Redox flow batteries

Redox flow batteries (RFBs) represent one class of electrochemical energy storage devices. They are a type of rechargeable battery that store energy in liquid electrolytes. They are unique compared to conventional batteries because their energy storage capacity can be easily scaled up by increasing the size of the storage tanks.

Classification of redox flow batteries

Redox flow batteries differ primarily in the composition of the electrolytes and the solvents.

Redox couple	Cell voltage
Hydrogen bromine	1.1 V
Iron-chrome	1.2 V
Vanadium/polyhalide	1.3 V
Vanadium/Vanadium	1.4 V
Bromine polysulphide	1.5 V
Zinc-Bromine	1.8 V

Hydrogen-Bromine Redox Flow Battery
Consists of Hydrogen and bromine.
How it works: Hydrogen is oxidized, and bromine is reduced to store energy.

Iron-Chromium Redox Flow Battery
Consists of Iron on one side and chromium on the other.
How it works: Iron and chromium changes forms to store and release energy.

Vanadium Polyhalide Redox Flow Battery
Consists of Vanadium in one half-cell and halides (like chlorine or bromine) in the other.
How it works: Vanadium changes oxidation states in the vanadium half-cell, and halides (such as bromine) undergo redox reactions in the other half-cell.

All-Vanadium Redox Flow Battery (VRFB)
Consists of Vanadium in both sides of the battery.
How it works: Vanadium changes its form (oxidation state) during charging and discharging.

Polysulfide-Bromine Redox Flow Battery
Consists of Polysulfide and bromine.
How it works: Polysulfide and bromine react to store energy.

Zinc-Bromine Redox Flow Battery
Consists of Zinc and bromine.
How it works: Zinc gets plated (deposited) on the electrode during charging, and bromine is produced.

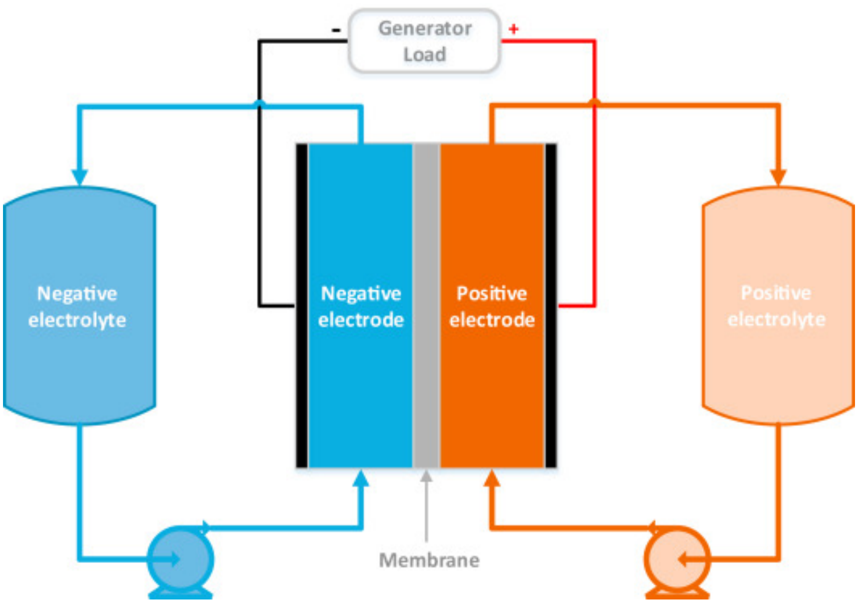
Construction and Working of Vanadium Redox Flow Battery

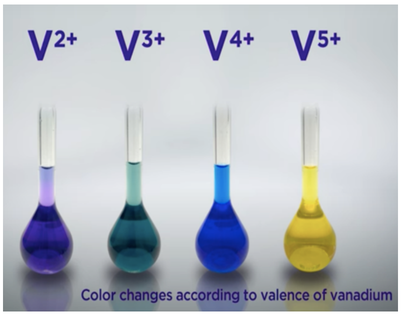
The vanadium redox flow battery is one of the most promising secondary batteries as a large-capacity energy storage device for storing renewable energy.
A vanadium redox flow battery (VRFB) is a specific type of redox flow battery that uses vanadium ions in different oxidation states to store and release energy.
Its key advantage lies in using the same element (vanadium) for both the positive and negative half-cells, which prevents cross-contamination of electrolytes, a common issue in other flow batteries.

Principle:
The electrolyte in the positive half-cell contains vanadium in the +5 and +4 oxidation states (VO_2^+/VO^{2+}), while the electrolyte in the negative half-cell contains vanadium in the +3 and +2 oxidation states (V^{3+}/V^{2+}). These reactions involve the transfer of electrons, converting electrical energy to chemical energy and vice versa.

Construction:

1. **Electrolytes:**
   - The electrolyte is prepared by dissolving vanadium pentoxide (V2O5) in H2SO4. Both the electrolytes are stored in separate tank. The **positive half-cell electrolyte contains** VO^{2+} (V^{4+}) and VO_2^+ (V^{5+}) and the other **negative half-cell electrolyte** contains V^{2+} and V^{3+}
2. **Electrochemical Cell Stack:**
   - The stack consists of multiple cells with electrodes where the redox reactions occur. These cells are separated by an ion-selective membrane, which allows ions (typically protons) to flow between the two half-cells while keeping the electrolytes separated.
3. **Ion-Selective Membrane:**
   - This membrane (e.g., Nafion) allows protons (H^+ ions) to pass through while preventing the vanadium ions from passing, maintaining separation between the positive and negative electrolytes.
4. **Pumps and Reservoirs:**
   - Pumps circulate the vanadium electrolyte solutions from external tanks through the cell stack, facilitating continuous operation.





Working Mechanism:

1. Charging Process: The reaction progresses as current flows from positive electrode to negative electrode.

At the **positive electrode (cathode)**:
$V^{+4} \rightarrow V^{5+} + e^-$
In this reaction, VO^{2+} (vanadium in +4 oxidation state) is oxidised to VO_2^+ (vanadium in +5 oxidation state)
At the **negative electrode (anode)**:
$V^{3+} + e^- \rightarrow V^{2+}$
Here, V^{3+} (vanadium in +3 oxidation state) gains the electron, thereby it is reduced to V^{2+} (vanadium in +2 oxidation state).

2. Discharging Process: During discharging, the reaction progresses as current flows from negative electrode to the positive electrode.

At the **negative electrode (anode)**:
$V^{2+} \rightarrow V^{3+} + e^-$
Here, V^{2+} (vanadium in +2 oxidation state) is oxidised to V^{3+} (vanadium in +3 oxidation state)

At the **positive electrode (cathode)**:
$V^{+5} + e^- \rightarrow V^{4+}$ In this reaction, VO_2^+ (vanadium in +5 oxidation state) gain an electron and is reduced to VO^{2+} (vanadium in +4 oxidation state)

Since the charging and discharging reactions are taking place only due to the exchange of electrons between the ions in the electrolyte, so it can be said that the redox flow batteries are batteries that will not deteriorate.

Advantages:
1. High safety - The electrolyte used is non-flammable. (even positive and negative liquids are mixed will not ignite)
2. Eco friendly – No electrolyte degradation. Electrolyte can be recycled and reused
3. Long life -No need to replace battery
4. Low life cycle cost – As electrolyte can be recycled and reused, the life cycle cost is low with long term capacity
5. Easy operation
6. Flexible design – number of cell stack can be increased and electrolyte tank size can be increased.

Applications:
1. It is used in power stations for storing electricity
2. It can be used for storing renewable energy
3. It helps in reducing the power bills in industries
4. It is eco-friendly as it do not release toxic gases.

Introduction to Next-Generation Sodium-Ion Batteries (SIBs)

As the global demand for energy storage rises—especially for applications like electric vehicles (EVs) and renewable energy storage—there is an increasing need for sustainable and cost-effective alternatives to lithium-ion batteries (LIBs). Sodium-ion batteries (SIBs) have emerged as a promising contender due to the abundance of sodium, lower costs, and potential for environmental benefits.

The working principle of Sodium-Ion Batteries (SIBs) is similar to that of lithium-ion batteries.

Construction and Working Principle of SIBs:

Anode: Usually made of hard carbon or other carbon-based compounds.

Cathode: Transition metal oxides (such as $NaMnO_2$) or polyanionic compounds (like $Na_3V_2(PO_4)_3$).

Electrolyte: Sodium salts like $NaPF_6$ or **$NaClO_4$** dissolved in organic solvents serve as the electrolyte, facilitating the movement of sodium ions between the electrodes.

Working Principle:

Charging: Sodium ions (Na^+) de-intercalate from the cathode and travel through the electrolyte to intercalate into the anode.

Discharging: The sodium ions flow back from the anode to the cathode, generating electricity. This movement of sodium ions between the electrodes drives the charging and discharging processes.

Advantages of Sodium-Ion Batteries over Lithium-Ion Batteries:

1. Abundance of Sodium:

Sodium is the sixth most abundant element on Earth, making up roughly 2.6% of the Earth's crust. In contrast, lithium is much rarer, constituting about 0.002%.

2. Cost-Effectiveness:

The raw materials needed for sodium-ion batteries, especially sodium, are cheaper compared to those used in lithium-ion batteries. Sodium is readily available and can be sourced from inexpensive materials like seawater, which leads to potentially lower production costs compared to lithium-ion batteries.

3. Environmental Benefits:

The mining and extraction processes for sodium are less environmentally damaging than lithium, cobalt, and nickel, which are often used in LIBs.

4. Thermal Stability and Safety:

Sodium-ion batteries are inherently safer than LIBs due to their superior thermal stability. This reduces the risk of thermal runaway—a dangerous condition where batteries overheat and potentially catch fire or explode.

Challenges in Sodium-Ion Batteries:

1. Lower Energy Density:

Sodium-ion batteries generally have lower energy density than lithium-ion batteries. Since, Sodium atoms are larger and heavier than lithium atoms, it reduces the amount of energy that can be stored in a given volume or weight of the battery.

2. Limited Commercial Availability:

Although there has been significant research in SIBs, the technology is not as mature as lithium-ion, meaning commercial-scale production is still developing.

3. Anode and Cathode Material Limitations:

Traditional graphite anodes used in LIBs are not compatible with sodium-ion batteries, leading to the need for alternative materials like hard carbon or other carbon-based compounds.

Applications of Sodium-Ion Batteries (SIBs)

1. Grid Energy Storage:

Used to store excess energy from renewable sources (solar/wind) and balance electricity supply during peak demand.

2. Electric Vehicles (EVs):

Suitable for short-range EVs like e-bikes and scooters, focusing on affordability and environmental benefits.

3. Consumer Electronics:

Potential for use in smartphones, laptops, and portable devices, offering faster charging and improved safety.

4. Backup Power Systems:

Ideal for uninterruptible power supplies (UPS) in critical infrastructures like hospitals and data centers ensuring continuous operation.

5. Industrial Applications:

Useful in forklifts, telecom networks, and other industries needing reliable backup power or sustainable energy solutions.

Overview of Battery Technology for E-Mobility

E-mobility refers to the electrification of transportation, primarily through the use of electric vehicles (EVs) powered by rechargeable batteries. The performance of these vehicles is largely dependent on battery technology.

Lithium-Ion Batteries (LIBs):
Most common in electric vehicles (EVs).
Advantages: High energy storage, fast charging capabilities, and long lifespan.
Disadvantages: High cost, safety concerns (thermal runaway), and reliance on rare materials like lithium, cobalt, and nickel.

Solid-State Batteries:
Future technology replacing liquid electrolytes with solid ones.
Advantages: Higher energy density, improved safety, longer lifespan, and reduced risk of overheating.
Disadvantages: Expensive and still under development for commercial viability.

Nickel-Metal Hydride (NiMH):
Used in hybrid vehicles (HEVs), not full electric vehicles.
Advantages: Affordable and reliable.
Disadvantages: Lower energy density compared to LIBs, making them unsuitable for long-range EVs.

Sodium-Ion Batteries (SIBs):
Emerging technology as a cheaper alternative to LIBs.
Advantages: Abundant raw materials (sodium), safer, and more environmentally friendly.
Disadvantages: Lower energy density than LIBs, still in the development stage.

IoT-Based Battery Monitoring System for Electric Vehicles (EVs)

An IoT-based Battery Monitoring System is crucial for ensuring the safety, reliability, and efficiency of electric vehicles by continuously tracking the battery's health and performance in real time. This helps in,

1. Real-Time Data Collection:

IoT sensors continuously monitor key battery parameters like temperature, voltage, current, and state of charge (SOC).

2. Remote Monitoring:

Vehicle owners and fleet managers can check battery status anytime using a phone app or website.

3. Predictive Maintenance:

IoT systems use data analytics to predict potential problems (like battery failure) before they happen, so that it can be fixed early.

4. Battery Health Management:

IoT helps monitor battery degradation over time, ensuring optimal performance and extending battery life.

5. Energy Optimization:

The system can suggest to use the battery more efficiently by providing suggestions on when to charge or discharge.

6. Alerts and Notifications:

The system can send alerts in case of abnormalities, such as overheating or overcharging, reducing risks of battery damage or failure.

Battery Management System

Li-ion battery hazards

The key hazards associated with Li-ion batteries are:

Overheating & Thermal Runaway: Battery can overheat and catch fire or explode due to Overcharging, high temperature, or short circuits.

Fire Hazard: Damaged batteries can trigger a fire due to physical damage, high heat, or defects in manufacturing.

Toxic Chemical Leakage: Damaged or improperly handled Li-ion batteries can leak toxic electrolytes. These chemicals are harmful to humans and the environment, causing skin burns, respiratory issues, and environmental pollution. This may happen due to improper charging cycles or Degradation due to overuse.

Explosion Risk: Battery can explode if it overheats too much due to overcharging leading to gas buildup, and exposure to extreme temperatures or physical impact.

Short Circuiting: Can cause overheating or battery failure. This may be due to the faulty internal design or external factors like damaged insulation Or Contact between battery terminals due to improper handling or storage.

Electrochemical Recovery of Lithium from Spent Batteries

Recovering lithium from used lithium-ion batteries (LIBs) is important for recycling and sustainability.

Steps involved in the process are:

1. Disassembly of Spent Batteries: Used batteries are carefully taken apart to separate different parts, especially the cathode (which contains lithium).

2. Leaching Lithium: The cathode material is treated with acids (like sulfuric or hydrochloric acid combined with oxidants like hydrogen peroxide (H_2O_2).) to dissolve lithium into a solution.

3. Electrochemical Recovery: Lithium ions (Li^+) are recovered from the leached solution using electrochemical techniques like electrodeposition or electrodialysis.

Electrodeposition: Lithium is deposited onto an electrode by applying an electric current through the leachate solution containing lithium ions. This forms metallic lithium or lithium compounds on the cathode.

Electrodialysis: An electric field is applied across a membrane, driving lithium ions through the membrane to be collected on the other side. This is a separation process used for selective ion recovery.

4. Post-Processing of Lithium: After electrochemical recovery, the lithium product need to be refined or converted into commercially valuable lithium compounds like lithium

carbonate (Li_2CO_3) or lithium hydroxide ($LiOH$). This is to make lithium suitable for making new batteries.

Best storage and handling practices of Li ion batteries, and their Safe disposal:

Best Storage Practices:

Keep Cool: Store in a cool, dry place, ideally between 15°C and 25°C. Avoid hot or freezing places, which can damage the battery.

Partially Charged: Store batteries at about 40% to 60% charge. This helps extend their life.

Dry Area: Store in a place without moisture to avoid corrosion or damage.

Keep Away from Fire: Store far from flammable objects.

Best Handling Practices:

Always use the charger made for the device to avoid overheating.

Handle Carefully as it may cause them to overheat or catch fire.

Unplug once the battery is fully charged and don't leave it charging overnight.

Check for bulging, leaking, or cracks. If so to stop using the battery immediately.

Safe Disposal of Li-ion Batteries:

Safe Disposal of Li-ion Batteries is important because:
Electrolytes used in LIBs can react with moisture or air to form hydrofluoric acid (HF), a highly corrosive and toxic substance. Improper disposal can lead to these dangerous chemicals seeping into soil and water, causing environmental damage and health risks.

Preventing Fires and Explosions: Li-ion batteries are highly reactive and can easily ignite if punctured or exposed to high temperatures. The organic solvents used in the electrolyte are highly flammable.

Heavy Metal Contamination: Metals like cobalt, nickel, and manganese can be harmful to ecosystems. Cobalt is especially toxic and can cause both environmental pollution and human health issues if not disposed of correctly.

Some safe disposal tips are:

1. **Neutralizing Electrolytes:** The electrolytes need to be neutralized to prevent them from reacting with the environment. This is done through chemical treatments that decompose the harmful compounds into less hazardous forms.

2. **Recovery of Valuable Metals:** Electrochemical, Hydrometallurgical or pyrometallurgical processes are used to recover metals like cobalt, nickel, lithium, and aluminum from batteries.

Using acids (like sulfuric acid) to dissolve metals for recovery.
Then the metals are precipitated from solutions or recovered using electrical currents.

3. **Preventing the Formation of Toxic Compounds:** When Li-ion batteries are incinerated improperly, they can produce toxic fumes, including dioxins and furans. Recycling centers use controlled environments to prevent the formation of these toxic compounds.

Temperature sensing for battery management systems using thermocouple technology

Battery Management Systems (BMS): It is required to monitor and manage the performance of battery systems, ensuring safety, efficiency, and longevity.

Thermocouple:
A thermocouple is a type of transducer that converts thermal energy into electrical energy. It is a temperature sensor that measures temperature by measuring the voltage.
It consists of two dissimilar metal wires or elements, which are joined together at one end to form a junction. When this junction is exposed to a temperature gradient, it produces a voltage that is proportional to the temperature difference between the junction, and the other end of the wires.

Types of Thermocouples:
Type K (Chromel-Alumel): Commonly used, suitable for a wide range (−200°C to 1260°C).
Type J (Iron-Constantan): Limited range, used in lower temperature applications (−40°C to 750°C).
Type T (Copper-Constantan): Good for low-temperature applications (−200°C to 350°C).

Others are
Thermocouple type E
Thermocouple type R
Thermocouple type S
Thermocouple type B

Thermocouple types J, K, T, and E are also known as Base Metal Thermocouples.
Types R, S, and B thermocouples are known as Noble Metal Thermocouples

Working Principle of a Thermocouple:

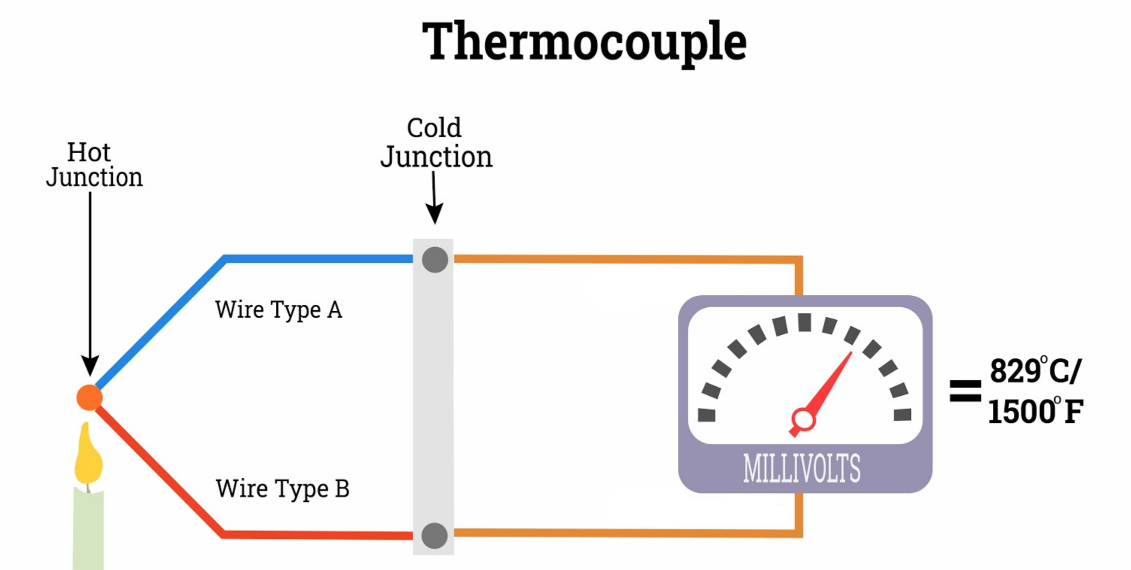
The thermocouple operates based on the Seebeck Effect, it occurs when two different metals are joined together at two junctions, creating an electromotive force (emf). This emf varies depending on the types of metals used and the temperature difference between the junctions

Basic Structure: A thermocouple consists of two wires A and B made from different metals joined together at one end (e.g., copper and constantan for Type T, or chromel and alumel for Type K) to form a junction known as the hot junction while the other ends are connected to a measuring instrument (the cold junction).

Temperature Difference: When the hot junction is heated compared to the other end i.e., the cold junction remain at a different temperature, a temperature difference is created.

Voltage Generation: Due to this temperature difference, a small voltage is generated at the hot junction. This happens because the different metals react differently to heat, causing electrons to move and create a voltage.

Measurement: The generated voltage can be measured using a voltmeter. The voltage corresponds to a specific temperature based on the type of metals used.



Advantages of Thermocouples for BMS

- **Wide Temperature Range**: Can measure extreme temperatures beyond the capabilities of other sensors.
- **Fast Response Time**: Quick detection of temperature changes.
- **Robustness**: Suitable for harsh environments; less susceptible to damage compared to other temperature sensors.
- **Cost-Effectiveness**: Generally less expensive than other temperature sensing technologies.