that heat sinks/fins added to cold plates increases dissipation capabilities and stabilizes the operating temperature.

Electrode Design and Porosity Control: Modifying the porous characteristics and design of the electrodes has been described in numerous past works in enhancing the transport of mass and charges. The use of Teflon in impregnation or as a coating on carbon porous electrodes (CPEs) has been found to affect the rates of crossover of the reactants together with the ability of the ions to transport across the electrode surface. These modifications necessary for the increase in performance, however, should be coordinated to prevent the increase in thermal losses.

Computational Modeling: The prediction and control of flow patterns and temperature distribution within the electrochemical ML-RFB systems have recently been approached comprehensively employing the computational fluid dynamics or CFD as well as the electrochemical modeling (Tian, 2019). These models assist to learn how various operating conditions, including flow rate, electrode layout, and temperature changes, influence battery operation to promote efficiency and thermal enhancement.

Material Selection: Research also focuses on the choice of right electrode materials, electrolyte and cold plates since they affect the thermal conduction and the energy density of ML-RFBs in EV use. All these secondary methods that are derived from the thermal management approaches, the electrode design optimization, and the computer aided analysis provide costly ways of improving the ML-RFB efficiencies in the EV battery systems.

RESULT



(Source: https://www.mdpi.com/2313-0105/9/4/211)

Figure 3: Redox flow battery or ML-RFB

The integration of a membrane-less redox flow battery or ML-RFB shows the opportunity in energy storage technology improvement by the efficiency and their design aspects. As cited in Marma et al. (2019), the membrane-less hydrogen-iron RFB solves the high cost and safety issues encountered by incorporating efficacious membranes with a carbon porous electrode or CPE Teflon impregnation (Rajarathnam and Vassallo, 2016). The envisaged membrane-less reactor was equally efficient as the conventional RFBs with stable Ohmic values and comparative low levels of crossover hence proving to be an efficient system in energy storage.

In this scenario, Arenas et al. (2017) pointed out that fundamental engineering considerations in thermal management of RFB include mass transport, pressure drop assessment, as well as distribution of the electrolyte flow for the improvement of the batteries. This was helpful in identifying significant design factors that could affect cell potential, with a suggestion on need for additional studies to enhance scale-up, and enhanced longevity.

For the thermal control of the batteries used in electric vehicles (EVs), Li et al. (2020) conducted several surveys of the cooling plate shapes applying CFD computations. The authors discovered that the convex-structured cooling plate was more effective in cooling than other structures at different mass flow rates. This design was solved as the most effective way of achieving an improvement in thermal characteristics of EV batteries.

Additional advanced methods of organisation and management of EV battery packs were discussed by Zhu et al. (2020) who considered the thermal efficiency of battery packs using Bernardi's heat generation approach. This study revealed that the inlet temperature and flow rate affected the system's thermal performance rates. Enhancement of these parameters offered better means of controlling thermal issues of EV batteries that are workable for practical application.
These papers in total outline the significance of design, thermal issues, and optimization in the improvement of both the redox flow batteries and the EV battery systems.

DISCUSSION

The results from various studies on membrane-less redox flow batteries (ML-RFBs) and their thermal management in electric vehicle or EV battery systems demonstrate significant advancements in both efficiency and design optimization. Marma et al. (2019) highlighted the potential of the membrane-less hydrogen-iron RFB, where the use of inexpensive iron and Teflon-impregnated carbon porous electrodes or CPEs mitigated some of the issues seen in traditional membrane-based systems (Holland-Cunz, 2019). While Teflon increased kinetic and Ohmic losses, it did not significantly impact overall efficiency, marking a promising direction for reducing the cost and improving the stability of energy storage systems. Arenas et al. (2017) emphasized the critical need for engineering considerations in the scale-up of RFB systems, with techniques like mass transport measurements and flow dispersion analysis playing a crucial role in improving performance. In EV battery thermal management, Li et al. (2020) found that convex-shaped cooling plates demonstrated superior thermal performance compared to other designs, with flow rate significantly impacting heat dissipation. Zhu et al. (2020) further reinforced the importance of thermal optimization in EV battery packs, identifying inlet temperature and flow rate as the most critical factors influencing performance (Wu et al. 2019). Together, these studies highlight the importance of integrating advanced cooling systems, efficient electrode designs, and computational modeling to optimize the performance and thermal management of both ML-RFBs and EV battery systems.

Future Direction

Research on ML-RFBs and thermal management of EV battery systems should consider the following issues to increase the storage capacity, increase scalability and practical application of these technologies. First, the creation of new advanced electrode materials are necessary to reduce Ohmic-losses and enhance ionic-conduction (Lagadec and Grimaud, 2020). Possibilities are also available in developing new coatings or altering the structure of the CPE to help increase efficiency and lower cost. Also in addition, advanced modeling approaches which would allow multi-dimensional simulations could be used to gain improved understanding with regard to how coupling between the electrochemical processes and thermal processes influence the performance of ML-RFBs.

More research is required for thermal management systems with focus on the hybrid coolings or phase change materials that propound significantly better overall thermal conductivity and stability. These systems, when coupled with optimised cooling plates such as those with convex surfaces can improve the dissipation of heat by a large margin, and also extend the life of the batteries. In addition, there is a critical need for experimental validation in real-world conditions more frequently, in order to obtain long-term performance and degradation data under different operating conditions (Gandomiet al. 2018). Updating AI and machine learning approaches to predict and adaptively control the system characteristics of ML-RFBs and

EV battery systems could also be the key player. Further development of these systems to large scalable systems and optimization of them under standard commercial EV usage will be critical.

CONCLUSION

Here mainly conclude that ML-RFBs are believed to be the cost-effective solution for electrochemical energy storage that can improve the safety and efficiency of redox flow batteries. Incorporation of iron, modified carbon porous electrodes, together with Teflon impregnation, has been proved to maintain stability and overcome problems such as degradation observed in the conventional systems. Battery thermal management is one of the significant factors to affect battery performance; some of the new advancements such as convex structure of cooling plates are efficient in the case of electric vehicles. Mathematical models and parametric studies have further helped to identify the performance enhancing indices of both ML-RFB and EV battery thermal management like; inlet temperature and flow rate. However, more development in electrode design, cooling systems and detailed system modelling is required to advance the scalability, steadiness and overall feasibilities of these systems for the commercial use in electric vehicles category.

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