

Environmental and Health Impacts of Vanadium Redox Batteries: from Chemical Properties to Ecological Safety

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Abstract. Due to its distinct design and operation, the vanadium redox flow battery (VRFB) is a cutting-edge energy storage technology that has received a lot of attention lately. The active material of VRFB exists in liquid form, which brings many unique advantages to the battery. Unlike traditional solid-state batteries, the electrodes do not directly participate in chemical reactions during charging and discharging, thus significantly improving the service life of the battery. It is possible to change the VRFB's capacity without changing the battery itself, providing users with great flexibility. VRFB also has some other significant advantages, such as no toxicity by-products, environmental friendliness, high energy efficiency, and rapid response capability. In particular, for large-scale energy storage applications like grid peak shaving, Due to its excellent efficiency, VRFB has attracted a lot of interest, reliability, and economy. However, despite the aforementioned advantages of VRFB, it still faces some challenges in commercialization and large-scale application, such as cost, system complexity, and technology. Furthermore, this paper analyzes the security issues of VRFB in large-scale applications and aims to provide a comprehensive overview of the current state-of-the-art in VRB technology and its applications in various fields.

Keywords: VRBs, toxicology, VRBs' safety production.

1. Introduction

An advanced energy storage device that has received a lot of interest lately is the vanadium redox flow battery (VRFB). It occupies a place in the field of modern energy storage with its unique design and working principle. Unlike traditional solid-state batteries, the active material of VRFB exists in liquid form (Figure 1), and this design brings many unique advantages to the battery.

First, since the electrodes do not directly participate in chemical reactions during charging and discharging, there will be no shape change and deformation inside the battery thus significantly improving the service negative electrode use of vanadium ions and active materials, which avoids cross-contamination between different of the battery. In addition, the capacity of the VRFB can be adjusted volume and concentration of the electrolyte can be adjusted independently of the battery itself, providing users with great flexibility. VRFB also has some other significant advantages, such as no toxicity by-products, environmental friendliness, high energy efficiency, and rapid response capability. Especially in large-scale energy storage applications, such as grid peak shaving extensive attention due to their high efficiency, reliability, and economy. However, despite the aforementioned advantages of VRFB, it still faces some challenges in commercialization and large-scale application, such as cost, system complexity, and technology. Furthermore, the security issues of VRFB in large-scale applications are also analyzed. This article seeks to give a thorough review of the state-of-the-art VRB technology at the moment and how it is used in many fields.

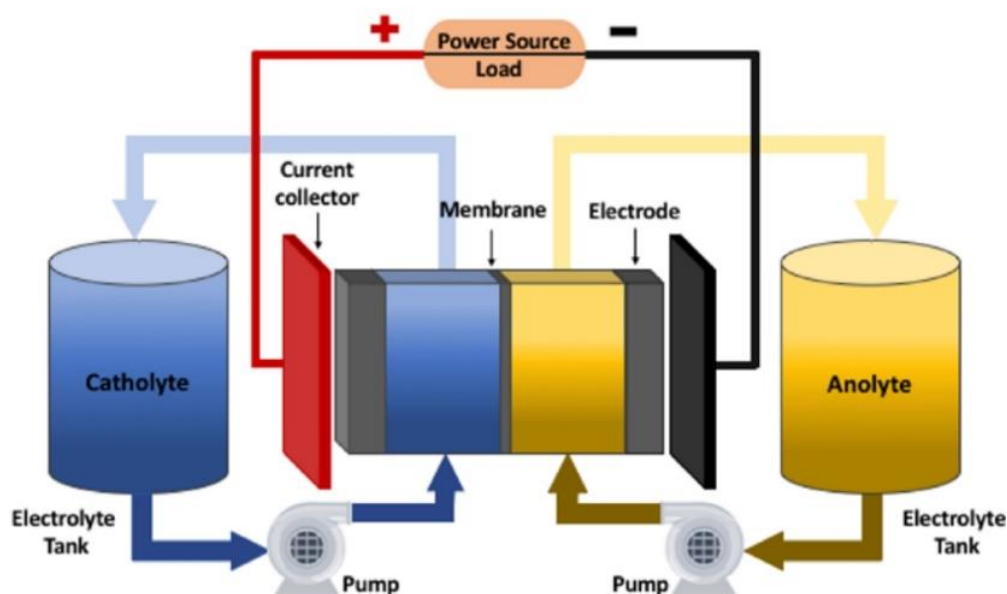


Figure 1. Schematic diagram of VRB [1]

2. Advantages and Disadvantages of VRBs

2.1. Advantages

The benefits of VRBs over other types of batteries are their scalability, quick response time, high capacity for storage, low cost, high efficiency, long life, and minimal impact on the environment [2]. And that's because, unlike other battery types, a redox battery only holds a small fraction of the electroactive material between the electrodes at any given moment. As a result, the fast release of energy that results from electrical shorting is somewhat constrained along with the vanadium electrolyte's comparatively low energy density. The aqueous electrolyte's large heat capacity is also helpful in preventing a temperature increase [3].

For example, in comparison with traditional lithium-ion batteries, VRBs are non-flammable, reusable over long periods, discharge 100% of the stored energy, and can last for over 20 years without degradation. Traditional lithium-ion batteries, however, require frequent renewal. VRBs also have a lower energy density – they are better at delivering a consistent amount of power over significantly longer periods. A VRB can tolerate many more charge-discharge cycles than a lithium-ion battery, which is more significant. They also provide other advantages, such as up to 30% less carbon dioxide intensity compared to other battery technologies and simple vanadium recovery from the electrolyte at the end of the battery life.

For another example, the main benefits of VRFBs over zinc-ion batteries include the lack of an upper limit on energy capacity, the ability to be discharged indefinitely without causing damage, the fact that mixing electrolytes does not permanently harm the battery, the fact that a single charge state across the electrolytes prevents capacity degradation, the use of a safe, non-flammable aqueous electrolyte, and the absence of noise or emissions. Additionally, they are simpler to recycle, and once a battery's vanadium solutions can be used again. Further, regular vanadium batteries are relatively poor in round-trip efficiency, and the heavy weight of the aqueous electrolyte makes regular vanadium batteries only useful for stationary applications. They are also less efficient and substantial than redox ones [4].

2.2. Disadvantages

The VRFB is a notable energy storage technology, yet it faces challenges such as high initial investment costs influenced by vanadium price fluctuations. When compared to alternatives like lithium-ion batteries, VRFBs have a lower energy density, necessitating more substantial storage

spaces. Further, the operation of VRFB hinges on intricate systems involving pumps, valves, and controls, which can introduce the maintenance of VRFB is generally minimal, the electrolyte might need periodic replacement, and system components like pumps and valves could require upkeep. The performance of VRFB can be temperature-sensitive, especially in extreme conditions, potentially demanding supplementary temperature management systems. Extended use might compromise electrolyte stability. While VRFBs excel in smaller applications, scaling up introduces technical and economic hurdles. Despite these challenges, they remain advantageous for large-scale grid storage and renewable energy integration. However, risks like electrolyte leakage, and venting fumes. The inherent safety concerns, especially at its operating temperature of around 40 °C cannot be overlooked. The limited availability and high cost of vanadium, coupled with the need for a bidirectional DC/AC inverter for grid interfacing, further complicate its widespread adoption.

2.3. Toxicity of Vanadium

In the toxicological study of vanadium redox flow batteries, the chemical properties of vanadium and its forms in the battery, especially its different oxidation states (V(II), V(III), V(IV) and V (V)) and their corresponding chemistry and reactivity need to be explored [5]. Subsequently, potential routes of exposure need to be assessed, including inhalation (especially during battery production and disposal), skin contact (considering possible skin penetration and skin reactions caused by vanadium compounds), and ingestion (although less common, the health effects of oral ingestion still need to be studied).

Further, the mechanisms of vanadium toxicity need to be understood, which include possible cytotoxicity (e.g., damage to cell membranes and oxidative stress), genotoxicity (possible accumulation and toxic effects of vanadium compounds in specific organs such as the lungs, liver, or kidneys), and genotoxicity (affecting DNA synthesis and repair mechanisms, possibly producing cancer-promoting effects). Through such research, an in-depth understanding can be provided of the safety and potential environmental and health impacts of vanadium redox flow batteries and provide a scientific basis for formulating corresponding safety measures and regulatory policies.

The majority of vanadium concentrations are not harmful. Vanadium's potentially hazardous effects are mostly brought on by exposure to high levels of vanadium oxides in industrial vanadium processing facilities' breathing air. The most common way for vanadium to enter the body is through the lungs. The majority of dietary vanadium is eliminated in the stomach¹. Reduced appetite and other gastrointestinal problems are the main signs of vanadium poisoning. Vomiting, diarrhea, and vanadium. Additionally, weight has nephrotoxic and hepatotoxic effects. consisting of pyelonephritis and glomerulonephritis. Vanadium is a trace mineral that is regularly consumed in mushrooms, and shellfish, blacking the diet. It's found in pepper, parsley, grains, and drinking water. Vanadium might act like insulin or help to increase the effects of insulin. It has been shown to improve insulin utilization and glucose tolerance, especially when used in combination with Chromium. The recommended daily dosage of vanadium is 20-30 mcg, but no established exists. A lack of vanadium has been associated with higher neonatal mortality, cardiovascular problems, and kidney illness. Vanadium is not quickly absorbed, though. Higher vanadium dosages may enhance insulin sensitivity and lower blood sugar in diabetics, although the dosage and long-term safety of this approach has not been proven. Vanadyl sulfate may help reduce blood pressure, according to certain animal studies, but no human studies have been conducted. Toxic levels of vanadium can have a variety of negative health effects, including loss of appetite, typical digestive issues (such as nausea, vomiting, stomach discomfort, gas, diarrhea, and loose stools), liver and neurological system damage, kidney failure, and stunted growth [6].

Furthermore, studying the relationship between dose and effect is also a core link. This involves the assessment of the toxic effects of vanadium and its related compounds at different doses, as well as the determination of potential upper exposure limits and hazard thresholds. Such research could provide a solid scientific basis for the safe use and handling of vanadium. Finally, the potential environmental impact of vanadium and its related compounds should not be ignored. Research in this

area should focus on the distribution, transport, and transformation processes of vanadium in the environment, as well as its possible effects on ecosystems. Mastering this knowledge can help formulate policies and measures to protect the environment and ecological health.

3. Production Process of Vanadium Redox Batteries

VRBs are produced by a multi-step procedure. To create a battery with a single electroactive element rather than two, VRBs use vanadium ions as charge carriers and take advantage of vanadium's capacity to exist in a solution in four different oxidation states [7]. The concentration of vanadium affects the energy density of VRBs; the higher the concentration, the higher the energy density. The electrolyte employed in modern VRBs, sulfuric acid solutions, has a limited capacity to store vanadium ions before they become trapped, and only a narrow temperature range is suitable for the battery's operation.

When vanadium is dissolved in sulfuric acid, vanadium pentoxide (V_2O_5) solution is produced electrolytically. Both half cells in vanadium redox flow batteries are connected to pumps and storage containers. Electrolytes can go in and out of half cells in large quantities [8]. A membrane that permits protons to pass through only on the positive and negative sides of a vanadium redox flow battery divides the positive and negative sides. An applied voltage during charging causes each of the positive vanadium ions to lose an electron. The released electrons move to the negative side of the circuit through the external circuit, where they are stored [8]. In VRFBs, an electrical charge is produced by the back-and-forth movement of electrons during charging and discharging in two tanks of vanadium electrolyte that flow next to one another past a membrane. With larger electrolyte storage tanks, this battery offers simple infinite energy capacity. (Figure 2) [9].

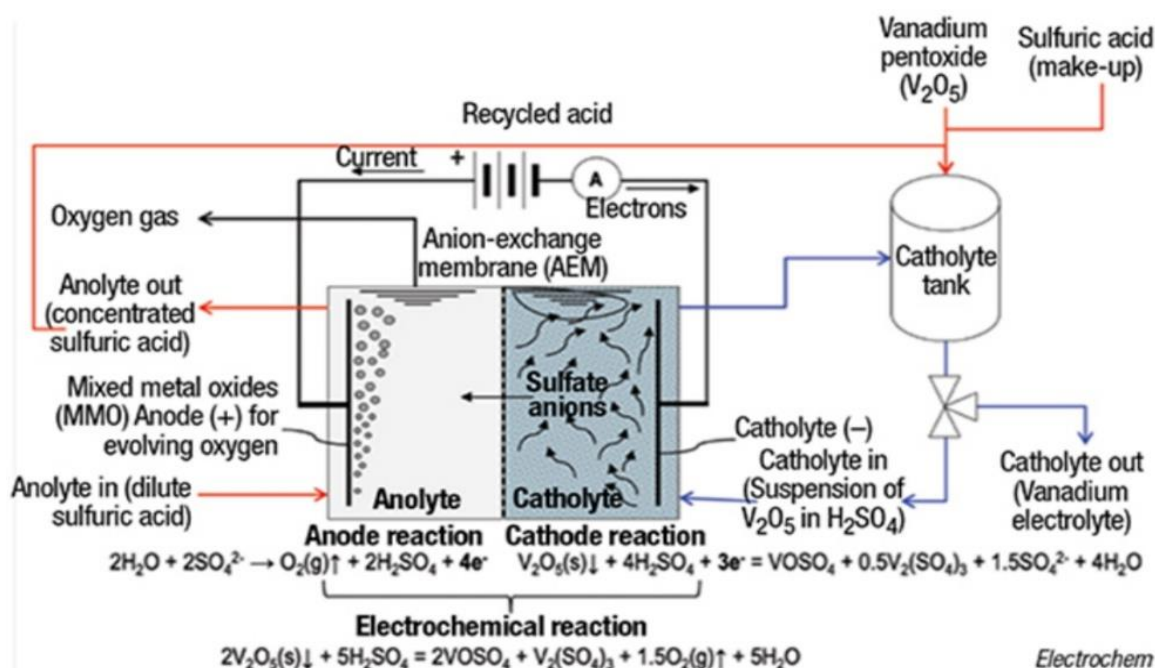


Figure 2. Production and recycle process of VRBs [10]

4. Control measures for the safety production of VRBs

Vanadium redox flow batteries (VRBs) are considered safe energy storage technology due to their intrinsic non-flammability of the water based. However, there are still some potential safety issues that need to be considered during the production of VRBs. One potential safety issue is the handling of vanadium pentoxide (V_2O_5), which is used to form the electrolyte solution. V_2O_5 is a hazardous substance and can irritate the skin, eyes, and respiratory system if not handled properly. Proper protective equipment and handling procedures should be in place to ensure the safety of workers

during the production of VRBs. One potential safety issue is the handling of vanadium pentoxide (V_2O_5), which is used to form the electrolyte solution. V_2O_5 is a hazardous substance and can irritate the skin, eyes, and respiratory system if not handled properly. Proper protective equipment and handling procedures should be in place production to ensure the safety of workers during the process. Another potential safety issue is the handling of sulfuric acid. Which is used as the electrolyte in VREBs. highly corrosive substance and sulfuric acid causes severe burns if it comes into contact with the skin with proper protective equipment and handling or eves. procedures should be in place to ensure the safety of workers during the production process. However, several strategies can be implemented to mitigate the risk of workers getting injured during the production of VRBs. One approach is to take a layered approach to risk mitigation, as suggested by Don Tolbert, the technical director of risk control services for LibertMutualGroup. This implements a hierarchy of hazard control measures, including:

1. Personal protective equipment (PPE): This is the final line of defense, and it entails giving workers the proper safety gear, including gloves and glissandi respirators, to shield them from dangers.
2. Engine workers withrining controls: To lessen or get rid of dangers, physical adjustments to the equipment or workplace must be designed and put into place. Putting in ventilation systems, for instance, can lessen exposure to dangerous pollutants.
3. Administrative controls: involves implementing policies and procedures to reduce or eliminate hazards. For example, providing training education to workers on safe procedures for hazardous substances
4. Elimination or substitution: This involves removing the hazard altogether or replacing it with a less hazardous alternative. Using a less dangerous chemical in exchange for one that is more dangerous, for instance.

It is crucial to remember that these actions ought to be taken gradually rather than all at once. By implementing a combination of these measures, the risk of workers getting injured during the production of VRBs can be significantly reduced.

5. Conclusion

VRBs have a good application prospect despite the challenges they face in commercialization and large-scale application. They still have plenty of aspects that need improvements, but their unique design and working principle make them an advanced energy storage technology that has attracted much attention in recent years. The capacity of the VRFB can be adjusted independently of the battery itself, providing users with great flexibility. VRFB also has some other significant advantages, such as no toxicity by-products, environmental friendliness, high energy efficiency, and rapid response capability. Due to its great efficiency, dependability, and affordability, VRFB has drawn a lot of attention, particularly in large-scale energy storage applications like grid peak shaving. This article seeks to give a thorough review of the state-of-the-art VRB technology at the moment and how it is used in many fields. References

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