

Optimize Strategy of Hollow Fiber Membrane Modules for Industrial Wastewater Treatment

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Abstract

The optimization and enhancement of the performance of, as a highly efficient means of water treatment, is particularly important in However, oriented to industrial wastewater treatment, it is a common research strategy to improve the structure of hollow fiber membrane (HFM) modules to improve the flow properties of the flow field within the membrane module and enhance the efficiency. In this paper, around (1) membrane module housing materials (2) inlet and outlet design of the membrane module housing (3) HFM membrane device nanofiltration technologyNF the current context of increasing global water resource constraints and intensifying environmental protection needs.an effective strategy to improve the nanofiltration performance of HFM modules is systematically discussed four aspects: optimization of the flow field of the (4) baffle design.at the housing side.

Keywords

Hollow Fiber Membrane; Membrane Module; Water Treatment; Fluid Simulation.

1. Introduction

As the world seeks to shift to greener energy technologies and reduce carbon footprints and emissions, membrane separation technology has been recognized as a high-tech advancement of great significance and application in the century, with the strategically transform industrial technology 21st potential to ^[1]. The rapid progress of industrialization has led to an upsurge in the discharge of industrial wastewater, and its complex composition (such as high salinity, difficult-to-biodegrade organics, and heavy metal ions) has posed a serious challenge to traditional wastewater treatment technologies^[2]. Membrane separation technology has gradually become one of the core processes for industrial wastewater treatment due to its high efficiency separation, low energy consumption and modularity advantages. Among them, hollow fiber membrane modules, with their high packing density (>10,000 m²/m³), excellent anti-pollution performance, and flexible operation modes, have

demonstrated significant in the field of deep wastewater treatment and resource utilization economic feasibility^[3].

In recent years, the synergistic innovation of material science and engineering design has promoted the rapid development of hollow fiber membrane modules. In terms of membrane materials, polyvinylidene fluoride have been significantly improved in terms of contamination resistance and chemical stability through blend modification or surface polyvinylidene fluoride (PVDF) and polyethersulfone(PES) . For example, Kumar and Isloor (2020) by introducing reduced the contact angle of hollow fiber membranes to for oily wastewater PVDF 42°, with a flux recovery rate of more than amphiphilic block copolymers 90%. Meanwhile, ceramic hollow fiber membranes have achieved breakthrough applications in extreme wastewater environments, such as electroplating and metallurgy, due to their high-temperature, acid and alkali resistance properties.

At the level of module design optimization, the computational fluid dynamics simulation and experimental validation CFD greatly improves the mass transfer efficiency. Wickramasinghe et al. (2020) reduced the dead zone volume of the membrane module by through the construction of an asymmetric flow channel structure, 35% which increased the removal rate to COD 98.5%. In addition, a forward for high-salt wastewater coupled system was optimized by the balance of water recovery and energy consumption through the hierarchical integration of hollow fiber membrane modules.

However, during long-term operation the problem of is still a bottleneck restricting the technology diffusion. Recent studies have shown that by dynamic hydraulic modulation and membrane contamination flux decay can be effectively delayed hydrophilic-hydrophobic heterogeneous structure design. In this paper, we systematically sort out the key advances in material development, structural design, and industrial applications of hollow fiber membrane modules, and discuss their future directions.

2. Structural Design of Membrane Module Housing

In general, membrane modules can be classified into three types, i.e., plate and frame, spiral wound and hollow fiber modules^[4]. Hollow fiber membrane module is a high-efficiency water treatment technology based on the principle of microporous or ultrafiltration membrane separation, the core of which consists of thousands of diameter of hollow fiber membrane filaments parallel with a 0.1-2 mm encapsulated in within the housing. Module operation, wastewater in the shell pressurized flow through the membrane filament surface, water molecules and small molecules through the membrane wall microporous (pore size 1 nm-0.1 μm) into the inner cavity to achieve selective separation, while the pollutants are retained in the concentration side, the separation efficiency of the membrane surface by the hydrophilicity, pore size and the distribution of the flow field of the module joint influence. Taking a typical hollow fiber membrane module as an example, as shown in Figure 1 these devices are equivalent to shell and tube heat exchangers for mass transfer, consisting of a bundle of tubes with the ends embedded in tube sheets. The tubesheet is created to allow separate fluid communication with the inner (lumen) and outer (shell) spaces of the fiber, the lumen is open along the tubesheet, and after sealing the tubesheet to the shell, separate manifolds on the outside of the shell allow for the introduction and removal of fluid streams into and out of the lumen and heat exchanger shell. The feed can be introduced into either the tube lumen or the shell. Permeate scans can also be fed to the module. Scanning mixed with permeate can by increasing the chemical potential difference across the membranes significantly improve module performance^[6] .

For the optimization of membrane module housings, many researchers have started from the construction of advanced composite systems, using a multi-scale structural design of carbon fiber reinforced polyether ether ketone (CF/PEEK) matrix composite nano-ceramic coatings (NCCs) to achieve cross-scale synergy between carbon fibers (T700-grade) and boron nitride nano-sheets (BNNSs, with thicknesses of 3-5 nm) through an in-situ polymerization process. The composite exhibits anisotropic mechanical properties at 25 °C: the axial tensile strength reaches 580 MPa (37% enhancement), and the radial creep resistance is improved by 52% (1000 h/60 MPa). Surface

functionalization using plasma-activated grafted amphiphilic polymer (SBMA-co-AA) stabilized the surface zeta potential at -15 mV (pH=7), and protein adsorption was reduced to 3.2 $\mu\text{g}/\text{cm}^2$ (89% reduction compared to conventional materials)^[6].

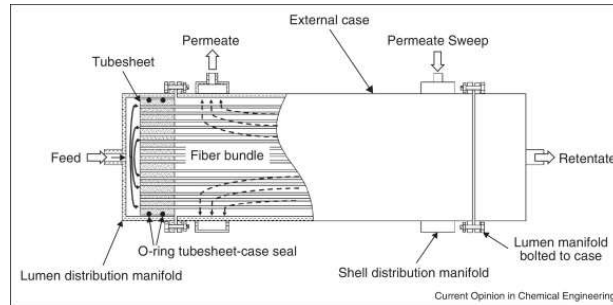


Figure 1. Cut-away view of a typical hollow fiber membrane module with a lumen feed and shell sweep operating in counter-current contacting mode.

3. Performance Optimization of HFM Membrane Modules

(1) Inlet and outlet designs for membrane module housing

The inlet and outlet design of the membrane module housing is the core element that affects the uniformity of fluid distribution, pressure drop control and contamination resistance. Proper flow channel geometry and hydrodynamic optimization can significantly reduce concentration polarization and the risk of, while improving separation efficiency and system stability. Under turbulent conditions, Computational Fluid Dynamics (membrane contaminationCFD) is able to analyze the flow dynamics within the module subject to obtain the optimized membrane module induced local flow velocity and membrane surface shear stresses. As shown in **Figure 2**. The simulation results show that the tangential inlet and outlet enable rotating flow, which provides a better distribution of wall shear stresses on the fiber surface. The normal inlet and outlet produce almost the same average shear stress as the tangential port, but the high flow velocity dissipation is not as good as the tangential port, i.e., the rotating flow produces high shear stress and reduces the pore plugging, which leads to a lower pressure drop^[7].

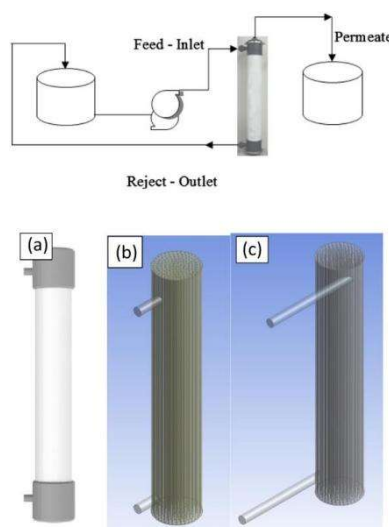


Figure 2. (a) CAD view of the module and CFD calculation domain extracted from this CAD data, (b) classical inlet outlet configuration, (c) second inlet outlet configuration. (b) classical inlet outlet configuration, (c) second inlet outlet configuration.

Based on the flow field reconstruction technology of Computational Fluid Dynamics (CFD) simulation, a multi-stage tapering inflow structure is adopted to realize the efficient conversion of fluid kinetic energy to pressure potential energy. By implanting 3D-printed topology-optimized deflector plates (thickness 0.2-0.5 mm), the laminar flow can still be maintained at Reynolds number $Re \leq 2000$, and the velocity distribution inhomogeneity coefficient (SV) can be controlled within 8%. The latest research shows that the bionics-based fractal channel design (Fractal Channel Design) can reduce the inlet pressure drop by 23.6%, the structure mimics the bifurcation mode of lung bronchial tubes, and adopts a four-stage fractal branching to realize the distribution of equal amount of fluid. In terms of anti-pollution design, Asymmetric Acceleration Geometry (AAG) is used together with micro-texturing ($Ra=0.8-1.6\mu m$) to increase the wall shear stress to 12-15Pa, which effectively inhibits biofilm formation. Experimental data showed that the design reduced the membrane flux attenuation rate from 0.8%/h in the traditional structure to 0.25%/h^[8].

(2) HFM membrane device Optimized design of flow field in shell-side

The distribution characteristics of for nanofiltration (hollow fiber membrane shell-side flow field are decisive the separation efficiency and stability of) and permeation processes. NFThe hydrodynamic behavior of directly affects the mass transfer boundary layer thickness, concentration polarization strength, and shear stress distribution on the membrane surface, which in turn regulates transmembrane flux (J) and retention rate (R)^[9] . In recent years, researchers have significantly improved the homogeneity and shear distribution of the shell-side flow field through structural innovations and multi-physics field coupled simulations.

Conventional parallel arrangement of hollow fiber bundles tends to lead to uneven flow field distribution, forming local dead zones and exacerbating concentration polarization. Allan Soo et al. (2021) proposed the by preparation of asymmetric deflector sheets printing, which combined with fiber staggered arrangement strategy, 3D resulted in a shell-side flow rate 42% enhancement of The design was shown to in desalination applications enhance to NaCl retention from 94.5% to 97.8%^[10]. Takafumi Horie et al. (2022) investigated the use of a combination of helical baffles and oscillating flow, where the helical baffles generate vortices that lead to tangential flow on the membrane surface. This inhibits humic acid from approaching the membrane surface and reduces the concentration Polarization effect .

(3) Baffle design

As the hollow fiber core component of regulation, its geometric configuration and spatial layout membrane module shell-side flow field directly determines the fluid distribution uniformity, shear stress strength and system anti-pollution performance. The module inlet and outlet are arranged on the upper and lower sides of the membrane module shell, and on baffles to allow the fluid are set the shell side of the membrane module to contact the hollow fiber membrane or at a specific angle on to achieve the crossover. In recent years, with the development of numerical simulation technology and advanced manufacturing process, baffle design has evolved from traditional static structure to dynamic response and bionic optimization, which for in industrial wastewater treatment vertically the shell side of the membrane module provides innovative solutions enhancement . membrane process.

Takafumi Horie et al. (2022) investigated the use of a combination of helical baffles and oscillatory flow, where the helical baffles generate vortices that lead to tangential flow at the membrane surface. This inhibits humic acid from approaching the membrane surface and reduces the concentration polarization effect. When oscillations are added to the upstream flow, vortices appear between the baffles and enhance the tangential flow to renew the concentration polarization layer and shear stress on the membrane surface to remove fouling. The effect of vortex propagation was effective around . Under optimal operating conditions, the normalized permeate flux was 0.050.69 and the retention rate was 99%, while under baffle conditions without oscillating flow, could be achieved 0.30% and 80%^[11]. Schematic illustrations of the membrane module with a helical baffle insert and laboratory-scale membrane filtration apparatus with an oscillator. The specific display is shown in Figure 3^[11].

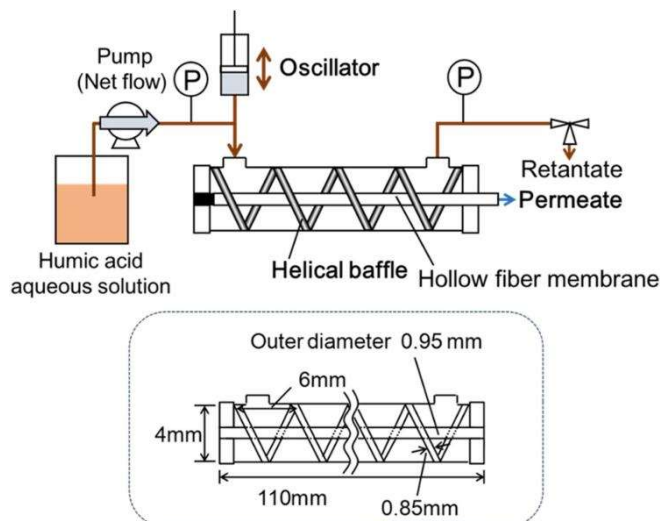


Figure 3. Schematic illustrations of the membrane module with a helical baffle insert and laboratory-scale membrane filtration apparatus with an oscillator.

To improve the performance of the component, it is important to optimize the geometry of the component, but the baffle design is not suitable for all cases, in the experimental process, it is important to avoid that the baffle obstructs the normal flow of fluid when the flow velocity is too small and thus causes a dead zone.

4. Evaluation Method of Shell Side Performance

It is necessary to evaluate the shell range performance of the designed membrane module, and the current evaluation of the membrane module shell range performance mainly focuses on the impact of the configuration of the membrane module and the fiber arrangement on the mass transfer performance of the membrane module. Parallel-flow hollow-fiber modules are generally characterized by an uneven distribution of fluxes, a decrease in the center of the fiber bundles of fluid fluxes, and an increase in the radial velocity of the fluids. This phenomenon of non-uniform flow distribution is mainly affected by the design of the module, such as hollow fiber membrane diameter, length, packing density or spacing between fibers, bundle diameter, Reynolds number, bundle spacing, shell diameter, and possible flow dead zones around the basin end of the module. Because local velocities and shear flow determine local mass transfer coefficients, variations in radial flow through the bundles result in lower total mass transfer rates and reduced performance of the shell course [12]. For shell-side performance, quantitative characterization of hydrodynamic parameters, multi-scale evaluation of mass transfer characteristics, dynamic assessment of contamination resistance, coupled structure-performance analysis, and smart sensing and digital twin verification can be used.

(1) Quantitative characterization of fluid dynamics parameters, evaluation of uniformity of velocity field distribution. Particle Image Velocimetry (PIV) coupled with Laser Doppler Velocimetry (LDV) was used in combination with a high speed camera (Phantom VEO 410L, frame rate 20 kHz) to acquire 3D flow field data. The fluid distribution uniformity index (FUI) was introduced:

$$FUI = 1 - \frac{\sqrt{\sum_{i=1}^n (v_i - \bar{v})^2 / n}}{\bar{v}} \times 100\%$$

(2) Multi-scale evaluation of mass transfer characteristics, determination of local mass transfer coefficients. The electrochemical limit current method (ELCM) was applied to arrange microelectrode arrays (50 μm in diameter and 1 mm in spacing) on the shell side. The Sherwood number was calculated according to the Levich equation:

$$\text{Sh} = 0.62 \left(\frac{d_h^2 \omega}{\nu} \right)^{1/3} \left(\frac{\nu}{D} \right)^{1/3}$$

5. Conclusion

By systematically combing the innovative breakthroughs of multidisciplinary cross research in hollow fiber membrane module material modification, structure optimization, and flow field regulation strategies, this study reveals the regulation of membrane-pollutant-fluid synergistic mechanism on the separation performance, and for the breakthrough of lays a theoretical cornerstone the triad paradox of flux-selectivity-life. By quantifying the kinetic parameters of the mass transfer boundary layer and research results the constitutive relationship between the membrane contamination resistance, the have established a cross-scale optimization paradigm from microscopic interface engineering to macroscopic component design, which points out the direction of technological evolution for the development of the next-generation of high-flux contamination-resistant membrane systems.

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