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Review Article

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Filter Membranes: A Review

S. Bokka

Independent Researcher, CA, US

Abstract Filter membranes are widely used in the filtration and separation industry. Researchers are developing filter membranes to capture particles smaller than submicron size without significantly increasing the pressure drop. Filter membrane properties such as polymer material, pore size, and thickness of the membrane affect the filter membrane performance. In this review, a summary of the filter membrane types, their fabrication techniques, growing trends in filtration applications, and a few challenges are discussed.

Keywords Fiber membrane, Application trends, Challenges

1. Introduction

The filtration process is a physical or biological filtration process where the separation of solid particles or removes chemical species or biological organisms using a filter membrane. Filtration is achieved by entrainment, adsorption, or absorption processes. The four different single-fiber capture mechanisms of filtration are Diffusion, Interception, Impaction, and Electrostatic attraction as shown in Fig. 1. The capture of particles (or drops) on a fiber occurs when the particle comes close enough to the fiber surface that short-range forces, such as Van der Waals forces, exceed other forces and hold the particle to the surface. The single-fiber capture mechanisms are essentially mechanisms that bring particles close to the fiber surface.

The Diffusion mechanism as shown in Fig. 1 is caused when a particle below the diameter of 0.1μm is slowed and delayed in its path because of the collision of the particle with the fiber. This behavior of the particle is like the Brownian motion and further increases the probability that the particle will be stopped by either interception or impaction. This mechanism is dominated by lower airflow velocities. In the Interception mechanism, the particles following a line of flow in the airstream adhere to the fiber when they come within one radius of a fiber. The larger particles are unable to follow the curving contours of the air stream and are forced to embed in the fibers resulting in an Impaction mechanism. For higher airflow velocity and with decreasing fiber separation, the inertial impaction mechanism increases. Both impaction and interception are dominated for particles above the diameter of 0.4μm. In the Electrostatic attraction process, the particles of opposite charges are captured effectively by electrostatic attraction and separated by electrets mainly depending on the coulomb and induction forces. The surface area and fiber diameter are important factors for the particle capture in the Electrostatic attraction process. Other phenomena that are possible in filtration are gravity settling and absorption.

The mechanisms of filtration along with the filter membrane are very crucial for filtration applications. The following sections provide a review of the various filter membranes, their fabrication techniques based on their applications, and a few challenges with the application of filter membranes.

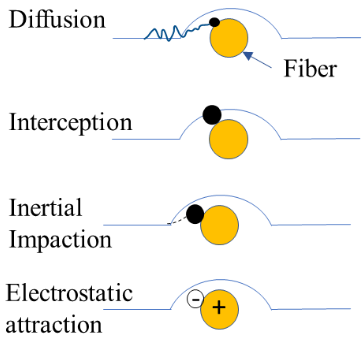

Figure 1: Mechanism of filtration

2. Filter Membrane

A woven filter membrane is a semi-permeable membrane, where the flow-through rate is very low, while nonwoven membranes are permeable allowing certain materials to pass through and block other materials, their flow-through rate is very high. A woven membrane is made up of individual threads of fiber that are woven together to create a filter membrane. Since these are woven structures with fixed pore openings, the woven membranes are not very porous and thus allow all the material to flow through without any separation. Filtration depends on the type of filters chosen for the application. For the separation of solid aerosols from an airstream, a nonwoven filter membrane with high permeability and porosity is used to increase the capture of solid aerosols and to allow air to pass through the filter membrane. Separation of water, oils, and other organic fluids is very important to various industrial applications. Membrane filtration is effective for the separation of dissolved materials, colloids, fine particles, and separate molecules such as oil from water[1], water from fuels[2,] and organic material. The pressure difference between the two sides of the membrane acts as the driving force for separating particles in a liquid solution or gas mixture. The four categories of pressure-driven filtration are microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Fig. 2 shows the particle size comparison between various membrane filtration processes. Microfiltration is a process where large particulates, colloids, and bacteria are separated from the feed streams. Ultrafiltration is a process of rejecting viruses, protein concentration, and in wastewater treatment. Nanofiltration rejects multivalent salts and uncharged solutes where a porous membrane is used to capture particles which are removed as retentate where the smaller particles such as suspended solids, bacteria are allowed through as permeate. Ultrafiltration involves membranes where viruses and proteins are rejected. Reverse osmosis (RO) can remove all inorganic contaminants, organic substances, bacteria, and viruses.

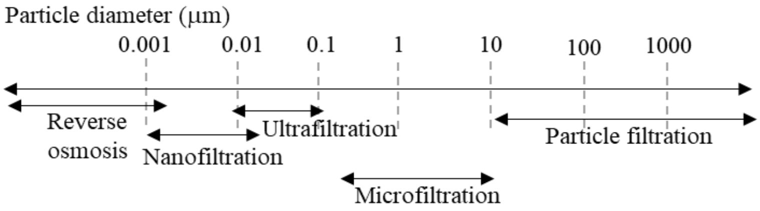

Figure 2: Particle size cut-offs of different liquid filtration techniques

In addition to the single fiber capture mechanisms, particles can be captured by multiple fiber straining when the pore sizes between the fibers are smaller than the size of the particle, preventing the particle from moving through the pore. Straining can occur at the inlet to the pore or inside of the filter depth where a pore opening constricts. This leads to the particle separation at the surface referred to as surface filtration and in the particle separation inside the depth of the filter referred to as depth filters as shown in Fig. 3.

The media or depth filtration system uses sand, organics, or other materials to physically capture the particles and adsorption phenomena through chemical, molecular action, or cation exchange processes. The membrane filtration process uses a permeable layer of the material which allows a specific material to flow through the membrane and restricts the flow of other particles in a liquid solution or gas mixture. Depending on the application of the filter membrane the pore size, thickness, chemical compatibility, wettability, and mechanical properties of the filter membranes are controlled to enhance the filtration performance. Membranes are produced by various techniques electrospinning, wet-laid, electrospinning process. Materials that can be used in membrane fabrication are cellulose acetate (CA), cellulose nitrate (CN), polyamide (PA), polycarbonate (PC), polypropylene (PP), Polysulfone (PSf), Polyethersulfone (PES), Polytetrafluoroethylene (PTFE), and Polyvinylidene fluoride (PVDF), Polypropylene (PP), and Polyamide (PA). A few advantages of membrane filtration are low operating costs, improved filtration efficiency, flexibility, and low production costs.

Surface filters stop most of the particles (or drops) at the inlet surface of the medium by preventing the particles from penetrating the depth of the medium. In the capture of solid particles, this generally leads to the formation of a cake layer on the surface of the filter. As the cake increases in thickness, it becomes a filter itself and often has smaller pores than the original fiber medium thus increasing the capture efficiency for finer particles, forming a layer of material that increases the efficiency of the filtration over time and captures much finer particles. Particles captured in this media are in micron size.

Depth coalescing filters have higher thickness compared to surface filters. These filters work on both Direct interception and absorption, they are usually created with single thick media or stacking multiple layers together. Particles with bigger sizes are captured at the surface and finer particles are captured throughout the thickness of the media.

When the incoming stream has a wide particle size distribution some of the particles may be strained (surface filtration) and some may enter the filter and be captured in depth, while some particles may be so small that they pass through. Also, liquid drops perform differently than solid particles because liquids may move after capture on the fibers. If the fibers are highly non-wetting and the pores are smaller than the drops, as in a barrier filter, the drops are prevented from penetrating the filter medium. If the medium has pores about the size of the drops or larger the drops will enter the pores as in a depth filter. This is shown in Fig. 3.

If a depth filter is highly wet, the drops may adsorb and be held strongly to the fibers. This could result in a large pressure drop as the medium void space fills with liquid. If the depth filter is highly non-wetting, the drops may be captured, but are held loosely to the fibers and easily migrate through the medium and do not coalesce or change size. At an intermediate wetting, the drops have time to merge and coalesce within the filter medium and enlarged drops exit the depth filter, as shown in Fig. 3.

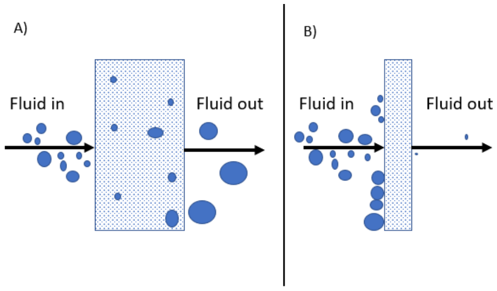

Figure 3: Filter types, A) Depth Coalescing filter and B) Surface or Barrier filter

The larger diameter droplets > 100 mm, at low flow rates, may separate from the fluid stream due to the influence of gravity. The gravity settling occurs on the larger drops if the density of the drop is sufficiently different from the density of the continuous phase. Drops with sizes <100 mm become harder to separate with gravity because the gravitational forces are not as strong compared to surface forces and Brownian motion affects the small drops. By using a coalescing filter, the drops can be enlarged to > 100 mm to allow gravity settling to be more effective.

The fluid flow patterns are also an important factor that determines the filtration performance of the membrane. The flow of the filter membrane occurs in two configurations – dead-end filtration and crossflow filtration. Crossflow filtration occurs when the feed flow is tangential to the surface of the membrane. The retentate is removed from the same side further downstream and the permeate is tracked on the other side. Tangential flow or crossflow filtration examples are flat sheets, spiral wound membranes, and hollow fiber membranes.

Dead-end filtration occurs as the direction of the fluid flow is normal to the membrane surface. Usually operated as a batch process, the dead-end filter membrane is easier to fabricate and operate. Disadvantages of these dead-end filtration are fouling and concentration polarization.

3. Growing Trends in Filter Membrane Applications

As the industrial filtration market is growing in existing markets of air, fuel, paper and pulp, biotechnology, power plants, automotive, and water filtration segments, the industry is gaining more control in emerging markets of Biotechnology.

Biomedical applications of a filter membrane include particle removal, sterilization, protein/nucleic acid analysis, and quality control in the pharmaceutical and food/beverage industry. Food industry segments include applications of the dairy industry (into processing applications to milk, whey, and clarified cheese brine) and the sugar industry (to clarify, divide, and concentrate solutions). In the Chemical industry applications into wastewater treatment, concentration and dehydration of minerals, production of polymers, and desalination. Pharmaceutical applications of filter membranes to concentrate enzymes in the fermentation process. High demand for air filtration applications in Heating, Ventilation, and Air conditioning (HVACs), and filter masks.

4. Challenges in Filter Membrane Applications

A. AI and IoT devices: Applications with constant monitoring

Recent development of the filter membrane is achieved by developing filter membranes that can monitor and record the performance of the filter membrane, to identify the point when a filter change or cleaning is required and to avoid any downtime. Pressure drop across the filter membrane is a factor that drives the cost of the operation resulting in high energy consumption. Having a good understanding of the filter membrane performance gives better control to schedule maintenance, reduce any downtime, and increase the performance of the filter membrane.

B. Cost-efficient manufacturing and operation

Converting a viable R&D idea into a cost-efficient product is a major challenge in the current scenario. The cost of manufacturing includes the cost of raw materials, design cost, labor, and time required for production.

C. Supply chain

The COVID pandemic has exposed the filtration industry to many of its supply chain challenges such as lack of visibility and demand forecasting. This has increased the need to find an effective solution to the existing challenges of supply chain shortages, increasing freight prices, and labor shortages. Rather than depending on solutions from overseas, the Industry is spearheading the development of a solution within the United States. This will boost self-reliance eliminating the dependence on growing material costs, freight prices, and supply chain shortages.

D. Strict environmental and regulatory guidelines

Many national and international government agencies are enacting strict environmental and regulatory guidelines to reduce carbon dioxide emissions by 80% by 2050. This intensifies the need for high-performance air filter media to capture finer particles without further increasing the pressure drop and energy consumption, to comply with the stricter regulations.

5. Conclusion

Filter membranes have many advantages in various industries, but further improvements in membrane fabrication are needed to enhance the performance of the filter membrane to focus on the growing demands. In this review paper, the types of filter membranes are studied to identify the growing research and development trends in filter membrane fabrication and applications.

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