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Comparative Evaluation of Pressure-Driven Polymeric Membranes

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ABSTRACT

Pressure-driven membrane technologies play a critical role in many fields today, including water treatment, wastewater reuse, food processing, pharmaceutical production, and gas separation. The membrane materials used in these technologies are among the most important factors determining system performance. Polysulfone (PSF), polyethersulfone (PES), polyacrylonitrile (PAN), and polypropylene (PP) are among the most widely used polymeric membrane materials and are preferred in various applications due to their distinct physical and chemical properties. In this review study, the structural characteristics, hydrophilic/hydrophobic behaviors, mechanical strengths, chemical stabilities, and fouling tendencies of these polymers are examined and compared in detail. In addition, surface modification techniques and recent research trends aimed at improving membrane performance are also discussed.

Keywords: Membrane, Polymeric membrane, PSF, PES, PAN, PP

INTRODUCTION

Membrane technology has become a critical separation technology at the center of sustainable water management and environmental protection strategies in recent years. Compared to conventional separation methods, its advantages such as lower energy consumption, higher efficiency, and compact design have led to the rapid expansion of membrane systems in industrial and environmental applications. Pressure-driven membrane processes include different separation mechanisms such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), and the success of these processes largely depends on the membrane material used (Baker, 2012).

Polymeric membranes constitute the most widely used membrane type due to their lower cost and suitability for easy fabrication compared to ceramic and metallic membranes. These membranes can be produced using techniques such as phase inversion, electrospinning, and casting, offering great flexibility in terms of pore structure and surface properties. Therefore, polymers such as PSF, PES, PAN, and PP can be optimized for different separation applications (Mulder, 1996).

The main parameters determining membrane performance include permeability (flux), selectivity, mechanical strength, chemical stability, and fouling resistance. These properties are directly related to membrane surface chemistry, pore size, and polymer chain structure. Fouling, in particular, is one of the most critical limiting factors in membrane technology, directly affecting membrane lifetime and operational costs (Lee et al., 2011).

Recent studies have focused on improving membrane performance through approaches such as surface modification, nanoparticle incorporation, and the development of hybrid membranes. Despite these advancements, the physical and chemical properties of the base polymer remain a key determining factor. Therefore, a detailed understanding of commonly used polymers such as PSF, PES, PAN, and PP is of great importance (Zhao et al., 2013).

Furthermore, increasing industrial water demand and the contamination of water resources necessitate the development of more durable and high-performance membranes. In this context, polymer selection is considered a critical parameter not only in terms of performance but also in terms of economic and environmental sustainability (Shannon et al., 2008).

PSF (Polysulfone)

Polysulfone (PSF) is an amorphous thermoplastic polymer containing aromatic rings and sulfone groups. Due to its high glass transition temperature (~190°C) and excellent thermal stability, it maintains structural integrity even at elevated temperatures. These properties make PSF a preferred material, especially in ultrafiltration and microfiltration applications (Baker, 2012).

One of the main advantages of PSF membranes is their high mechanical strength. This property prevents deformation under high pressure and allows long-term operation. In addition, PSF exhibits chemical stability over a wide pH range and is resistant to structural degradation in both acidic and alkaline environments (Mulder, 1996).

However, PSF is intrinsically hydrophobic. This characteristic may increase the adsorption of organic matter and proteins on the membrane surface, leading to fouling. To overcome this limitation, PSF membranes are often modified using hydrophilic additives or surface modification techniques (Liu et al., 2011).

PSF is also sensitive to oxidizing agents such as chlorine, which can be a limiting factor in drinking water treatment applications. Therefore, modified PSF derivatives are being developed for use in oxidative environments (Lee et al., 2011).

PES (Polyethersulfone)

Polyethersulfone (PES) has a structure similar to PSF but offers higher hydrophilicity and better oxidative stability. PES membranes exhibit high performance, particularly in ultrafiltration applications (Zhao et al., 2013).

The hydrophilic nature of PES enhances its interaction with water molecules, resulting in higher water flux. Additionally, hydrophilicity reduces the adhesion of organic contaminants to the membrane surface, thereby improving fouling resistance (Shi et al., 2014).

PES membranes also exhibit high mechanical strength and stable performance during long-term operation. Compared to PSF, their improved resistance to oxidative conditions makes them more suitable for applications involving chlorine-containing environments (Baker, 2012).

Nevertheless, PES membranes may still exhibit some degree of hydrophobicity and are often modified to further enhance their performance (Zhao et al., 2013).

PAN (Polyacrylonitrile)

Polyacrylonitrile (PAN) is a polymer containing nitrile (-CN) groups and is intrinsically hydrophilic. This property provides PAN membranes with lower fouling tendencies (Wang et al., 2008).

PAN membranes are particularly advantageous in the filtration of solutions containing biological and organic components. Their low protein adsorption helps maintain membrane performance over extended operation (Zhao et al., 2013).

Another important feature of PAN is its suitability for surface modification. The nitrile groups are chemically reactive and can be easily functionalized, making PAN a promising candidate for advanced membrane technologies (Liu et al., 2011).

However, PAN membranes have lower mechanical strength compared to PSF and PES, and their thermal stability is limited, restricting their use in high-temperature applications (Mulder, 1996).

PP (Polypropylene)

Polypropylene (PP) is a semi-crystalline polymer with low cost and high chemical resistance. Due to its hydrophobic nature, it is widely used in membrane distillation and gas separation processes (Gryta, 2008).

PP membranes allow only vapor-phase transport due to their hydrophobicity, making them highly efficient in membrane distillation processes (Lawson & Lloyd, 1997).

PP exhibits excellent chemical resistance and remains stable in acidic and alkaline environments. However, its thermal stability is lower than that of PSF and PES, and it may deform at high temperatures (Gryta, 2008).

The main disadvantage of PP membranes is their hydrophobic nature, which limits their direct use in aqueous filtration processes. Therefore, surface modification is often required to improve their applicability (Liu et al., 2011).

Comparison of membranes

PSF and PES membranes exhibit similar properties in terms of mechanical strength and thermal stability. However, PES offers better fouling resistance due to its higher hydrophilicity (Shi et al., 2014).

PAN membranes show low fouling tendencies due to their hydrophilic nature but have lower mechanical strength, which often necessitates their use in composite structures (Wang et al., 2008).

PP membranes, on the other hand, differ significantly from the others due to their hydrophobic nature and are particularly suitable for membrane distillation applications (Lawson & Lloyd, 1997).

In general:
PSF: High strength, low hydrophilicity
PES: Balanced properties, good fouling resistance
PAN: High hydrophilicity, low mechanical strength
PP: Hydrophobic, suitable for specialized applications
These differences make polymer selection highly dependent on the intended application (Baker, 2012).

CONCLUSION

The PSF, PES, PAN, and PP polymers used in pressure-driven membrane technologies exhibit distinct physical and chemical characteristics, and these differences directly influence application performance. As discussed in this study, each polymer presents unique advantages and limitations, requiring a multi-dimensional evaluation during membrane selection.

PSF and PES membranes stand out due to their high mechanical strength, thermal stability, and wide pH tolerance. Among these, PES offers superior fouling resistance owing to its higher hydrophilicity, which translates into lower cleaning frequency and more stable flux over long-term operation. However, both polymers still require surface modification due to their inherent hydrophobic nature.

PAN membranes provide significant advantages in applications involving organic and biological contaminants due to their hydrophilic structure and low protein adsorption. Their chemical reactivity also makes them suitable for functional membrane development. Nevertheless, their lower mechanical and thermal stability necessitates their use in supported or composite structures.

PP membranes, characterized by their hydrophobic nature, play a crucial role in membrane distillation and gas separation processes. Their low cost and high chemical resistance further enhance their industrial applicability. However, their limited use in aqueous filtration processes requires surface modification to expand their application range.

The comparative evaluation of these four polymers demonstrates that membrane performance is governed by multiple parameters, including hydrophilicity, pore structure, surface energy, mechanical strength, and chemical stability. Therefore, membrane design is a complex process that requires multi-criteria optimization.

Current research in membrane technology focuses on improving the surface and structural properties of these polymers through nanoparticle incorporation, plasma treatment, grafting techniques, and composite membrane development. These approaches significantly enhance fouling resistance and permeability, particularly for hydrophobic polymers such as PSF and PES.

In addition, sustainability has become an increasingly important aspect of membrane technology. Low energy consumption, extended membrane lifetime, and the use of recyclable materials are expected to be key focus areas in future research. Developments in biopolymers and environmentally friendly modification techniques are also gaining attention.

From an industrial perspective, proper membrane selection directly affects operational costs, energy consumption, and system efficiency. Therefore, not only initial performance but also long-term durability, cleaning requirements, and chemical stability must be considered. Understanding fouling behavior is especially critical for extending membrane lifespan.

In conclusion, PSF, PES, PAN, and PP polymers constitute the fundamental building blocks of pressure-driven membrane systems, each optimized for specific applications. Future advancements in nanotechnology and material science are expected to further enhance membrane performance. Interdisciplinary research will play a key role in achieving both academic and industrial progress in this field.

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