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Perspective

Advances in Polysulfone Applications for Membrane Technologies and Biomedical Innovations

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DESCRIPTION

Polysulfone (PSU) is an amorphous, high-performance thermoplastic polymer known for its remarkable mechanical strength, chemical resistance and thermal stability. Since its introduction in the 1960s, polysulfone has found extensive use in industries requiring durable materials that can withstand harsh operating conditions. Its structure, characterized by aromatic rings linked by Sulfone (SO_2^-) and Ether (-O-) groups, provides rigidity while maintaining flexibility and transparency. The polymer's stability across a wide temperature range and resistance to hydrolysis and oxidation make it a preferred material for advanced filtration, biomedical devices and aerospace components.

The intrinsic properties of polysulfone stem from its molecular structure, which combines strength with processability. It maintains its physical and chemical integrity up to 150°C, enabling it to operate in environments unsuitable for many conventional plastics. The polymer's hydrophobic nature and resistance to acids, bases and organic solvents make it an excellent candidate for applications in aggressive chemical conditions. Moreover, polysulfone can be easily processed by extrusion, injection molding and solution casting, which has facilitated its widespread use in the fabrication of membranes and composite materials.

Among its many applications, polysulfone is best known for its role in membrane technology. It serves as a base material for Ultrafiltration (UF), Nanofiltration (NF) and Reverse Osmosis (RO) membranes used in water purification and wastewater treatment. Polysulfone membranes possess excellent mechanical integrity and thermal resistance, allowing for efficient operation under pressure and temperature fluctuations. However, the inherent hydrophobicity of PSU can lead to fouling by organic matter and microbial growth. To mitigate this, surface modification techniques such as blending with hydrophilic polymers (e.g., polyvinylpyrrolidone or polyethylene glycol) or surface grafting with charged or polar molecules are employed.

These modifications enhance hydrophilicity, reduce fouling tendencies and improve overall membrane performance.

In biomedical applications, polysulfone's biocompatibility and sterilization resistance have made it an essential material for medical devices, particularly in blood-contact applications. It is widely used in the fabrication of hemodialysis membranes due to its ability to maintain selective permeability, high flux and minimal protein adsorption. Polysulfone-based dialysis membranes allow efficient clearance of uremic toxins while retaining essential plasma proteins, providing life-sustaining treatment for patients with kidney failure. Furthermore, the polymer's resistance to repeated sterilization processes such as autoclaving and gamma irradiation ensures durability and patient safety. Research has also extended its applications to microfluidic devices and implantable systems, where chemical inertness and transparency are vital design requirements.

The versatility of polysulfone extends to gas separation and pervaporation membranes. Its excellent thermal and mechanical properties allow it to be used in the separation of gases such as hydrogen, oxygen, nitrogen and carbon dioxide. In these applications, the polymer's glassy nature contributes to selective permeability, enabling efficient molecular sieving. Additionally, polysulfone-based composite membranes incorporating inorganic nanoparticles such as silica, titanium dioxide, or graphene oxide have demonstrated improved selectivity, permeability and antifouling characteristics. These hybrid materials combine the strengths of both organic and inorganic phases, opening pathways for advanced applications in energy and environmental engineering.

From a sustainability perspective, efforts are being made to develop greener methods for polysulfone synthesis and membrane fabrication. Traditional solvent-based membrane casting uses toxic organic solvents like N-Methyl-2-Pyrrolidone (NMP) or Dimethylformamide (DMF), raising environmental and health concerns. Researchers are exploring the use of less hazardous solvents such as ionic liquids and bio-based alternatives, alongside solvent recovery systems to minimize

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waste. Furthermore, recycled polysulfone and blends with biodegradable polymers are under study to promote circular economy principles without compromising performance.

Polysulfone's mechanical robustness and dimensional stability also make it suitable for aerospace, automotive and electrical engineering components. In aerospace applications, PSU's flame retardancy, low smoke emission and high strength-to-weight ratio are essential for ensuring safety and performance. In the electronics sector, polysulfone serves as an insulating material for connectors, circuit boards and housings due to its dielectric stability and resistance to thermal deformation. The polymer's ability to retain transparency even at elevated temperatures also makes it ideal for optical and lighting components.

Recent research has focused on polysulfone modification through polymer blending and copolymerization to achieve tailored properties for specific applications. Blending PSU with polymers like Polyetherimide (PEI) or Polyphenylsulfone (PPSU) enhances impact strength, toughness and processability. Functionalization with sulfonic acid or amine groups introduces ion-exchange properties, enabling its use in fuel cells and proton exchange membranes. Moreover, advancements in additive manufacturing have made it possible to process polysulfone through 3D printing, expanding its potential in customized components and biomedical implants.

Nanotechnology has played a transformative role in improving the performance of polysulfone membranes. Incorporating nanoparticles such as zeolites, Metal-Organic Frameworks (MOFs), or carbon nanotubes can significantly enhance

permeability, selectivity and fouling resistance. These nanocomposite membranes demonstrate superior separation efficiency and durability, particularly in challenging environments like saline or industrial wastewater. The synergistic combination of nanomaterials and polysulfone provides an avenue for next-generation membrane systems that balance performance with sustainability.

Despite its numerous advantages, the high cost of polysulfone compared to conventional polymers such as polyethylene or polypropylene limits its widespread use in some industries. However, the longevity and reliability of PSU-based products often offset initial expenses by reducing maintenance and replacement costs. As sustainability and efficiency continue to guide material selection in engineering and biomedical fields, the long-term benefits of polysulfone make it a valuable investment.

CONCLUSION

In conclusion, polysulfone remains one of the most versatile and reliable engineering polymers available today. Its balance of thermal stability, mechanical strength and chemical resistance has secured its position in industries ranging from water treatment to medicine and aerospace. Continuous advancements in material modification, nanocomposite design and green fabrication methods are expanding its capabilities while addressing environmental concerns. As global demand grows for durable, high-performance materials, polysulfone stands out as a polymer of the future, combining scientific innovation with sustainable application potential.