Removal of Sulfur from Gasoline Using Pervaporation: A Review

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Abstract

Gasoline desulfurization is a vital process in the petroleum industry aimed at reducing the sulfur content in gasoline to meet the updated regulations. Sulfur, a naturally occurring element found in crude oil, poses environmental and health risks when released into the atmosphere during the combustion of gasoline. To address these concerns, desulfurization techniques have been developed to minimize the sulfur content in gasoline, leading to cleaner and more environmentally friendly fuels. Within this context, membrane technology is considered one of the most promising methods for separation applications in several industries including gasoline desulfurization. In this review article, the desulfurization of gasoline using pervaporation (PV) process will be presented in theoretical aspects of material selection and process modification. In addition, parameters such as feed temperature and flow rate are discussed. PV unit has attracted an increasing attention as it provides an effective approach towards an eco-friendly sulfur removal method in petrochemical industries in terms of high selectivity, feasible economics, and safety procedure.

1. Introduction

The combustion of sulfur-containing fuels, such as gasoline, releases sulfur dioxide (SO_2) and nitrogen oxides (NOx) into the air. These compounds contribute to air pollution, smog formation, and the formation of acid rain [1,2]. Such pollutants have adverse effects on human health, including respiratory problems and increased risk of cardiovascular diseases. Additionally, sulfur compounds can damage emission control systems in vehicles, reducing their effectiveness in reducing harmful emissions [3-6]. To mitigate these issues, gasoline desulfurization plays a crucial role in ensuring compliance with stringent environmental regulations and improving air quality. The process involves the removal of sulfur compounds from gasoline, resulting in cleaner-burning fuels that emit significantly lower levels of harmful pollutants. There are several methods employed for gasoline desulfurization i.e., Hydrodesulfurization (HDS), Adsorbent-based process, Oxidative desulfurization (ODS), Extraction processes, and Catalytic cracking [7]. Hydrodesulfurization (HDS) being the most common. HDS utilizes hydrogen gas (H_2) and a catalyst to facilitate the reaction between sulfur compounds and hydrogen, resulting in the formation of hydrogen sulfide (H_2S) [7-9]. This process effectively reduces the sulfur content in gasoline, making it more environmentally friendly. Adsorptive desulfurization is another technique used in gasoline desulfurization, particularly when extremely low levels of sulfur are required [7, 10]. In this process, adsorbent material is used to selectively adsorb sulfur compounds from gasoline. Commonly used adsorbents include activated carbon, zeolites, and metal oxides [10]. The gasoline is passed through a bed of adsorbent, and the sulfur compounds adhere to the surface of the adsorbent, allowing for their removal. On the other hand, ODS involves the oxidation of sulfur compounds in gasoline to convert them into more polar compounds that can be easily separated [7,11]. Oxidizing agents, such as hydrogen peroxide or ozone, are used to react with the sulfur compounds and facilitate their removal.

In the extraction processes, various extraction methods can be employed to remove sulfur compounds from gasoline [12,13]. For example, liquid-liquid extraction uses a solvent that selectively extracts sulfur compounds from gasoline. The solvent is then separated from the gasoline, and the sulfur compounds are recovered.

As for the Catalytic cracking processes, such as fluid catalytic cracking (FCC), are primarily used for producing gasoline from crude oil [14-16]. These processes can also help in reducing the sulfur content of gasoline. During catalytic cracking, sulfur compounds are converted into hydrogen sulfide and other gases, which can be separated from the gasoline. Advancements in desulfurization technologies and the implementation of more stringent regulations are driving the development of cleaner and more sustainable fuel options for a greener future [17-22]. Currently, membrane technology has been explored as a potential method for gasoline desulfurization, although it is not as commonly used as other methods such as hydrodesulfurization (HDS) [7-9, 23-25]. Membrane-based desulfurization typically involves the use of selective membranes that can separate sulfur compounds from the gasoline stream. These membranes have specific pore sizes or chemical properties that allow them to selectively permeate sulfur compounds wh ile excluding other gasoline components [26-29]. This process is often referred to as selective permeation. There are different types of membranes that have been investigated for gasoline desulfurization, including polymeric membranes and inorganic membranes [29]. Polymeric membranes are typically made from synthetic polymers, such as polyimides or polymeric blends, and they rely on size exclusion or chemical affinity to separate sulfur compounds. Inorganic membranes, on the other hand, are usually made from ceramic materials, such as zeolites or metal oxides, and they exploit differences in molecular size or charge to achieve selectivity. One of the potential advantages of membrane-based desulfurization is its ability to operate at ambient conditions, unlike HDS, which requires high temperatures and pressures [30]. This could lead to energy savings and lower operating costs. However, there are several challenges associated with membrane technology, including membrane fouling, low selectivity, and limited scalability. While research and development efforts are ongoing to improve the performance and commercial viability of membrane-based desulfurization, it is important to note that HDS remains the dominant method for gasoline desulfurization in the industry due to its well-established technology and efficiency. However, HDS holds some disadvantages including; the requirement of constant supply of hydrogen gas, which can be expensive [31]. Also, the process operates at high temperatures and pressures, making it energy-intensive. Finally, catalysts used in HDS can be prone to deactivation, leading to reduced efficiency and increased maintenance requirements.

2. Gasoline and sulfur species

Gasoline typically contains trace amounts of sulfur species, primarily as impurities. These sulfur species can be categorized into organic sulfur compounds and inorganic sulfur compounds. Organic and inorganic sulfur compounds are two broad categories of compounds that contain sulfur atoms. Organic sulfur compounds contain carbon-sulfur bonds. In contrast, inorganic sulfur compounds lack carbon-sulfur bonds, and have diverse industrial and environmental applications [32]. The major sulfur compound are listed in Table 1.

Table 1: Major sulfur compounds in gasoline

Sulfur compounds	Boiling range °C	Sulfur content	
		ppm	%
Mercaptans	66	34	4.5
Thiophene	65-93	37	4.9
C1-thiophenes	92-121	106	14.1
Tetrahydrothiophene	191	24	3.2
C2-thiophenes	120-149	118	15.6
C3-thiophenes/thiophenol	149-190	76	10.1
C4-thiophenes/C1-thiophenol	177	83	11
Benzothiophene	190	276	36.6

2.1 Organic sulfur compounds

Organic sulfur compounds are a class of chemical compounds that contain carbon-sulfur (C-S) bonds. Sulfur is an essential element in organic chemistry, and it plays a crucial role in the structure and function of many biological molecules [29]. Organic sulfur compounds are widespread in nature and can be found in various forms, ranging from simple molecules to complex polymers. Organic sulfur compounds mainly includes, gasoline thiols and disulfides [33]. Gasoline thiols, also known as mercaptans, are a class of organic compounds that contain a sulfur atom bonded to a hydrogen atom (SH group). They are characterized by their strong and unpleasant odor, often described as a "rotten egg" smell. In the context of gasoline, thiols are typically present in small amounts as impurities. Thiols can be formed during the refining and processing of crude oil, which is used to produce gasoline. They can also result from the degradation of sulfur-containing compounds in the fuel. While modern refining techniques aim to minimize the sulfur content in gasoline, trace amounts of thiols may still be present. The presence of gasoline thiols is undesirable due to their odor, which can be irritating and unpleasant [34,35]. In addition, thiols can contribute to the formation of air pollutants, such as sulfur dioxide and particulate matter, which have negative effects on air quality and human health. To mitigate the presence of thiols in gasoline, various methods are employed, including hydrotreating and catalytic processes during the refining stage. These processes help reduce the sulfur content and remove thiols or convert them to less odorous compounds. It's worth noting that gasoline thiols are different from methyl mercaptan, which is a thiol compound commonly added to odorless natural gas to give it a distinct smell for safety purposes. The addition of methyl mercaptan allows the detection of gas leaks by the characteristic odor [34,36]. On the other hand, gasoline disulfides, also known as sulfur compounds or sulfur-containing compounds in gasoline, refer to organic compounds that contain two sulfur atoms bonded together [37, 38]. They are typically formed by the oxidation of thiols. These compounds are formed during the refining process or can be introduced through various sources, such as crude oil impurities or fuel additives. Disulfides are a subset of sulfur compounds found in gasoline, and they include different chemical species, such as dimethyl disulfide (DMDS), diethyl disulfide (DEDS), and other similar compounds [39, 40]. These compounds contribute to the overall sulfur content of gasoline, which is regulated in many countries due to environmental concerns. The presence of disulfides in gasoline can have several effects including emissions, catalyst poisoning and odor.

- Emissions: Sulfur compounds in gasoline can contribute to the emission of sulfur dioxide (SO_2) and other sulfur-containing pollutants when the fuel is burned. These pollutants are known to be harmful to human health and the environment, contributing to air pollution, acid rain, and respiratory issues.

- Catalyst poisoning: Sulfur compounds can poison catalytic converters used in vehicle exhaust systems. These converters are designed to reduce emissions of pollutants like nitrogen oxides (NOx) and carbon monoxide (CO). The sulfur compounds can interact with the catalyst, reducing its efficiency and leading to increased emissions.
- Odor: Some sulfur compounds, such as DMDS, have a distinct odor, which can contribute to the unpleasant smell associated with gasoline.

2.2 Inorganic sulfur compounds

Inorganic sulfur compounds can be present in gasoline as impurities or as additives. These compounds are typically sulfur-containing chemicals that are not derived from crude oil but are introduced during the refining or blending process [41]. One common inorganic sulfur compound found in gasoline is hydrogen sulfide (H_2S). H2S is a colorless gas with a distinct rotten egg smell and is highly toxic. It is usually removed during the refining process to prevent its release into the atmosphere. Other inorganic sulfur compounds that may be present in gasoline include sulfur dioxide (SO_2) and sulfur trioxide (SO_3). These compounds can be formed during the combustion of gasoline and contribute to air pollution, leading to the formation of acid rain and the exacerbation of respiratory problems [42].

3. Sulfur removal from FCC gasoline using PV

Fluid catalytic cracking is a widely used refining process in the petroleum industry to convert heavy hydrocarbon feedstocks into lighter, more valuable products such as gasoline and diesel [43,44]. However, one of the challenges associated with FCC is the presence of sulfur compounds in the products, which are undesirable due to their detrimental effects on the environment and catalytic activity [45-48]. Pervaporation offers an effective solution for removing sulfur from FCC products.

3.1 Basics of PV

Pervaporation is a membrane separation process used to separate liquid mixtures based on their vapor pressure differences [49-55]. In pervaporation, a liquid mixture is brought into contact with a selective membrane, and a partial vacuum is applied on one side of the membrane as illustrated in Figure 1. As a result, one component of the liquid mixture selectively permeates through the membrane as vapor, while the other components remain behind as a concentrated liquid or retentate [55]. The driving force behind pervaporation is the vapor pressure difference between the components of the liquid mixture. The membrane used in pervaporation is typically a thin, selective layer that allows the preferential transport of one component while rejecting the others. The selective layer can be made of various materials, including polymers, ceramics, or composite materials. The permeated vapor is collected on the other side of the membrane, where it can be condensed and separated from the permeate. The permeate usually contains a higher concentration of the more volatile component of the liquid mixture. The retentate, on the other hand, becomes more concentrated in the less volatile component. Pervaporation has several advantages over traditional separation processes such as distillation or absorption. It operates at lower temperatures and pressures, making it more energy-efficient. It is particularly useful for separating azeotropic or close-boiling mixtures that are difficult to separate by conventional means. Pervaporation is also effective for removing volatile organic compounds from water or solvents. Applications of pervaporation include the dehydration of organic solvents, the removal of water from organic compounds, the recovery of organic solvents, and the purification of specialty chemicals. It is also used in the food and beverage industry for the concentration of fruit juices and the removal of alcohol from beverages. Currently, pervaporation is being used in removing sulfur from fluid catalytic cracking (FCC) products [55-59].

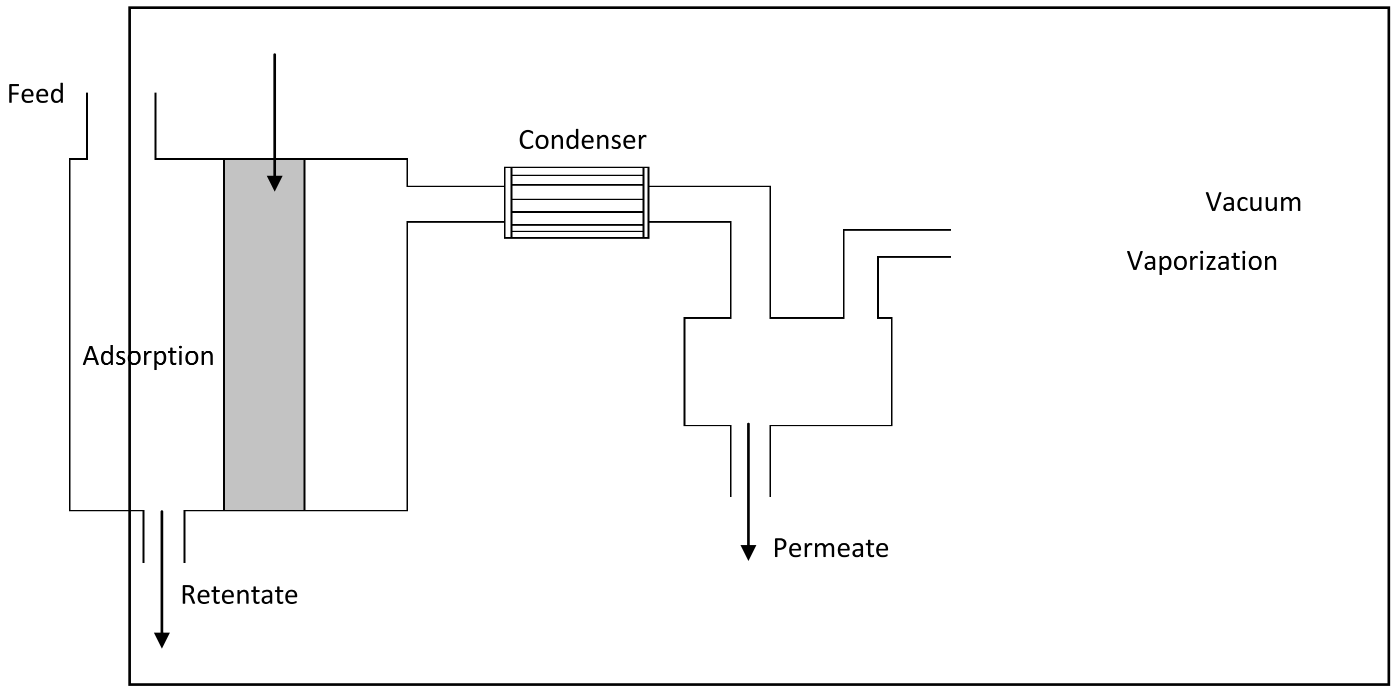

Figure. 1. Schematic diagram on gasoline desulfurization using PV.

3.2 PV process and operation

The process involves passing the FCC products through a membrane that selectively permeates sulfur compounds, allowing them to be separated from the desired hydrocarbons [57]. The membrane used in pervaporation is typically made of a polymer material with high sulfur selectivity [60]. During pervaporation, the FCC product mixture is heated and brought into contact with one side of the membrane. The sulfur compounds present in the mixture have higher affinity and permeability through the membrane compared to hydrocarbons. As a result, sulfur compounds preferentially permeate through the membrane, while hydrocarbons are retained on the feed side. The permeated sulfur compounds can be collected and further treated or processed to recover valuable sulfur or disposed of in an environmentally friendly manner. The purified hydrocarbon stream is obtained from the feed side of the membrane, free from significant amounts of sulfur compounds. Pervaporation for sulfur removal from FCC products offers several advantages. It operates at relatively mild conditions, requiring moderate temperatures and pressures, which can reduce energy consumption compared to conventional sulfur removal methods. Additionally, pervaporation is a continuous process and can be integrated into existing FCC units, making it a potentially cost-effective solution [61,62]. However, it's important to note that pervaporation for sulfur removal is still a developing technology, and there may be challenges related to membrane fouling, membrane selectivity, and overall process efficiency [63]. Research and development efforts are ongoing to optimize membrane materials and process parameters to enhance the performance and commercial viability of pervaporation for sulfur removal in FCC applications.

4. Materials selection

The selection of membrane materials for pervaporation process in FCC gasoline desulfurization depends on several factors, including the desired separation performance, chemical compatibility, stability, and cost-effectiveness. Materials such as zeolites, polymers, and biological materials have been applied as membranes for this application [64-66]. Table 2 presents the PV membrane materials reported recently and their sulfur removal performance.

Table 2: Comparison of the separation efficiencies of various membranes.

Membrane	Sulfur Content, ppm	Temperature, ^oC	Flux, (J, kg/m^2h)	Separation factor	Reference
UF G - 10	4239	-	0.45	53.61	67
PI	248	71	6.2	2.18	68
PDMS-Ag_2O/PAN	3640	30	1.65	3.9	69
PDMS-AgY/PAN	3700	31	1.04	4.4	70
PDMS/ ceramic	1000	50	3.31	3.35	71
PEG/PES	1300	33	6.95	3.15	72
EC	300	80	0.7	3.75	73
PBPP	400	55	0.038	11.92	74
CI-PBPP	400	85	1.38	5.6	75
PEBA / PVDF	1000	40	3.8	4	76
PDMS-GNS	1312	40	6.22	3.58	77

Nevertheless, polymers are currently the most broadly used materials [78 – 82] due to the fact that polymer materials offer several advantages over other materials when it comes to membranes including;

- Versatility: Polymer membranes can be designed to have a wide range of properties, making them highly versatile. They can be tailored to have specific pore sizes, surface chemistries, and permeability characteristics to suit various applications [79,83].

- Selectivity: Polymer membranes can exhibit excellent selectivity, allowing them to separate specific molecules or ions from a mixture. By controlling the polymer composition and structure, it is possible to achieve high selectivity for a particular substance, which is crucial in applications such as water purification, gas separation, and drug delivery [78].
- Scalability: Polymer membranes are often more scalable than other materials, such as ceramic or metal membranes. They can be manufactured through various techniques, including phase inversion, electrospinning, and casting, which are relatively cost-effective and suitable for large-scale production [81].
- Energy Efficiency: Polymer membranes can offer high permeability with low energy consumption, making them energy-efficient. They can enable efficient separation processes by requiring less pressure or lower temperature differentials compared to other membrane materials. This is particularly important in applications like reverse osmosis for desalination or gas separation for industrial processes [82,84].
- Chemical Resistance: Many polymer materials exhibit excellent chemical resistance, allowing them to withstand exposure to harsh chemicals, acids, and solvents without significant degradation. This makes them suitable for applications in corrosive environments or when dealing with aggressive substances [78-85].
- Flexibility and Ease of Processing: Polymer membranes are typically flexible and can be easily formed into various shapes or configurations, including flat sheets, hollow fibers, or tubular structures. Their flexibility enables their use in applications where conformability or flexibility is required, such as in wearable devices or flexible electronics [86].
- Cost-Effectiveness: Polymer membranes are often more cost-effective compared to other membrane materials, such as ceramics or metals. The raw materials for polymers are relatively

inexpensive, and the manufacturing processes can be less complex and more cost-efficient, resulting in lower production costs [87].

5. Effect of the gasoline components on membranes performance

The effect of gasoline on a polymer membrane can vary depending on the specific polymer composition and the exposure conditions [88,90]. When gasoline comes into contact with a polymer membrane, several potential interactions can occur including; swelling, solvent action, Permeation and Chemical degradation. Some polymers may absorb gasoline and swell as a result. This can lead to changes in the dimensions and mechanical properties of the membrane. Also, gasoline can act as a solvent for certain polymers, causing them to dissolve or soften. This can lead to a loss of structural integrity and a breakdown of the membrane. Gasoline molecules may diffuse through the polymer membrane, leading to permeation [91]. This can be problematic in applications where the membrane is intended to provide a barrier against the passage of liquids. Chemical degradation can take place because the aromatic components of gsoline can chemically react with certain polymer materials, resulting in degradation of the polymer chains. This can lead to a loss of mechanical strength, embrittlement, or cracking of the membrane. To mitigate the potential negative effects of gasoline on a polymer membrane [92], various strategies can be employed. These include selecting a polymer material with high resistance to gasoline, using barrier coatings or laminates to protect the membrane, or incorporating additives that enhance resistance to gasoline exposure [93,94]. It is important to consider the specific requirements of the application and consult the manufacturer's recommendations or conduct appropriate testing to ensure the compatibility of the polymer membrane with gasoline [95].

6. Operating parameters

The operating conditions in pervaporation can significantly influence its performance. Here are some key factors:

6.1 Effect of feed temperature

Pervaporation is a temperature-dependent process [96]. As temperature increases, the vapor pressure of the components in the liquid mixture also increases, resulting in enhanced permeation rates as illustrated by Arrhenius relationship (Figure 2) [96,97] . In addition, higher temperatures accelerate the diffusion rate of solutes in the solution [98]. This increased molecular motion results in a greater concentration gradient across the membrane, leading to enhanced mass transfer through the membrane and consequently higher flux [99]. Moreover, the permeability of the membrane itself can be influenced by temperature. In some cases, higher temperatures can reduce the resistance of the membrane, leading to increased permeability and flux [100]. For example in polymeric membranes, the polymer chains become flexible at higher temperatures, resulting more available free volume and paths within the membrane structure. However, the selectivity of the membrane may decrease at higher temperatures due to increased diffusion of both components. Therefore, an optimal temperature must be selected to achieve the desired separation performance.

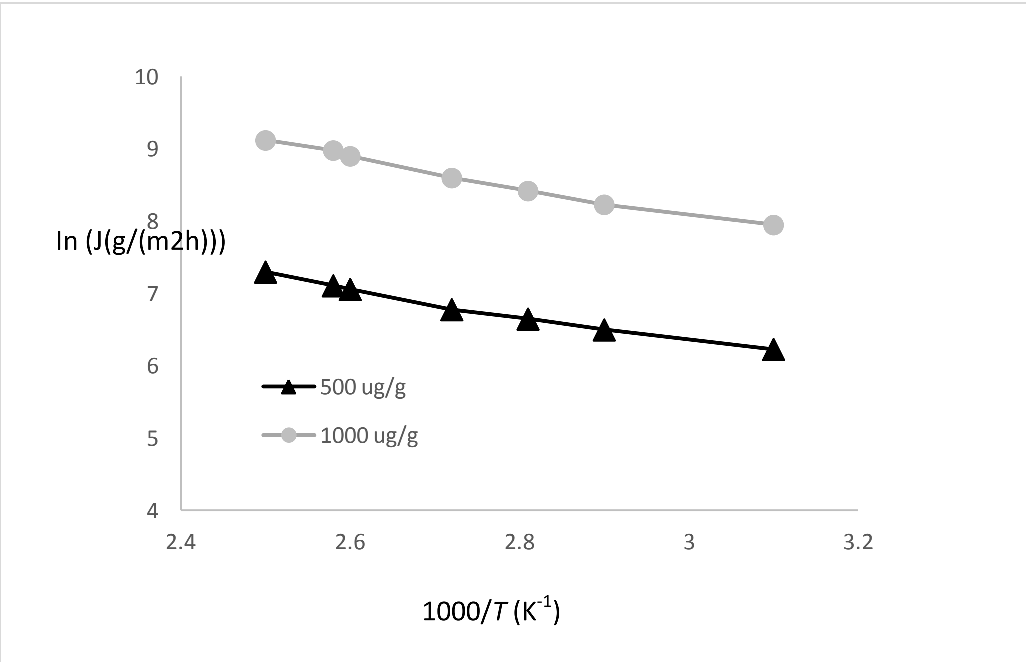

Figure 2: Arrhenius relationship between flux and temperature [70].

6.2 Effect of feed pressures

Feed pressure is an important operational parameter that can significantly affect the performance of a pervaporation membrane system used for separating gasoline components [101]. The feed pressure in a pervaporation system affects the separation performance in several ways:

1. Permeation Flux: Generally, increasing the feed pressure in a pervaporation system leads to an increase in the permeation flux. Higher pressure can enhance the driving force for mass transfer across the membrane, resulting in increased permeation rates. This can be beneficial for achieving higher separation efficiency and higher productivity [102, 103].

2. Selectivity: Feed pressure can influence the selectivity of the membrane system. In some cases, high feed pressures can cause a reduction in selectivity, leading to increased co-permeation of undesired components. This can result in lower separation efficiency and reduced product quality [102-104] .

3. Membrane Performance: Pervaporation membranes have certain operating limits, including pressure differentials, beyond which their performance may deteriorate or they may be damaged [105]. Excessive feed pressures can cause membrane compaction, increased mechanical stresses, or even membrane rupture, leading to a loss in separation efficiency and membrane integrity [102, 106]. It is important to operate the pervaporation system within the recommended pressure range specified by the membrane manufacturer.

6.3 Effect of feed composition

Specific effects of gasoline on a membrane will depend on factors such as the membrane composition, thickness, exposure duration, and the concentration and composition of the gasoline itself [107]. Different types of membranes may exhibit different responses to gasoline exposure. Gasoline contains a mixture of hydrocarbons, some of which can be chemically reactive. Prolonged exposure to gasoline can lead to chemical degradation of the membrane material [108]. This degradation can result in changes to the membrane's structure, loss of mechanical strength, and reduced performance. In addition, gasoline may cause the leaching of certain additives or plasticizers present in the membrane material. This leaching can alter the membrane's properties and potentially contaminate the surrounding environment.

6.4 Influence of feed sulfur concentration

Sulfur compounds, especially inorganic sulfates and sulfides, can cause fouling on the membrane surface. Fouling refers to the accumulation of unwanted substances on the membrane, which can reduce its performance and efficiency [109]. Sulfur fouling can be particularly problematic because sulfur compounds tend to form insoluble precipitates that adhere to the membrane surface. Other sulfur compounds, such as hydrogen sulfide (H_2S), can react with the membrane material and cause degradation. This degradation may result in changes in membrane morphology, reduced mechanical strength, and increased susceptibility to fouling and chemical attack [109,110].

6.5 Effect of feed flow rate

The gasoline feed flow rate can have several effects on a membrane system. The feed flow rate will generally lead to higher permeate flux. However, there is a limit to this relationship as excessively high flow rates can result in reduced efficiency due to limitations in the membrane's permeability and fouling resistance [111]. Also, higher feed flow rates can help to minimize fouling by promoting a higher shear rate and maintaining a more turbulent flow. This can help prevent the deposition of particles on the membrane surface and improve overall efficiency. Another aspect that should be considered is the pressure drop. The feed flow rate is directly related to the pressure drop across the membrane system. Increasing the flow rate will generally lead to a higher pressure drop [111,112]. The feed flow rate can impact the energy consumption of the membrane system. Higher flow rates typically require more energy to maintain the desired pressure and flow conditions. Therefore, it is important to consider the energy requirements and cost-effectiveness when determining the optimal feed flow rate. Also, The feed flow rate can also affect the lifespan and durability of the membrane. Operating at excessively high flow rates for extended periods may result in increased mechanical stress on the membrane, potentially leading to damage or reduced membrane lifespan. It is important to operate within the recommended operating conditions specified by the membrane manufacturer to ensure longevity.

7. Economic analysis

Pervaporation is a membrane separation process that has been explored for various applications, including the desulfurization of gasoline. The economic analysis of pervaporation for gasoline desulfurization involves evaluating the costs and benefits associated with implementing this technology. Here are some key factors to consider in such an analysis. The capital costs are the initial investment required to set up a pervaporation system for gasoline desulfurization includes the cost of purchasing and installing the pervaporation membranes, pumps, and other equipment. These costs can vary depending on the scale of the operation and the specific membrane materials used. As for the operating costs of a pervaporation system include energy consumption, maintenance, and replacement of membranes [113, 114]. Energy costs will depend on the power requirements of the pumps and other equipment. Membrane replacement is necessary over time due to fouling or degradation, and the frequency and cost of replacement will impact the overall operating costs. In general, the effectiveness of pervaporation in removing sulfur compounds from gasoline will influence the economic analysis. Higher sulfur removal efficiency means a higher-quality desulfurized product, which may command a premium price in the market. The quality of the desulfurized gasoline product produced through pervaporation will play a significant role in the economic analysis. If the desulfurized gasoline meets the regulatory standards and has desirable properties, its market value may be higher compared to conventional gasoline. The cost of the gasoline feedstock is an important consideration. If the pervaporation process allows for the use of lower-cost, high-sulfur feedstocks, it can provide a cost advantage compared to alternative desulfurization methods that require more expensive low-sulfur feedstocks. Environmental regulations regarding sulfur content in gasoline can impact the economic analysis. If pervaporation enables compliance with stricter regulations at a lower cost compared to alternative technologies, it can provide a competitive advantage. On the other hand, the scale at which the pervaporation system is implemented can affect the economics. Large-scale operations may benefit from economies of scale, potentially reducing capital and operating costs per unit of desulfurized gasoline produced.

8. Final remarks and future prospects

In conclusion, gasoline desulfurization using pervaporation has proven to be a promising technology for the removal of sulfur compounds from gasoline. It offers several advantages over conventional methods, such as higher selectivity, lower energy consumption, and simpler operation. Pervaporation has demonstrated its efficiency in removing both organic and inorganic sulfur compounds, including difficult-to-remove compounds like thiophene and benzothiophene. The use of selective membranes in pervaporation enables the separation of sulfur compounds from gasoline based on their molecular size, polarity, and affinity to the membrane material. By optimizing the membrane properties and operating conditions, high desulfurization efficiency can be achieved while maintaining a high gasoline recovery rate. As for the future prospects, continued research and development efforts should focus on designing and optimizing membranes specifically tailored for gasoline desulfurization. This includes improving the selectivity, permeability, and stability of the membranes to enhance their performance and longevity. Also, Pervaporation can be integrated with other desulfurization technologies, such as hydrotreating or adsorption, to create hybrid processes that offer synergistic benefits. The combination of different technologies can potentially enhance the overall desulfurization efficiency and reduce operating costs. While pervaporation has shown promise at the laboratory scale, further efforts are needed to scale up the technology for industrial applications. The development of large-scale pervaporation systems and the evaluation of their economic feasibility will be crucial steps towards commercialization.

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