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(54) Title: IMPROVED HYBRID TFC RO MEMBRANES WITH NON-METALLIC ADDITIVES

(57) Abstract: A process for preparing a reverse osmosis membrane that includes: (A) providing a polyamine, a polyfunctional acid halide, and a flux increasing additive having the formula Z^+B^-, where Z^+ is an easily dissociable cation and B^- is a beta-diketonate; (B) combining the polyamine, polyfunctional acid halide, and flux increasing additive on the surface of a porous support membrane; and (C) interfacially polymerizing the polyamine and the polyfunctional acid halide, and flux increasing additive on the surface of the porous support membrane to form a reverse osmosis membrane comprising (i) the porous support membrane and (ii) a discrimination layer comprising a polyamide. The reverse osmosis membrane is characterized by a flux that is greater than the flux of the same membrane prepared in the absence of the flux increasing additive.

IMPROVED HYBRID TFC RO MEMBRANES WITH NON-METALLIC ADDITIVES

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Application Serial Number 61/412,184 filed November 10, 2010, the content of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

This invention is related to discrimination membranes for use in reverse osmosis and forward osmosis processes, e.g., for purifying water.

BACKGROUND

Reverse osmosis membranes made by interfacial polymerization of a monomer in a nonpolar (e.g., organic) phase together with a monomer in a polar (e.g., aqueous) phase on a porous support membrane are known as TFC membranes and are used where flux and substantial rejection characteristics are required, for example in the purification of water. Various materials have been added to TFC membranes in the hopes of increasing flux without reducing rejection characteristics and have met with limited success. In addition, such membranes are subject to fouling resulting in reduced flux as contaminants, for example from the brackish or seawater to be purified, are believed to build up on the surface of the discrimination layer of the TFC membrane.

SUMMARY

A process for preparing a reverse osmosis membrane is described that includes: (A) providing a polyamine, a polyfunctional acid halide, and a flux increasing additive having the formula Z^+B^-, where Z^+ is an easily dissociable cation and B^- is a beta-diketonate; (B) combining the polyamine, polyfunctional acid halide, and flux increasing additive on the surface of a porous support membrane; and(C) interfacially polymerizing the polyamine and the polyfunctional acid halide, and flux increasing additive on the

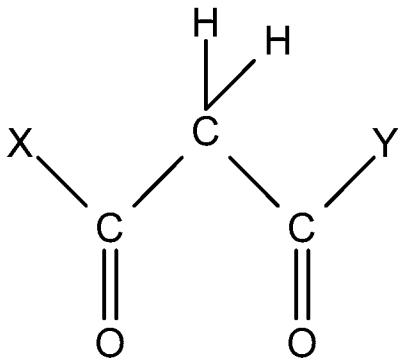
surface of the porous support membrane to form a reverse osmosis membrane comprising (i) the porous support membrane and (ii) a discrimination layer comprising a polyamide. The reverse osmosis membrane is characterized by a flux that is greater than the flux of the same membrane prepared in the absence of the flux increasing additive.

The polyamine may be selected from the group consisting of diaminobenzene, triaminobenzene, m-phenylene diamine, p-phenylene diamine, 1,3,5-diaminobenzoic acid, 2,4-diaminotoluene, 2,4-diaminoanisole, xylylene diamine, ethylenediamine, propylenediamine, piperazine, and tris(2-aminoethyl)amine. The polyfunctional acid halide is selected from the group consisting of trimesoyl chloride, trimellitic acid chloride, isophthaloyl chloride, and terephthaloyl chloride.

In some embodiments, the polyamine, polyfunctional acid halide, and flux increasing additive may be combined with nanoparticles (e.g., zeolites or carbon nanotubes). Interfacial polymerization then yields a reverse osmosis membrane that includes (i) the porous support membrane and (ii) a discrimination layer comprising a polyamide and the nanoparticles. The porous support membrane may also include nanoparticles. In other embodiments, the polyamine, polyfunctional acid halide, and flux increasing additive may be combined with mono-hydrolyzed trimesoyl chloride prior to the interfacial polymerization.

In some embodiments, Z^+ has the formula $R^1R^2R^3R^4N^+$, where R^1, R^2, R^3, and R^4, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group, or a phenyl group. For example, in some embodiments, R^1, R^2, R^3, and R^4 are ethyl groups, while in other embodiments, each R^1, R^2, and R^3 group is an ethyl group, and R^4 is H.

B^- may have the formula:



where X and Y, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group, a phenyl group, $-OR^5$, or NR^6R^7, each optionally substituted with fluorine, and R^5, R^6, and R^7, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group or a phenyl group. For example, X and Y may be methyl groups, or X and Y may be trifluoromethyl group.

Reverse osmosis membranes prepared according to this process may be capable of exhibiting a flux of at least 30 gfd, determined by exposing the membrane to deionized water containing 32,000 ppm NaCl at a temperature of 25°C and a pressure of 800 psi. the membranes may also be capable of exhibiting a salt rejection of at least 99.5%, determined by exposing the membrane to deionized water containing 32,000 ppm NaCl at a temperature of 25°C and a pressure of 800 psi. The membranes may be used to purify brackish water or seawater.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

Fig. 1 is a block diagram of hybrid TFC membrane 10 during fabrication in which aqueous phase 14 including β-carbonyl additive 17, which may be positioned on support 12, which may be strengthened by fabric 20, contacted by organic phase 14 which may include nanoparticle additives 16 to create a thin film TFC membrane by interfacial polymerization (IFP).

Fig. 2 is a block diagram of hybrid TFC membrane 10 during operation in which feed stream 29 is applied to discrimination membrane 24 – formed by IFP in the presence of a β-carbonyl additive 17 and/or nanoparticle additives 16 – through which purified water 34 permeates while salts and other contaminants are rejected.

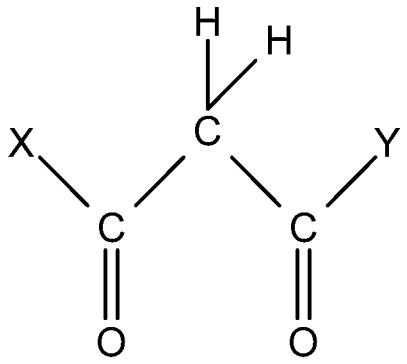
Fig. 3 is a graph of the test results for 0.11 wt% and 0.26 wt% $Et_3NH(F_6acac)_2$ additive 17 with error bars indicating +/- standard deviation representing the numerical test results shown in Table 1.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

A TFC membrane may be advantageously formed by interfacial polymerization (IFP) between an organic phase which may optionally contain nanoparticle additives and an aqueous phase containing a β–carbonyl anion, released from a β–carbonyl additive, such as triethylammonium hexafluoro-acetylacetonate. In general, the β-carbonyl additive is in the form of Z^+B^- where Z may be H^+ or Z may be $R^1R^2R^3R^4N^+$ where $R^1R^2R^3R^4$ may be independently -H, -C_1-C_6 hydrocarbyl, -benzyl or –phenyl. For example, in some embodiments, R^1, R^2, R^3, and R^4 are ethyl groups, while in other embodiments, each R^1, R^2, and R^3 group is an ethyl group, and R^4 is H.

B may be:



where Y and X may be independently -H, -C_1-C_6-hydrocarbyl, -benzyl, -phenyl, -OR_5, or -NR^6R^7, each optionally substituted by fluorine, wherein R^5, R^6, and R^7 are independently -H, -C_1-C_6-hydrocarbyl, -benzyl or –phenyl. In another preferred embodiment, X and Y may be CH_3 so that B may be the β-dicarbonyl compound acetylacetone, optionally substituted with fluorine.

Z^+B^- is easily dissociated in the aqueous phase solution.

B^- is preferably added in an amount that improves the permeability or flux of said reverse osmosis membrane and/or which maintains the salt rejection at a level greater than that of a control membrane made without additive. For example, the flux improvement preferably is on the order of at least 20%, at least 35% and preferably at least 50%. The salt rejection preferably is at a level of at least 99% and preferably at least 99.5%. The flux is preferably at least 27 gfd, more preferably at least 30 gfd, and most preferably on the order of about at least 35 gfd, while the salt rejection is on the order of about at least 99% or preferable on the order of about 99.5%.

In addition to triethylamine, several other bases may be used to form the β-diketonate salt. For instance, other alkyl or substituted alkyl groups may be present on the nitrogen, and the alkyl group may be either all the same, may be different. In addition to tri-substituted amines, ammonia, primary or secondary amines may be used. Quaternary ammonium hydroxide solutions may also be used to prepare quaternary salts.

Other nitrogenous bases may also be used including aniline, or aromatic substituted nitrogens, and heterocycles such as piperazine, pyridine, or imidazole.

Effective β-diketonates include 5-carbon or larger carbon framework compounds where ketones are present on either side of a proton containing carbon atom. Atoms and substitutents may be present throughout the compound. Other electron withdrawing substituents such as fluorine can more preferably be present adjacent to the ketones to aid in the formation of the enolate compound.

Figs 1 and 2 describe a representative process for preparing a reverse osmosis membrane by IFP using a Z^+B^- flux enhancing additive. The discrimination layer of the membrane illustrated in Figs. 1 and 2 also contains nanoparticles 16; the resulting TFC membrane is referred to as a "hybrid TFC" membrane. Such nanoparticles, however, are optional.

Referring now to Figs. 1 and 2, a hybrid TFC membrane is shown in fabrication and then again in operation. In fabrication, aqueous phase 14 is applied to support membrane 12, which preferably rests on fabric 20. Support membrane 12 is typically a polymeric microporous support membrane, which in turn is often supported by non-woven or woven fabrics, such as fabric 20, for mechanical strength. Fabric 20 is preferably a polyester fabric having a basis weight of 60-120 grams per meter or gsm, and a thickness of 50-200 microns. Support membrane 12 may be made from polysulfone or other suitably porous membranes, such as polyethersulfone, poly(ether sulfone ketone), poly(ether ethyl ketone), poly(phthalazinone ether sulfone ketone), polyacrylonitrile, polypropylene, cellulose acetate, cellulose diacetate, or cellulose triacetate. Support membrane 12 may be 25-100 nm in thickness, preferably about 35 nm to about 75 nm and most preferably about 50 nm in thickness and may have the smallest pores located very near the upper surface. Porosity at the surface may be low, for instance from 5-15% of the total surface area.

Aqueous phase 14 contains a β-dicarbonyl additive 17, such as $Et_3NH(F_6acac)_2$. It is believed that $Et_3NH(F_6acac)_2$ is easily dissociated into an Et_3NH^+ cation Z^+ and an $(F_6acac)_2^-$ anion in aqueous phase 14. Additive 17, as shown in Fig. 1, has the formula

Z^+B^-, wherein B is an acetylacetonate moiety defined above and Z is an easily dissociated moiety such as ammonium ion defined above, which improves the permeability of the resulting reverse osmosis membrane 10 relative to a control membrane made without additive 17. Without wishing to be bound by theory, it is thought that additive 17 interferes with full cross linking of the polyfunctional acid halide (e.g., trimesoyl chloride) and polyamine (e.g., methylene phenylene diamine) compounds during IFP.

Aqueous phase 14 is contacted with organic phase 18, which may contain another additive such as nanoparticles 16, to create discrimination membrane 24 by IFP as illustrated in Fig. 2. Examples of nanoparticles, including nanostructured materials such as carbon nanotubes and metal organic frameworks (MOF), that may be combined with the polyamine, polyfunctional acid halide, and beta-diketonate flux increasing additive, include:

Linde Type A (LTA) zeolites available freeze dried, 100nm diameter from Nanoscape AG, Am Klopferspitz 19, D-82152 Planegg, Germany;

Linde Type Y (FAU) zeolites as described in MICROPOROUS AND MESOPOROUS MATERIALS Volume: 59 Issue: 1 Pages: 13-28 Published: APR 18 2003 by Holmberg BA, Wang HT, Norbeck JM, Yan YS;

Zeolite Beta as described in MICROPOROUS AND MESOPOROUS MATERIALS Volume: 25 Issue: 1-3 Pages: 59-74 Published: DEC 9 1998 by Camblor MA, Corma A, Valencia S); and

Cu MOF: A metal organic framework complex prepared from Cu and trimesic acid as described in Science 283, 1148 (1999); Stephen S.-Y. Chui, et al. "[Cu3(TMA)2(H2O)3]n A Chemically Functionalizable Nanoporous Material".

Either during IFP, or once the polymer matrix is formed, the anion believed to be present in this solution may interfere with the formation of covalent crosslinking. Instead, ionic cross linkages between the hydrolyzed acyl halide groups and the terminal amines are formed. Such ionic cross-links, compared to the largely covalently crosslinked controls, promote increased water uptake and flux. At the same time,

rejection may be maintained by virtue of these ionic crosslinks between the charged groups. Relative to ionic interactions in solution, these ionic crosslinks are stabilized by the rigidity of the polymer network keeping the two charged centers close to each other. The ionic crosslink may also allow a slight expansion of the matrix relative to a covalent bond, thereby increasing water uptake.

EXAMPLES

The general procedure for the preparation of a flat cell test membrane was to prepare aqueous and organic phases, add the desired additives to one or both of these phases, apply the aqueous phase to a wet polysulfone membrane support on a glass plate, and then apply the organic phase to the aqueous phase on the membrane support as described in more detail immediately below. Control membranes were made in a similar way, except without the additive(s). All performance data unless otherwise noted was obtained from flat sheet testing on NaCl (32,000 ppm.53 mS/cm) in tap water tested at 25°C and 800 psi. Flow and rejection were measured after 1 hour of running.

Aqueous Phase 14: An aqueous solution of MPD, 4.5 wt% of triethylammonium camphorsulfonate (TEACSA), and 0.06 wt% sodium lauryl sulfate (SLS) in DI water, and 0, 0.11, or 0.26 wt.% $Et_3NH(F_6acac)_2$ was prepared. $Et_3NH(F_6acac)_2$ was synthesized in-house and used without further purification. The procedure used was:

- Add 25 g ampoule hexafluoroacetylacetone (98%, Aldrich 238309, Lot MKBB2482) to 100 ml n-hexane that was stored over molecular sieves (96%, Acros 364370010, Lot 0930139) with stirring.
- Add 12.14 g triethylamine (Fluka 90342, Lot 1389546) added with stirring.
- 2 phases formed with bottom being a deep yellow color.
- After ca. 30 minutes, top layer decanted off and yellow phase stored overnight.
- Small amount of less dense phase collected overnight on top of the yellow phase and was removed the next day.

Organic Phase 18: An Isopar G® solution with 0.3 wt.% TMC and 4 wt.% mesitylene was also prepared and sonicated for up to 60 minutes. Isopar is a trademark of Exxon Corp.

Support membrane 12: A piece of wet polysulfone support was placed flat on a clean glass plate. An acrylic frame was then placed onto the membrane surface, leaving an area for the interfacial polymerization reaction to take place.

Discrimination membrane 24: Approximately 50 mL of the aqueous MPD solution was poured onto the framed membrane surface and remained for up to 2 min. The solution was drained by tilting the frame till no solution dripped from the frame.

i) The frame was taken off, and was left horizontally for 1 minute. The membrane was then clamped with the glass plate in four corners. An air knife was used to finish drying the membrane surface. The membrane was reframed using another clean and dry acrylic frame and kept horizontally for 1 min.

ii) Approximately 50 mL of the organic solution was poured onto the framed membrane surface and remained for 2 minutes. The solution was drained by tilting the frame (vertically) till no solution dripped from the frame. The acrylic frame was removed, and the membrane was kept horizontally for 1 minute. The membrane was then dried at 95° C for 6 minutes.

Two TFC membranes were synthesized and tested for each condition.

Referring now to Fig. 3, the results of the testing above discussed above for 0.11 wt% and 0.26 wt% $Et_3NH(F_6acac)_2$ additive 17 are shown with error bars indicating +/- standard deviation. These tests show that both flux and rejection are affected by the concentration of $Et_3NH(F_6acac)_2$ in a similar manner as they are affected by the addition of certain other additives 17 such as alkaline earth additives. Table 1 below provides the test numerical results. Example 1, which contained no beta-diketonate additive, was used as a control.

Table 1: Membranes with $Et_3NH(F_6acac)_2$ additives 17

x.#	MPD	TMC	Ratio	Aqueous 14	FLUXGFD	REJ.
1	4%	0.3%	13.3		21.8	99.5%
2	4%	0.3%	13.3	0.11 wt% $Et_3NH(F_6acac)_2$	26.9	99.53%
3	4%	0.3%	13.3	0.26 wt% $Et_3NH(F_6acac)_2$	29.6	99.27%
4	4%	0.3%	13.3	0.13 wt% $Et_3NH(F_6acac)_2$	30	99.57%
5	4%	0.3%	13.3	0.36 wt% $Et_3NH(F_6acac)_2$	32	99.52%
6	4%	0.3%	13.3	0.13 wt% Et_4N (F_6acac)2	32	99.57%
7	4%	0.3%	13.3	0.28wt% Et_4N (F_6acac)2	34	99.5%
8	4%	0.3%	13.3	0.08wt% F_6acac	32	99.57%
9	4%	0.3%	13.3	0.17wt% F_6acac	35.5	99.45%

Without being restricted to this hypothesis, it is believed that the mechanism of action of these β-diketonate salts may be a result of an interaction or reaction with one or more of the acyl chloride functionalities present on the TMC in organic phase 18. β-diketonate compounds and their enolate salts may react with acyl halides either through the carbon adjacent to both ketones, a substituted ketone, or through the oxygen forming an ester. These formed compounds may either participate directly in the film formation,

may react with end groups present after the initial polymerization, or the formed compound itself may undergo further reactions leading the true effective agent. These formed compounds are believed to be particularly effective when produced in concert with the IFP reaction itself, perhaps due to a decreased tendency to reduce molecular weight that may occur if the compound were present at the onset of the polymerization reaction. This may occur when the β-diketonate is brought into contact with TMC at the same time, or after the amine reactant.

This reaction may occur either in aqueous phase 18 after a small amount of TMC partitions into aqueous phase 14, at the aqueous-organic phase interface, or in organic phase 18 after the substituted ammonium β-diketonate salt partitions into organic solution 18.

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

WHAT IS CLAIMED IS:

1. A process for preparing a reverse osmosis membrane, comprising:
(A) providing a polyamine, a polyfunctional acid halide, and a flux increasing additive having the formula Z^+B^-, where Z^+ is an easily dissociable cation and B^- is a beta-diketonate;
(B) combining the polyamine, polyfunctional acid halide, and flux increasing additive on the surface of a porous support membrane; and
(C) interfacially polymerizing the polyamine and the polyfunctional acid halide, and flux increasing additive on the surface of the porous support membrane to form a reverse osmosis membrane comprising (i) the porous support membrane and (ii) a discrimination layer comprising a polyamide,
wherein the reverse osmosis membrane is characterized by a flux that is greater than the flux of the same membrane prepared in the absence of the flux increasing additive.

2. A process according to claim 1, wherein the polyamine is selected from the group consisting of diaminobenzene, triaminobenzene, m-phenylene diamine, p-phenylene diamine, 1,3,5-diaminobenzoic acid, 2,4-diaminotoluene, 2,4-diaminoanisole, xylylene diamine, ethylenediamine, propylenediamine, piperazine, and tris(2-aminoethyl)amine.

3. A process according to claim 1, wherein the polyfunctional acid halide is selected from the group consisting of trimesoyl chloride, trimellitic acid achloride, isophthaloyl chloride, and terephthaloyl chloride.

4. A process according to claim 1, comprising combining the polyamine, polyfunctional acid halide, flux increasing additive, and nanoparticles; and interfacially polymerizing the polyamine and the polyfunctional acid halide on the surface of the porous support membrane to form a reverse osmosis membrane comprising (i) the porous support membrane and (ii) a discrimination layer comprising a polyamide and the nanoparticles.

5. A process according to claim 1, wherein the nanoparticles comprise zeolites.

6. A process according to claim 1, wherein the nanoparticles comprise carbon nanotubes.

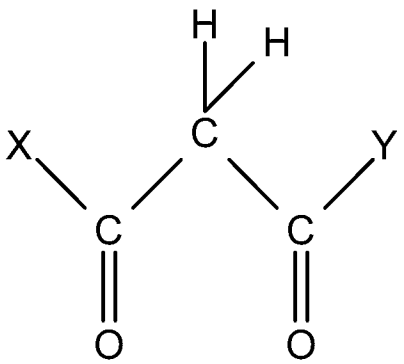
7. A process according to claim 1, wherein the porous support membrane comprises nanoparticles.

8. A process according to claim 1, wherein Z^+ has the formula $R^1R^2R^3R^4N^+$, where R^1, R^2, R^3, and R^4, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group, or a phenyl group.

9. A process according to claim 8, wherein R^1, R^2, R^3, and R^4 are ethyl groups.

10. A process according to claim 8, wherein each R^1, R^2, and R^3 group is an ethyl group, and R^4 is H.

11. A process according to claim 1, wherein B^- has the formula:



where X and Y, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group, a phenyl group, $-OR^5$, or NR^6R^7, each optionally substituted with fluorine, and R^5, R^6, and R^7, independently, are H, a C_1-C_6 hydrocarbyl group, a benzyl group or a phenyl group.

12. A process according to claim 11, wherein X and Y are methyl groups.

13. A process according to claim 11, wherein X and Y are trifluoromethyl groups.

14. A process according to claim 1, comprising combining the polyamine, polyfunctional acid halide, flux increasing additive, and mono-hydrolyzed trimesoyl chloride; and interfacially polymerizing the polyamine and the polyfunctional acid halide on the surface of the porous support membrane to form a reverse osmosis membrane comprising (i) the porous support membrane and (ii) a discrimination layer comprising a polyamides.

15. A reverse osmosis membrane prepared according to the process of claim 1.

16. A reverse osmosis membrane according to claim 15, wherein the membrane is capable of exhibiting a flux of at least 30 gfd, determined by exposing the membrane to deionized water containing 32,000 ppm NaCl at a temperature of 25°C and a pressure of 800 psi.

17. A reverse osmosis membrane according to claim 15, wherein the membrane is capable of exhibiting a salt rejection of at least 99.5%, determined by exposing the membrane to deionized water containing 32,000 ppm NaCl at a temperature of 25°C and a pressure of 800 psi.

18. A method of purifying brackish water or seawater comprising contacting the brackish water or seawater with a reverse osmosis membrane according to claim 15.

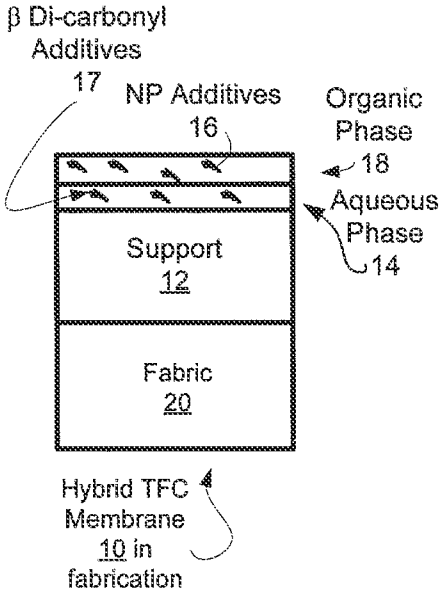


FIG 1

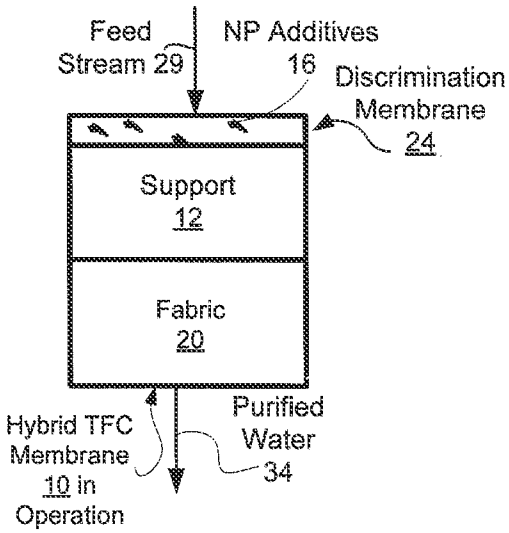


FIG 2

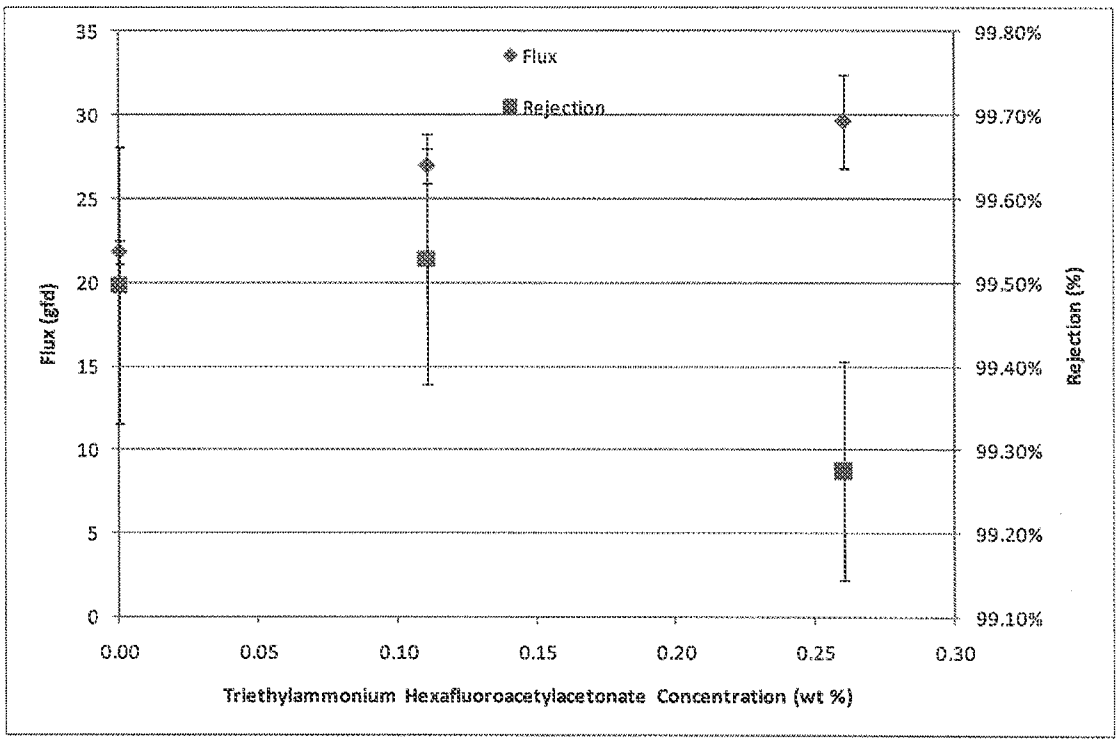


FIG 3