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Principles and Requirements of Battery Membranes: Ensuring Efficiency and Safety in Energy Storage

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Abstract:

This critical review highlights the latest improvements and special features regarding the membrane separators available for lead-acid, alkaline, metal-metal, metal-gas, and metal-ion batteries such as lithium-ion. In the recent years, there has been a surge in the intensive work aimed at developing innovative separators for rechargeable lithium-ion batteries, for example, electric vehicles (EVs), portable electronics and for energy storage in power grid. The separator finds itself in a very important place as it provides physical separation between two electrodes. It also acts as an electrical insulator. This separator is known as an electrolyte gateway which helps the movement of ions during charge/discharge cycles. This review addresses the requirements for battery separators and explains the structure and properties of various types of membrane separators; there are several types of membranes such as microporous membranes, modified microporous membranes, nonwoven mats, composite membranes and electrolyte membranes. Similarly, each type of separator has inherent advantages and disadvantages which in turn directly affects the performance of batteries. This review article systematically deals with the structures and working principle of separators, properties and main requirements and their characterization method of separators, generation, improvements, and function assessments of these separators. Furthermore, this study also enlightens the emerging research path and future prospects.

Keywords: *Ionic conductivity, Electron insulator, Porosity, Tortuosity, Chemical stability.*

Introduction

Batteries have become an inseparable part of our life because they powering a vast type of devices and vehicles that underpin our daily lives. This underpin cover from portable and light electronics to heavy electric vehicles and renewable energy storage, batteries are at the heart of our technological progress (Liu, et al., 2021). Within these energy storage devices, a critical but often underappreciated component takes center stage; the membranes are very important they serving as essential separators

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and facilitators of ion transport in batteries, influencing their performance, efficiency, and safety (Baldwin, et al., 2010). This review embarks on a journey to explore the pivotal requirements and distinctive characteristics of battery membranes, shedding light on their paramount role in energy storage technologies. The significance of membranes in batteries extends far beyond mere physical separation (Song, et al., 2021). These vital components must meet a stringent set of criteria to effectively function within the demanding environment of a battery are consist of, ionic conductivity (Li, et al., 2021), mechanical strength, chemical stability, thermal stability, high selectivity (Cannarella, et al., 2014) etc. Beyond these fundamental requirements, the characteristics of battery membranes, including material composition, porosity, thickness, surface chemistry, and manufacturing techniques (Arora, & Zhang, 2004), profoundly influence their performance and suitability for specific applications. Decisions regarding these characteristics are pivotal in shaping a battery's efficiency, safety, and lifespan (Liu, et al., 2020).

Principle and Role of Membranes in Batteries

Batteries are widely typified in an assortment of shapes and structures, like button, flat, prismatic (rectangular), and cylindrical (for instance, AA, AAA, C, D, 18650) (Schröder, Aydemir, & Seliger, 2017). The parts of a battery, such as separators, are engineered for the observation and specification of a certain cell. The separator is a membrane utilizing a permeable material that is situated in the midst of the battery anode and cathode to divide anode and cathode. More importantly, its function is separation between two electrodes such that any contact between two electrodes is not there for the sake of preventing electrical short circuits. At the same time, a separator activates the dispersion of ionic charge carriers required for current interruption in an electrochemical cell (Farooqui, Ahmad, & Hamid, 2016). The separators are an important component of the liquid electrolyte and jellyroll-type batteries, mostly builder with polymeric membrane with microporous layer. In order to be functional, a separator should be chemically and electrochemically stable with respect to the reliability of the electrolyte and the electrode materials, and with mechanical strength to take the tension created during the manufacture of the battery (Santhanagopalan, & Zhang, 2013). In batteries, their importance relies on the fact that the structure and properties of these materials play the core role in defining battery performance and the various relevant performances utilized are the energy density, power density, cycle life, stability and safety aspects (Nitta, et al., 2014).

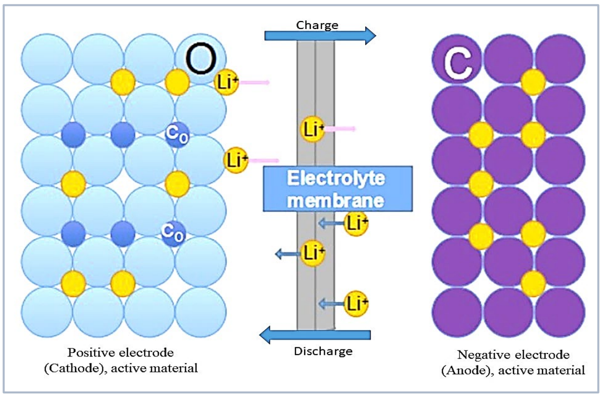

Figure 1. Illustrate the Working Principle of Li+ Battery Membrane

Requirements of Batteries Membrane

The optimal separator for a specific battery and application must consider a variety of parameters. It is necessary to compare the qualities of each separator on the market to the specifications and choose the one that best satisfies those requirements. The separators that are used in different type of batteries must meet a large rang of qualities and requirements (Luo, et al., 2021). The following are essential factors that affect the decision on the separator and should be considered.

Table 1. Exhibit the Common Requirements of Batteries Membrane and Their Types

	Thickness

Structural requirements of membrane	Pore structure
	Porosity
Intrinsic requirements of materials	Ionic conductivity
	Wettability
	Electrochemical stability
	Chemical stability
Requirements against external stimulus	Shutdown temperature
	Dimensional stability
	Tortuosity
	Thermal dimensional stability
	Puncture stability
	Tensile stability
	Melt stability

Electronic Insulator

Membranes in batteries must serve as electronic insulators, preventing the direct flow of electrons between the cathode and anode. This characteristic ensures that the electrical current flows through the external circuit, facilitating controlled energy release (Tan, & Rodrigue, 2019).

Minimal Electrolyte (Ionic) Resistance (High Ionic Conductivity)

While acting as electronic insulators, membranes should offer minimal resistance to ionic transport. High ionic conductivity is essential to facilitate the movement of ions between electrodes, reducing internal resistance and optimizing battery efficiency (Yang, & Hou, 2012).

Mechanical and Dimensional Stability

Membranes must maintain their structural integrity under mechanical stress, such as expansion and contraction during charge and discharge cycles. Dimensional stability ensures consistent performance throughout the battery's lifespan (McNeil, & Steinhardt, 1997).

Sufficient Physical Strength to Allow Easy Handling

Membranes should possess the necessary physical strength to withstand manufacturing processes, assembly, and handling during battery production, preventing damage or deformation (Cannarella, et al., 2014).

Chemical Stability

Batteries operate in chemically harsh environments, and membranes must resist degradation caused by interactions with the electrolyte, impurities, and reactants and products at the electrode interfaces. Chemical stability is paramount for long-term battery performance. Effective in preventing migration of particles or colloidal or soluble species between the two electrodes (Arora, & Zhang, 2004; Mohammadi, & Skyllas-Kazacos, 1995).

Readily Wetted by Electrolyte

To ensure efficient ion transport, membranes should readily absorb and be wetted by the electrolyte. This property allows ions to move through the membrane while preventing dry regions that can impede ionic conductivity (Cannarella, et al., 2014).

Uniform in Thickness

Membranes must maintain a uniform thickness across their entire surface. Thickness uniformity ensures consistent performance and prevents variations in resistance to ion transport (Song, et al., 2021; Deimede, & Elmasides, 2015).

High Porosity and Low Tortuosity

Porosity in membranes is essential to provide a network for ion transport, while low tortuosity ensures that ions can move through the membrane with minimal resistance. This combination enhances ionic conductivity and overall battery performance.

Each of these requirements and characteristics is interrelated and indispensable in the design and selection of membranes for various battery technologies. Balancing these factors is crucial to achieving optimal battery performance, safety, and longevity, and they remain at the forefront of battery research and development as we strive for more efficient, reliable, and sustainable energy storage solutions (Cannarella, et al., 2014).

Ion Selectivity

Membranes must facilitate the passage of specific ions, such as lithium ions in lithium-ion batteries, while blocking the movement of other ions or particles (Li, et al., 2021).

Table 2. General Requirements for Lithium-Ion Battery Separator

Parameter	Requirement
Chemical stability	Stable for a long period of time in battery
Wettability	Complete wet out in typical battery electrolyte.
Porosity (%)	~40
Dimensional stability	Membrane should be lay flat and stable in electrolyte
Thickness (μm)	<25
Electrical resistance (mac Mullin no)	<8
Electrical resistance(ohms.cm^2)	<2
Gurley (S)	~ 25/ml
Pore size(μm)	<1
Skewness (mm/m)	>0.2
Puncture strength (g/mil)	>300
Shut down temperature (^{0}C)	~130
Shrinkage (%)	>5 in both MD and TD
Tensile strength (%)	>2 offset at 1000 psi
High temp melt integrity(^{0}C)	~150
Mix penetration strength(kgf/mil)	>100

Source: Arora, & Zhang, 2004

Materials and Synthesizing of Batteries Membrane

The membrane materials in the powerhouse of electrochemistry batteries range from simple materials like linen and polymer films to complex items, such as ceramics and natural finds. As separators inside batteries, the functional purposes of these materials are dual in nature: they allow passages for ions to transfer between the electrodes and aerobat the physical interaction and shorts (Gubler, 2019). Nonwoven fabrics including cotton, nylon, polyesters, and glass can be found in most membranes for batteries. These fabrics are made up of different materials, which make them the perfect fit for practically any requirement. In this manner, whether the fibers are arranged either uni-directionally, or randomly in a specified direction, a fabric is created, in which porous has sufficient room for diffusion (Saal, Hagemann, & Schubert, 2021). The value of polymer films such as polyethylene, polypropylene, poly (tetrafluoroethylene) and polyvinyl chloride is manifold because of their amenability to variety of methods of fabrication and adjustable properties. It is possible to modify these films to accommodate varied functionality objectives, including pore size as well as overall strength. Ceramic substances based at ceramic materials are of the high thermal stability and awesome mechanical strength making them an appropriate choice for high temperature applications. There is a potential using natural items as a substitute for artificial compounds like rubber, asbestos and wood that have been considered for membrane battery materials. We also consider will be potential separators which are composed with complex polymers possessing alkali metal ions which, in turn, act as solid electrolytes with ion conductivity. Solid ion conductors can be applied as both separators and electrolytes which would thereby simplify the design of batteries with the advantage of productivity (Santhanagopalan, & Zhang, 2012).

Two main production methods for battery membranes. Those are dry method and wet one. Wet process seems as being the most common among them both. Dry processing involves extrusion and sintering processes and development of flat sheet (or disc) type membranes composed of porous low-density materials with well-controlled pore structures. While the so-called dry processes are based on forming pores using solvents or fluids to later obtain dense membranes, wet processes comprise of mixing, heating, extruding, stretching and additive removal of the membrane's components to finally obtain microporous membrane with dispersed round pores throughout the polymer matrix (Costa, et al., 2019).

Selection of polymer for membranes of the battery depends mainly on the things such as molecular disorder, solid-phase properties and compliance with the electrolytes. Non-metal based materials like polyethylene and polypropylene are highly demanded! This is because of their crystalline structure and physical features that are better than other materials. PLGA type polymers coupled with micro-porous PMMA (Poly methyl methacrylate) and siloxane-grafted PE (Polyethylene) and the studies into the applicability of PVDF nanofiber webs have appeared promising as new technologies to boost the battery performance. As a matter of what, battery membrane materials are vital for specifying the performance, safety of and the battery lifetime as well. To move on and achieve the desired amelioration in battery technology through research and development and this can facilitate battery technology for the better (Gubler, 2019).

Type of Membranes

Depending on their physical and chemical properties, separators for batteries can be categorized into many types. They could be laminated, molded, woven, nonwoven, microporous, bonded, or woven (Baldwin, et al., 2010).

Solid and gelled electrolytes that include the separator and electrolyte into a single element have become increasingly popular in recent years. The separators in most batteries are either made of microporous polymeric films or nonwoven textiles. Battery separators made of organic materials like cellulosic papers, polymers, and other textiles as well as inorganic materials like asbestos, glass wool, and SiO_2 are typically used in batteries that run at or near ambient temperatures. In alkaline batteries, microporous polymer sheets or regenerated cellulose are utilized as separators. Most of the microporous films used in lithium batteries with organic electrolytes (Cannarella, et al., 2014).

In this review we categorized the separators into six categories for discussion purposes: microporous films, nonwovens, supported liquid membranes, ion exchange membranes, solid polymer electrolytes, and solid ion conductors. Below, each sort of separator is briefly described along with how it is used in batteries.

Microporous Membranes

The pores of them usually exceed 50 - 100 angstroms in diameter and is formed variously of inorganic, organic or natural parts. For porous microporous separators that work in the ambient and low temperatures (<100°C), there are several types of materials used. They are nonwoven materials like nylon, cotton, polyester, and glass, polymer films such as polythene (PE), polypropylene (PP), poly tetrafluoroethylene (PTFE) and polyvinyl chloride (The choice of lithium-based nonaqueous batteries may be polyolefin (PP, PE, or laminates of PP and PE) while it is filled polyethylene separators in the lead-acid batteries (Cannarella, et al., 2014).

Nonwovens Membranes

Nonwoven membranes are engineered materials composed of fibers that are mechanically, thermally, or chemically bonded to create a porous structure. They find diverse applications in filtration, geotextiles, healthcare products, and battery technology. Nonwoven membranes offer advantages like customizability, high porosity, mechanical strength, and chemical resistance. In all battery technology, they act as separators to hinder electrical short circuits while allowing for ionic flow between the two electrodes. Such separators are fundamentals for the functioning of various battery types, such as lithium-ion batteries found in mobile phones, electric vehicles and renewable energy storage systems (Ajmeri, & Ajmeri, 2016).

Supported Liquid Membrane

A supported liquid membrane (SLM) is a specialized membrane technology where a liquid phase is immobilized within a porous support structure. This unique configuration allows selective transport of molecules, typically ions or small solutes, across the membrane. SLMs are utilized in various separation processes, such as extraction, metal recovery, and environmental remediation, where they provide high selectivity and efficiency. Their versatility and ability to handle challenging separations make them valuable in diverse industrial applications.

Ion exchange Membranes

Ion exchange membranes are selective barriers that facilitate the exchange of ions in aqueous solutions. These membranes contain ion-exchange groups that allow the passage of specific ions while blocking others. They find applications in water treatment, electrodialysis, fuel cells, and chemical processes, where they enable the separation, purification, and controlled transport of ions for various industrial and environmental purposes (Mohammadi, & Skyllas-Kazacos, 1995).

Solid Polymer Electrolytes

Solid polymer electrolytes (SPEs) are advanced materials used in batteries and fuel cells. Unlike traditional liquid electrolytes, SPEs are solid-state, consisting of a polymer matrix infused with ionic salts. SPEs offer improved safety, as they are non-flammable and resistant to leakage. These electrolytes elevate the total efficiency of energy storage by giving a secure medium where the ions get transported which results in achieving higher energy density and sustained life of the battery cells and fuel cells (Song, et al., 2021).

Solid Ion Conductors

Solid ion conductors are materials that facilitate the movement of ions within a solid-state structure. They are vital components in advanced energy storage systems, such as solid-state batteries. These materials offer advantages like enhanced safety, high ionic conductivity, and resistance to thermal issues, making them attractive for applications where traditional liquid electrolytes may be inadequate or pose safety concerns (Song, et al., 2021).

Characteristics Evaluation of Batteries Membrane

Wettability by Electrolyte

Poor wettability of isolators poses a serious problem with battery performance by enhancing resistance and negatively affecting cell function. High wetting speed is usually related to the electrolyte filling time in real cells, which depend on the cell material surface energy, pore size, porosity, and tortuosity. Even though there is not a standardized approach, the observation of the electrolyte droplet penetrating a surface or measurement of contact angle gives a clue of hydrophilicity (figure 3a). Increased electrolyte uptake in hydrophobic electrodes can be accomplished by wetting agents or dose ionic groups (Davoodabadi, et al., 2020).

Uniform in Thickness

For thickness measurement of membranes we can use appropriate measurement techniques, such as calipers or specialized equipment like profilometers, to ensure the membrane's thickness remains uniform (Li, et al., 2021).

Melt Integrity

The separator should have a high temperature melt integrity specially when we want to design lithium-ion batteries. In order to ensure that after shutdown the separator still maintains its melt integrity so that the electrodes do not short-circuit, another possibility is to use another type of separator. It eliminates any possibilities of having thermal runaway even when the cell is exposed to high temperatures. TMA is considered as a very good technique to measure the high-temperature melt of separators (Saal, Hagemann, & Schubert, 2021). TMA means the measurement of the profile change of a separator under external load as the temperature ranges linearly from low to high. Commonly, separators shrink and then before they break as indicated by (Figure 3b). The test uses a small separator sample (approximately 5-10 mm length and about 5 mm width) held in mini instron type grips. At an acceleration of 2 g, the sample is held and the temperature is increased by 5°C/min moving past the melting point until the tension ruptures the film. One parameter derived from the TMA tests is the shrinkage onset temperature, the melt temperature and the melt rupture temperature. It has been determined to be the more accurate measure of the quality of the separator (Lin, et al., 2022). (Figure 3b) represents the TMA data obtained for two different Celgard membranes. The beginning of shrinkage, deforming and rupture are presented in (Table 3) The single-layer PP membrane (Celgard 2400) had higher softening temperature (~ 121 °C), deformation temperature about 160 °C, and very high rupture temperature around 180 °C. The three-layer separator which combined the low-temperature shutdown property of polyethylene with high-temperature melt integrity of polypropylene resulted in a separator with softening (~105 °C) and melt temperature (~135 °C) similar to that of PE and rupture temperature (~190 °C) similar to that of PP (Arora, & Zhang, 2004).

This kind of separators, which withstand higher than 150 °C melting temperature, are preferable for lithium-ion cells. The trilayer separators with polypropylene on the outside will have better capability to hold the melt integrity at the elevated temperatures than the single layer PE separators (Lizundia, et al., 2020). This is especially crucial for bigger lithium-ion cells being developed for hybrid and electric vehicles.

Table 3. TMA Data for Tow Type of Commercial Celgard Membranes

Characters	Celgard 240	Celgard 2325
Rupture temperature (°C)	183	192
Shrinkage onset temperature (°C)	121	106
Deformation temperature (°C)	156	135

Shutdown

The performance of the shutdown function is determined based on impedance measurements taken at a linearly rising temperature. This procedure is shown in Figure 3C for the Celgard 2325 membrane. With a 60°C/min heating rate and impedance recorded at 1 kHz, any rise in resistance is taken to mean a damaged pore structure due to separator melting. A 100-times higher impedance is a must for preventing thermal runaway in batteries. Decrease in impedance refers to opening of separator from coalescence of polymers or electrode penetration which is called 'melt integrity loss'. Although this method is suitable for detecting the impedance rise onset, it is inconsistent in the description of the decline in impedance. Figure 3c depicts the shutdown curve, the impedance growth near the melting points of polyethylene (130°C) and polypropylene (165°C), thus the melting point of the separator material is directly related to shutdown temperature. Here, separator pores disappear to become virtually denser film between anode and cathode (Farooqui, Ahmad, & Hamid, 2016).

The shutdown of the membrane is the key point for the external short circuit and overcharging protection but is limited for the internal shorts. Whereas it can prevent delayed failures, those with instant internal short circuits have a destruction rate greater than the shutdown speed of separators, which hinders safety concerns (Santhanagopalan, & Zhang, 2013).

Ionic Conductivity

Conductivity Testing: Measure the membrane's ability to facilitate ion transport by conducting ionic conductivity tests. This involves determining how effectively ions move through the membrane (Díaz, & Kamcev, 2020).

Electrochemical Impedance Spectroscopy (EIS): Employ EIS techniques to analyze impedance and assess the membrane's resistance to ion flow (Díaz, & Kamcev, 2020).

Chemical Stability

Chemical Exposure Tests: Expose the membrane to the relevant chemicals, electrolytes, and electrode materials to assess its resistance and stability to chemical degradation. Spectroscopic analysis methods can be utilized to analyze chemical changes in the membrane after exposure to chemicals (Song, et al., 2021).

Thermal Stability

There are several methods to examine the thermal stability of membranes for instance Thermal Gravimetric Analysis (TGA) can be conduct to evaluate the membrane's stability at elevated temperatures and assess its decomposition or weight loss behavior. And also can utilize Differential Scanning Calorimetry (DSC); to examine the membrane's thermal properties, such as its glass transition temperature (Lee, et al., 2014).

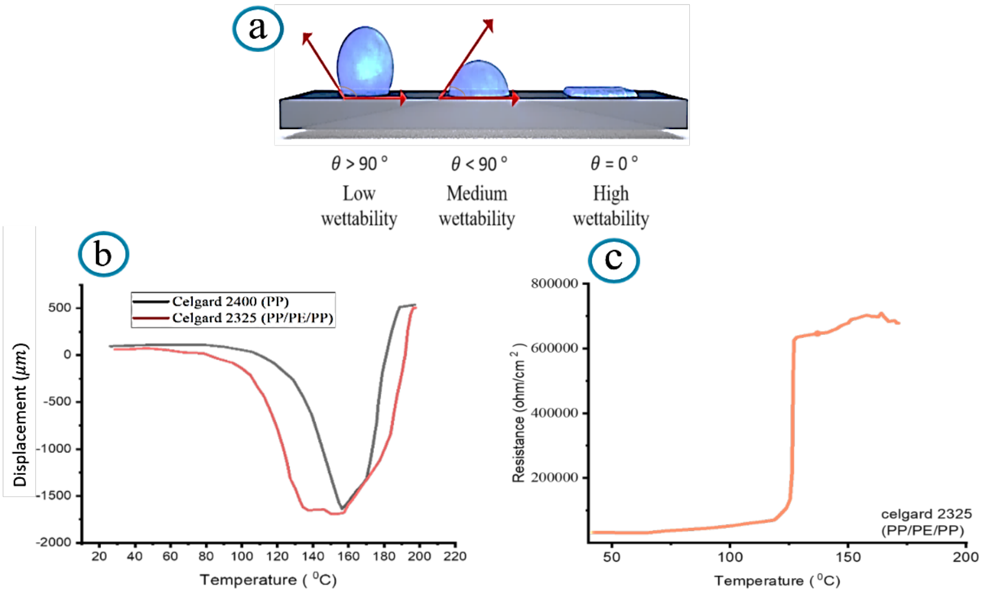

Figure 3. a) Exhibit the wettability of membrane by electrolyte, Ref. Lizundia, et al., 2020**. b) TMA of Celgard 2400 (PP) and 2325 (PP/PE/PP). A constant weight (2 g) is applied while the temperature is ramped at 5 °C/min. Reproduced by permission, Ref.** Arora, & Zhang, 2004**. c) Internal impedance (at 1 kHz) of Celgard 2325 (PP/PE/PP) separator as a function of temperature. Heating rate; 60 °C/min. Reproduced by permission, Ref.** Arora, & Zhang, 2004**.**

Shrinkage

The samples are shrunk in both MD and TD directions too. In this test, the dimensions of separators are measured and those are put for holding at 90 °C for a limited time. The computation of the shrinkage is made from the equations of changes in dimensions as described in (equation.1).

$$\text{Shrinkage (\%)} = \frac{L_i - L_f}{L_i} * 1 \qquad (1)$$

where L_i is an initial length and L_f is the final length of the separator after stored in high temperature. Only MD is shrunk in case of uniaxial stretch, meanwhile contraction is observed in both MD and TD for the biaxial ones. Similarly, the shrinkage of the separators can be determined by performing the thermomechanical analysis (TMA) test under a steady load as well as rate (Arora, & Zhang, 2004).

Tensile Strength

Different the methods of tensile strength determining may be applied including Young's modulus, percent offset strength, elongation at break as well as stress at break, followed by standards procedures. Some of the evaluations are carried out in the directions defined as a machine direction (MD) or a transverse direction (TD). The tensile characteristics are influenced by the manufacturing process: films that are uniaxial orientated are very strong, primarily in a single direction, as compared to the those that have uniaxial orientation, where they are strong in all directions (both MD and TD). The standard test method *D88-00*, as identified in ASTM is one of the most appropriate for the above studies.

The device must have enough ability to tolerate the hundreds of passes of the layer during cell winding coil manufacturing, as well as the correct handling during assembly and production. It must possess dimensional consistency and be resistance to experiencing necking down during winding, as a decrease in width could cause electrode contacts and short circuits would happen. Hence, the separator's tensile strength should be magnificently higher in the direction MD, rather than TD, to avert the risk of such unfortunate situations (Cook, & Kritzer, 2009).

Porosity

Pores play a crucial role in enhancing cell permeability and ion exchange, vital for cell activity. Maximizing transfer of ions relies on improved porosity and uniformity within separators. However, uneven impingement can disrupt charge current distribution, risking system failure. Controlling porosity is essential for high cycling stability and functional integrity of energy storage devices, although porosity measurements may not always align with surface resistivity, emphasizing the need for precise pore control (Arora, & Zhang, 2004).

$$\text{Porosity}(\%) = [1 - \frac{\left(sample \frac{weight}{sample} volume\right)}{polymer\ density}] * 100 \qquad (2)$$

The procedure of reference standard test method (D-2873) is applied to the methodology of porosity measurement. In addition to that, the equilibrium porosity may be established by measuring the weight of the liquid which is trapped in the separator during the process. Here, a measurement of the migration parameters of the separator is done before and after the hexadecane solvent immersion. Equation (3) asserts that the porosity is determined by the amount of hexadecane in the pores of the adsorbent. But, this method is the most convenient to investigate the separator porosity, and, caused by this, the performance of the latest development is tested in a proper way (Baldwin, et al., 2010).

$$\text{Porosity}(\%) = [\frac{volume\ occupied\ by\ hexadecane}{volume\ of\ polymer + volume\ occupied\ by\ hexadecane}] * 100 \qquad (3)$$

Tortuosity

Tortuosity is still a key factor for explaining the importance of the term, the effective mean length of capillary related to the separator’s thickness for classifying separators. At this step, one dimensionless or τ, an unmeasurable variable is used, so that the movement in the filtration material is simply described. We would have the displays of the data which will be conveying meaningful information including the fractal appearance and form to us in our experiment of electrochemistry settings. Tortuosity (the cumulative turn of two-dimensional oil field), as it is one of the influential parameters of the separator optimization, as well as a component of the general parameter, cell performance, remains the area of concern that should be taken into account (Sun, et al., 2023).

$$\tau = \frac{L_S}{d} \qquad (4)$$

Tortuosity, represented by the intertwining factor (L_s/d), plays a critical role in porous structure. It measures solidity, indicating how solid ions pass through the medium. Derived from specific resistivity, thickness, and porosity, τ measures dynamics, with pore blockade being significant. Higher τ indicates complex systems. Branching mode addresses forgetfulness but adds to separator resistance, integral to cell mechanism. Understanding tortuosity aids in optimizing separator design, enhancing electrolyte flow, and improving overall cell performance, offering insights into complex ion transport dynamics within porous media (Arora, & Zhang, 2004).

Pore Size and Pore Size Distribution

The uniform pore distribution with the battery application is quite imperative to the steady performance of the separator against a lopsided current distribution that may hurt the performance. In situ liquefying, which formed a depositional event, points to a deposition of high-salinity water during a short period in an uplifted area.

Dry processing involves screening separators whose pores (0.24-0.34μm) are relatively younger of size and distribution compared to wet processing screen separators whose pores (0.1-0.13μm) are relatively bigger and of wider distribution and issued by Asahi Chemical and Mitsui Chemical companies respectively (Arora, & Zhang, 2004).

The precise evaluation of the stress testing of battery separators and their pore sizes control is required for doing the right operation of the battery. Traditionally, mercury porosimetry was a characterization approach for internal porosity, measure and distribution of the pore size in separators. This approach is known as the pore-filling method. In it is measured the size and the volume of the pores while determining the amount of mercury that fills the pores under higher pressure. Since mercury is generally immiscible with most materials, a force produced to overcome surface tension force which counteract formation is an important task (Li, et al., 2021).

A hydrophobic separator like a polyolefin is tested by using Aqua pore method, a water porosimetry technique using a mixture of phosphoric acid and water. This approach has been successfully employed for separators made with polyolefin in lithium-ion batteries; it supplies information on volume and area with the pore size distribution and mean pore diameter. The interconnected molecules fill the pore proportionally and at different pressures; this relationship helps to understand the volume-pressure relationships under those quantities (Mohammadi, & Skyllas-Kazacos, 1995). pressure/permeability or pore diameter curve. The equation describing the pressure required for water intrusion into a pore of diameter D is as follows:

$$D = \frac{4\,\gamma * \cos\theta}{P} \qquad (5)$$

where (D) is the diameter of the pore assuming the pore to be cylindrical, (p) is the differential pressure,(γ) is the surface tension of the no wetting liquid, water, and (θ) is the contact angle of water.

The pores inside the separators of the battery never come with a constant diameter or spherical shape. Their geometry and dimensions are often different; hence, be careful when comparing specific pore diameter numbers.

One of the techniques, capillary flow porometry designed and patented by Porous Materials Inc. may be used for test battery separators. It is possible to determine various specifications with this device, such as the pore size of the separator at its minimum point, the maximum pore size, pore size distribution, permeability, and the external surface area of the envelope (Santhanagopalan, & Zhang, 2013).

Puncture Strength

The different type of separators has to be strong enough mechanically to cope with the assembly and cyclic charge-discharge phases (Xing, et al., 2022). Its robustness allows it to withstand ripping, pounding, and pressure so that there is no chance of short circuits. Demarcation Strength (PS) that is penetration force crucial to finding a breach of the seals. The so-called bacterial strength is based on the mix penetration strength. Material type and manufacturing processes highly depend on separation performance (Kalnaus, Wang, & Turner, 2017). The wetted biaxial tensile method offers anionic alignment of plastic directions, which is essential for ductility and tearing resistance. The best testing is by load frames or Instron Machines (Chen, et al., 2014).

Conclusion

According to different shapes and designs of batteries the selection of the type of separator and packaging of it is very crucial in order to increase the working ability, lifespan, and safety of the batteries. Separator is acting as a permeable membrane between tow electrode of a cell (anode and cathode), separators prevent electrical short circuits by providing a distance (separation) between the electrodes. Simultaneously, they facilitate the movement of ionic charge carriers crucial for current interruption in electrochemical cells. These separators, commonly found in liquid electrolyte and jellyroll-type batteries, are typically constructed with polymeric membranes featuring a microporous layer. Chemical and electrochemical stability, mechanical strength, and other properties are essential for effective separator function. The overall performance of batteries, including energy and power densities, cycle life, stability, and safety, hinges on the structure and properties of these crucial components. Moreover, the optimal separator for a specific battery must meet various requirements. Electronic insulation, minimal electrolyte resistance, mechanical and dimensional stability, physical strength, chemical stability, and wetting by electrolyte are among the critical factors. Additionally, uniform thickness, high porosity, low tortuosity, and ion selectivity contribute to optimal battery performance. Various materials, such as polyethylene, polypropylene, ceramics, polymer-ceramic composites, solid electrolytes, and tape casting, are employed to create battery membranes. The evaluation of membrane characteristics involves extensive testing, including ionic conductivity, mechanical and dimensional stability assessments, physical strength tests, chemical exposure experiments, thermal stability analyses, ion selectivity evaluations, wetting measurements, thickness uniformity checks, and porosity and tortuosity assessments. These evaluations, both experimental and computational, are crucial for ensuring the reliability, safety, and longevity of batteries, marking a continual focus in battery research and development.

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