Chapter 13

High Throughput Screening to Modify Surface Properties and Obtain High Performance Membranes

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A novel high throughput method for synthesis and screening of feed-specific fouling-resistant surfaces was developed. The method combines a high throughput platform (HTP) together with photo (UV)-assisted graft polymerization (PGP) of vinyl monomers to commercial poly(ether sulfone) (PES) membranes. This new HTP-PGP method was used to discover new surfaces able to resist membrane fouling by natural organic matter (NOM) and bovine serum albumin (BSA). Several surfaces, including grafted amides, amines, and poly(ethylene glycol) methyl ether methacrylates (PEG-MAs) produced excellent surfaces for both feeds. Grafted zwitterion surfaces appeared to work better for NOM feeds. With a few exceptions, our findings are consistent with known attributes of protein-resistant surfaces. Such exceptions include grafted quaternary amine and grafted carboxylic monomer surfaces that worked well for NOM (but not for BSA) and an aromatic monomer worked well for BSA but not for NOM.

Introduction

Customizing membrane surfaces for particular feeds is urgently needed to minimize the interaction of feed components (dissolved solutes and suspended particles) with membrane surface with the goal of minimizing flux decline and

In New Membranes and Advanced Materials for Wastewater Treatment; Mueller, Anja, et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2010.

maximizing flux recovery after cleaning. UV-assisted graft polymerization of vinyl monomers to commercial poly(aryl sulfone) membranes offers an attractive route to customizing membrane surfaces. To date, such surface modification has been implemented at the bench scale (*1, 2*), producing and testing new surfaces in a linear and sequential manner. Therefore, the process has been slow, with a low probability of success and with little mechanistic insight. As a result, developing new polymeric materials with appropriate surface or functional characteristics for different filtration applications has involved great effort and expense, and has taken many years.

High throughput techniques are powerful tools to quickly screen a variety of variables, such as compounds, reactions, operating conditions, and parameters. Such techniques have been widely and successfully used in chemistry and biology (*3-5*). In recent years, researchers have started to adapt this method to the membrane field. However, until now applications have been limited to optimizing process variables in the development of filtration processes using commercial available filtration membranes (*6, 7*), and optimizing membrane casting dope composition for some specific feeds (*8-10*).

Here, we adapt a high throughput platform (HTP) approach to the facile modification of poly(aryl sulfone) membranes, using a HTP together with our patented photo-induced graft polymerization (PGP) method. In the PGP method, depicted schematically in Figure 1, poly(ether sulfone) (PES) membranes are UV-irradiated, cleaving trunk polymer chains and forming reactive radical sites. Either water or ethanol-soluble vinyl monomers covalently bond to these radical sites and undergo free-radical polymerization (*2*). We call the combined method HTP-PGP. The novel method proposed here is inexpensive, fast, simple, reproducible and scalable way to synthesize and screen fouling-resistance surfaces by modifying poly(aryl sulfone), which has excellent physical and transport characteristics but poor surface chemistry.

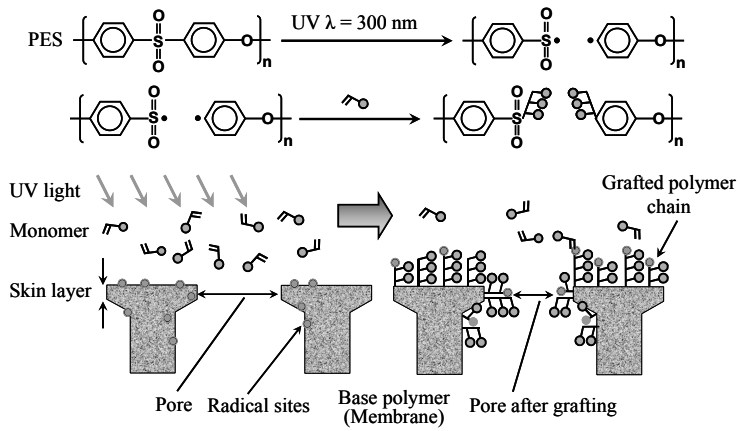


Figure 1. In the PGP method, poly(aryl sulfone) membranes are UV-irradiated (λ ≈ 300 nm), cleaving trunk polymer chains and forming reactive radical sites. Vinyl monomers chemically bond to these radical sites and undergo free-radical polymerization. After Yamagishi et al. (2).

Our approach involved selecting 66 commercially available monomers to create an initial monomer library of likely candidates. These monomers were then employed to modify PES surfaces using the HTP-PGP approach. Candidate surfaces were synthesized, characterized in terms of permeability, challenged separately by static adsorption of NOM and BSA solutions, and screened by subsequent water filtration in the same multi-well filter plate. HTP was used to discover new surfaces for applications involving NOM and BSA filtration. Grafted surfaces were challenged with a static adsorption assay, chosen because in preliminary experiments with BSA feeds it correlated with results from a filtration assay.

Materials and Methods

Materials

Membrane

Polypropylene 96-well filter plates (Seahorse Labware, Chicopee, MA) were used in HTP-PGP experiments. A 100 kDa cut-off PES membrane coupon (effective area 19.35 mm^2) was mounted by the manufacturer on the bottom of each 400-µL well. The hydraulic resistance of the 96 membranes ranged from 8.12×10^{11} to 9.49×10^{11} m^{-1} with a coefficient of variation equal to 4.0%.

Monomers

Commercial vinyl monomers (66 total) were purchased from Sigma-Aldrich (Saint Louis, MO) and were used as-received without further purification. These monomers were classified into 9 groups: hydrophobic methacrylates (HPO MAs, methacrylates having alkane chains or rings), hetero ring group monomers (having an oxygen or nitrogen-containing ring), aromatic monomers, hydroxy monomers (containing multiple OH groups), poly(ethylene glycol) (PEG) monomers (containing ethylene glycol repeating unit), strong and weak acid monomers (containing either carboxylic or sulfonic groups), amine monomers, basic and zwitterionic (zwit) monomers (basic monomers and zwitterions), and some other monomers which could not be classified into the above groups. A monomer concentration of 0.2 M was employed for grafting experiments. These monomers were either dissolved in reagent grade water or ethanol depending on their solubility.

Feed Solutions

Elliott Humic Acid (EHA) from International Humic Substances Society (St. Paul, MN) was applied as a model NOM. A solution containing 50 mg/L EHA (as TOC) and 0.01 M ionic strength at pH 7 was used in HTP-PGP static adsorption experiments. The ionic strength and pH were adjusted by adding NaCl solid, and HCl and NaOH solutions respectively.

Bovine serum albumin was chosen as a model protein to assess membrane fouling. BSA (MW = 67 kDa, pI = 4.7) is negatively charged under our

experimental conditions. Solution was prepared by dissolving BSA into phosphate buffered saline (PBS) solution to yield a protein concentration of 1 g/L. PBS buffer solution contained 10 mM phosphate buffer, 2.7 mM potassium chloride and 137 mM sodium chloride with pH 7.4 at 25 °C. BSA and PBS tablets were purchased from Sigma-Aldrich (Saint Louis, MO).

Methods

Preparation of Modified Surfaces

The membranes on the 96-well filter plates were modified using the UV-induced graft polymerization method. The approach is shown schematically in Figure 2. UV irradiation was conducted in a chamber (F300S, Fushion UV Systems, Inc. Gaithersburg, MD) containing an electrodeless microwave lamp (~ 7% of the energy was at < 280 nm). A bandpass UV filter (UG-11, Newport Corporation, Franklin, MA) was placed between the 96-well filter plate and the UV lamp to reduce the energy at wavelengths below 280 nm to < 1%.

The membrane modification consisted of the following steps. After washing, the hydraulic permeability of each well was measured simultaneously with DI water. The membranes were then modified by adding monomer solution (200 μL) to each well, shaking the plates on an orbital shaker at 100 rpm for 1 hr, reducing O_2 level by purging with N_2 for 15 min, and irradiating plates in the UV chamber for 30 s. After modification, the plates were washed by shaking in DI for 1 hr. Each monomer was evaluated with four replicates. Four membrane coupons were treated with ethanol without UV irradiation to serve as a control for membranes grafted with the monomers dissolved in ethanol, and another four membranes were used as-received to serve as a control for the membranes grafted with monomers dissolved in water.

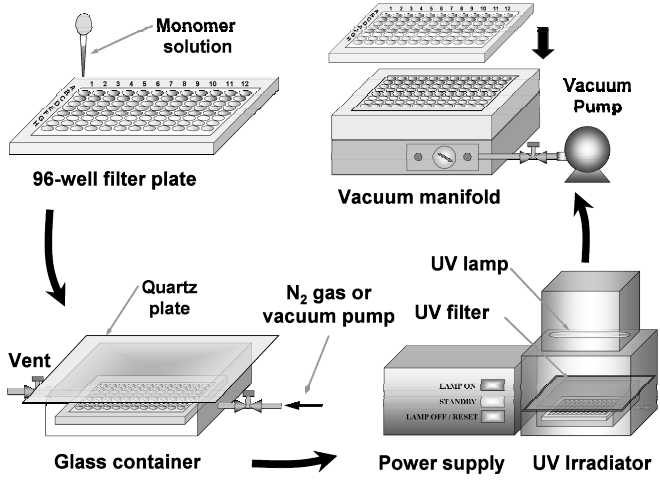


Figure 2. Schematic illustration of HTP-PGP experimental setup and approach. After Zhou et al. (11).

Evaluation of Modified Membranes by Static Adsorption

The fouling potential of modified and control membranes was evaluated using a static adsorption protocol. The water permeability after adsorption was measured as a criterion for membrane performance. In this method, 300 μL of foulant solution was added to each well, and the plate was sealed with adhesive film to eliminate evaporation. The plate was then placed on a shaker (as above) for 44 hrs. After equilibration, the wells were then gently emptied, and DI flux was measured. The membrane resistance was calculated using flux values. The resistance increase of the modified membranes caused by foulant adsorption was compared with that of control membranes to evaluate foulant/surface interactions.

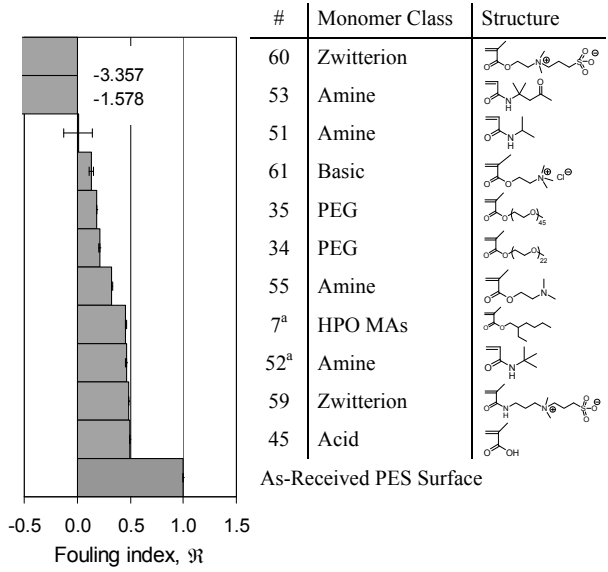
Analytical Methods

A Microplate Spectrophotometer (PowerWave XS, BioTek Instruments Inc., Winooski, VT) was used to measure the volume of permeate solution in the receiver plate wells. The acrylic 96-well receiver plates allow permeate analysis by light absorbance in near infrared region. The volume of permeate in each receiver well was measured at 977 nm. NOM and BSA do not absorb at this wavelength, whereas water exhibits an absorbance peak. Volumetric flux, J_v (m/s) was calculated as $J_v = V/At$, where V (m^3) is the cumulative permeate volume, A (m^2) is the membrane area, and t (s) is the filtration time. The resistance of membrane was calculated from $R = \Delta P/\mu J_v$, where ΔP (Pa) is the transmembrane pressure, μ (g/m s) is the solution viscosity at 22 ± 1ºC.

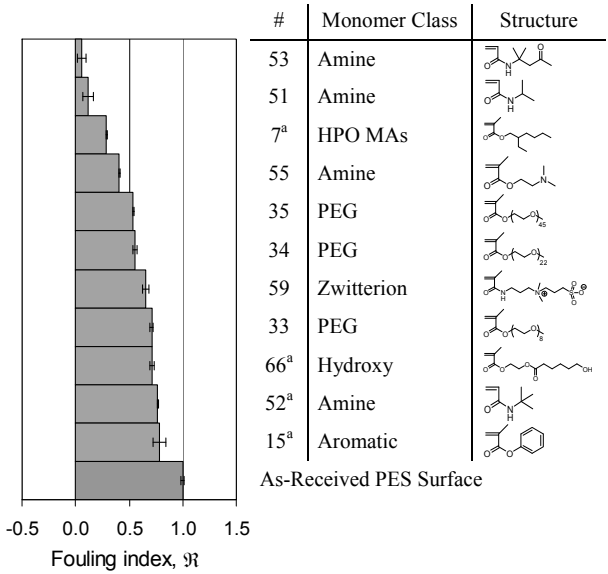
Results and Discussion

To assess foulant/surface interactions, a fouling index, $\Re$, was calculated as the resistance increase of grafted membranes caused by fouling normalized by that of ungrafted membrane control, $\Re = \Delta R_{mod}/\Delta R_{control}$, where $\Delta R_{mod} = (R_{fouled} - R)_{mod}$ and $\Delta R_{control} = (R_{fouled} - R)_{control}$. The control was the as-received membrane treated with either water or ethanol, depending on which was used to dissolve the monomer. The increase in the modified membrane resistance after foulant adsorption should be lower than that of the control when the modified surface resists foulant interactions. In other words, a fouling index lower than 1 indicates the produced new surfaces are better than PES materials in terms of resisting static adsorption of the feed components.

The fouling index of the best fouling-resistant surfaces is shown in Figure 3 for both NOM and BSA feeds. Of the top performers, 8 worked well for both feeds, including 4 amines (#s 53, 51, 55, 52), 2 PEGs (#34 and #35), an HPO MA (#7), and a zwitterionic monomer (#59). Several monomers performed well for NOM but did were not among the top performers for BSA. These include a zwitterion (#60), a basic monomer (#61), and a carboxylic acid monomer (#45).



(a)



(b)

Figure 3. Top fouling-resistant surfaces for NOM (a) and BSA (b) from a total of 66 commercial monomers relative to the as-received PES membrane using the HTP-PGP method. Success is measured in terms of fouling index, ℜ. Superscript "a" indentifies ethanol soluble monomers. #s represent the monomer number in the library of 66 monomers.

In addition, several monomers performed well for BSA, but did not produce surfaces that were among the best performers at resisting NOM fouling. These included a short-chain PEG (#33) a hydroxy monomer (#66) and an aromatic monomer (#15).

With some exceptions, our findings are generally consistent with results from studies of protein interactions with surfaces having a variety of functionality created using self-assembled monolayers (SAMs) of alkanethiolates on gold as a model substrate (*12-19*). Such studies have identified general features of surfaces having low affinity for proteins: (i) they are hydrophilic (wettable), (ii) they contain hydrogen bond acceptors, (iii) they lack hydrogen bond donors, (iv) they are electrically neutral (*12-15*).

Among the surfaces that mitigated fouling for both NOM and BSA feeds, the long-chain PEG monomers (#34 and #35), represent the "standard" for protein resistance, and satisfy all four of the above criteria. However, the best performing monomer for BSA, and the second best for NOM, diacetone acrylamide (#53), contains a secondary amine which can act as a hydrogen bond donor. It is likely that the location of the amine group adjacent to the carbonyl oxygen limits its reactivity. Others have noted that primary and secondary amines adsorb more protein than structurally similar groups in the form of amides (*15*). Furthermore, it should also be noted that other molecules containing hydrogen bond donors, such as mannitol, have exhibited protein resistance (*20*). Three other monomers containing amine groups also performed well. The 2-(dimethylamino) ethyl methacrylate (#55) contains a tertiary amine, the N-isopropylacrylamide (#51) and the N-tert-butylacrylamide (#52) also contains amide groups. The zwitterion [3-(methacryloylamino)propyl] dimethyl(3-sulfopropyl)ammonium hydroxide inner salt (#59) conforms to the net neutrality criterion, but also contains a secondary amine in an amide group. The most surprising monomer was the 2-ethylhexyl methacrylate (#7), which is much less hydrophilic than the other high performers.

For the BSA feed-specific fouling resistant surfaces, the PEG (#33) also satisfies all the four criteria. However, this PEG has only 8 ethylene glycol repeating units as compared with 22 for #34 and 45 for #35; therefore it is likely that the produced graft chains were shorter after surface modification, which may explain why monomer #33 did not work well for NOM. The caprolactone 2-(methacryloyloxy)ethyl ester monomer (#66) terminates in an alcohol group, separated from the hydrophilic portion of the molecule by a five-carbon chain. It is possible that this chain length is long enough to promote self-association and reduce the hydrogen bond donor reactivity with proteins. The success of aromatic monomer #15, phenyl methacrylate, was unexpected, because it is not as hydrophilic as other top performers.

For the NOM feed-specific fouling resistant surfaces, the zwitterion [2-(methacryloyloxy)ethyl]dimethyl-(3-sulfopropyl)ammonium hydroxide (#60) conforms to the net neutrality criterion. It performed the best for NOM; however, it was not ranked in top performers for BSA feed. Interestingly, a good performer for NOM feed was the basic monomer [2-(methacryloyloxy)ethyl] trimethylammonium chloride (#61). It was positively charged under our experimental conditions; therefore, it does not satisfy the general features of surfaces having low affinity for proteins. However, this monomer ranked the

fourth for NOM fouling resistant surfaces. The methacrylic (carboxylic) acid monomer (#45) performed well for NOM, likely because it induced charge repulsion between the grafted surface and the like-charged feed components. However, this monomer did not perform well for BSA, which was expected based on the general criteria for protein resistance.

Conclusions

A novel high throughput method for synthesis and screening of customized fouling-resistant surfaces was developed by combining a high throughput platform approach together with our patented photo-induced graft polymerization method, to allow facile modification of commercial poly(aryl sulfone) membranes. This method is inexpensive, fast and simple at discovering feed-specific fouling-resistant surfaces by static adsorption.

The HTP approach was employed in a discovery mode to identify many surfaces from a library of 66 monomers that perform significantly better than the as-received membrane, offering significantly lower resistance due to fouling of NOM and BSA. Our results are generally consistent with rules governing general features of surfaces having low affinity for proteins. The grafted amines (especially in the amide forms), and long chain PEGs produced excellent surfaces for both feeds. Grafted zwitterion surfaces appeared to work better for NOM feed. Some exception was also found for NOM feed: the grafted basic and acid surfaces worked well for NOM but not for BSA.

Future work will involve compiling foulant/surface interaction data, membrane performance parameters, and monomer structural features as input to develop structure/property relationships (QSPR), which will provide mechanistic insight that can be used for designing new surfaces for particular feed solutions, and for expanding the initial monomer library.

Acknowledgements

The authors acknowledge the U.S. Environmental Protection Agency (EPA grant RD83090901-0), U.S. National Science Foundation (CBET-0730449) for financial support, Seahorse Labware (Chicopee, MA) for filter plates, and Millipore Corporation (Bedford, MA) for membranes.

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