

**ISOPOROUS SELF-ASSEMBLED BLOCK COPOLYMER FILMS CONTAINING
HIGH MOLECULAR WEIGHT HYDROPHILIC ADDITIVES AND METHODS OF
MAKING THE SAME**

Field of the Invention

[0001] The invention relates to isoporous block copolymer ("BCP") films and methods for fabricating the same.

Background of the Invention

[0002] Membrane fouling and membrane compaction are two prime causes of flux degradation in membrane filtration processes. Membrane fouling is a commonly known hindrance to membrane performance. It occurs when a solution or particulate matter is deposited on a membrane during use. Membrane fouling results in the degradation of membrane performance. Membrane fouling mechanisms are well-understood and the flux degradation by fouling can be fully recovered in many filtration applications by designing fouling resistant membranes, process improvements, and clean-in-place techniques.

[0003] Unlike membrane fouling, which is in many applications reversible, membrane compaction results in non-reversible flux degradation and irreversible change in the porous substructure of the membrane. Membrane compaction thus affects filtration selectivity. Membrane compaction is a deformation of the membrane caused by the pressure differential across the membrane during use. When a membrane is exposed to high pressure differentials, the flux of water and dissolved constituents decrease through the membrane over time. In order to maintain flux, larger pressure differentials must be applied, resulting in even higher stress in the porous regions, which may result in a reorganization of polymers that increases the density of

the material. Additionally, physical compaction decreases the overall porosity of the membrane and can therefore exacerbate membrane fouling. Membrane compaction is a difficult problem to overcome because the applied feed pressure needs to be increased over time, in order to maintain the same throughput. All this results in increased capital expenditure vs. operating expense (“CAPEX/OPEX”) for a business, cutting into profits, due to higher energy demand and a shortening in the useful life of the membrane.

[0004] Preexisting membrane technologies utilize block copolymer (BCP) membranes based on such triblock polymers such as poly(isoprene-b-styrene-b-4-vinyl-pyridine) (“ISV”). Such a BCP membrane is disclosed in WO 2012/151482 A3, which describes the fabrication of such membranes through a combination of controlled solvent evaporation and well-established immersion precipitation processes. However, akin to membranes fabricated from conventional polymers, the BCP membranes produced from neat ISV polymers are also susceptible to physical compaction.

[0005] U.S. Patent Application 2010/0224555 A1 (“*Hoek et al.*”) discloses other membranes designed to resist compaction. The application teaches that membrane compaction can be improved by incorporating nanoparticles in the polymer matrix. The reference discloses that the inclusion of these nanoparticles improves the stiffness and toughness of the membrane material, and hence its ability to preserve its porous structure and resist physical compaction. However, incorporating nanoparticles into the block copolymer matrix of a membrane tends to disrupt the ordered self-assembly of microphase separated domains. Moreover, the addition of any foreign additives (e.g. nanoparticles, pore forming agents) to the casting dope formulation to fabricate BCP membranes is complex, and not as straightforward as with membranes produced from

conventional polymers. One of the unique advantage of ISV polymers is their ability to self-assemble and form uniformly sized micelles in the casting solution, which in turn, provides a highly ordered isoporous structure on the membrane's surface. The highly ordered uniformly sized pores give a very sharp molecular weight cut-off and provide excellent selectivity for separating molecules of differing size. In light of this, preserving the self-assembled structure of the membrane is of utmost importance. *Hoek et al.*'s disclosure therefore does not resolve the membrane compaction problems existing in the art.

[0006] In order to resolve those and other deficiencies in the art, the present invention is directed to BCP membranes that are resistant to compaction while maintaining a high level of selectivity in the separation of molecules. Methods for the fabrication of such membranes are also disclosed.

Brief Description of the Figures

[0007] A more complete appreciation of the invention and many of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. 1 shows a comparison of viscosities in BCP films formed with only ISV29 versus BCP films formed with ISV29 and 5% PVP-K90;

FIG. 2A and 2B show microscopic scans of BCP membranes with and without the incorporation of the high molecular weight additive, polyethylene glycol (PEG-150K);

FIG. 3 shows top surface of ISV BCP films with and without the high molecular weight

additive in different solvent systems;

FIG. 4 shows the flux decline of ISV films disclosed by the present invention compared to neat ISV polymer films;

FIG. 5 shows a table of flux decline percentages for BCP films embodying the present invention;

FIG. 6 shows a chart of the flux over a 70-minute time interval for four ISV22 BCP films incorporating either poly(vinylpyrrolidone) (PVP-K90) or a low molecular weight polyethylene glycol (PEG400);

FIG. 7A shows protein adsorption of a neat polymer film compared to adsorption of the ISV29 BCP film incorporating PVP-K90;

FIG. 7B shows a graph of the film selectivity of a BCP film incorporating PVP-K90 between 7 nm and 20 nm; Arrows indicate which axis the data points correspond to.

FIG. 7C is a chart showing the reproducibility of flux performance in BCP films of the present invention; and

FIG. 7D shows the effect of solvent systems on permeability in BCP films incorporating PVP-K90.

FIG. 8 is a chart of the flux retained (J/J_0) over a 270-minute (4.5 h) time interval for two ISV43 BCP films either with (white circles) or without (+ symbol) the PVP-K90 high molecular weight additive.

FIG. 9 is a chart showing the average pure water permeability (PWP) of six films each cast from a BCP ISV43, either without (left) PVP-K90 or with (right) PVP-K90 high molecular

weight additive.

Detailed Description of the Preferred Embodiments

[0008] In describing a preferred embodiment of the invention illustrated in the drawings, specific terminology will be resorted to for the sake of clarity. However, the invention is not intended to be limited to the specific terms so selected, and it is to be understood that each specific term includes all technical equivalents that operate in a similar manner to accomplish a similar purpose. Several preferred embodiments of the invention are described for illustrative purposes, it being understood that the invention may be embodied in other forms not specifically shown in the drawings. In some embodiments, the films are membranes, which are a subset of films. In the context of the invention, “high molecular weight” is defined as being equal to or greater than 50% of the molecular weight of the majority block copolymer comprising the material of the invention. The films have mesopores, defined as about between 1 nm and 200 nm. In the context of the invention, isoporous means having a substantially narrow pore diameter distribution. The films are either symmetric or asymmetric.

[0009] In films fabricated from conventional polymers, poly(vinylpyrrolidone) (PVP) of different molecular weights are added in the film casting solution to improve the water flux, hydrophilicity, tune the pore size and tune the viscosity of the casting solution. As disclosed herein, the inventors have discovered that the addition of a high molecular weight PVP to the formulation of the film improves its compaction resistance. The addition of a small amount (0.1-15 wt%) of high molecular weight (360,000 Da) poly(vinylpyrrolidone) (PVP-K90) in the

casting solution (relative to BCP) significantly improves the BCP film compaction resistance compared to films produced from neat ISV polymers. The inventors posit that these beneficial effects may be due to the PVP not only staying on the surface in the separation layer but also staying in the substructure and acting as a reinforcing agent that improves the stiffness of the film and therefore its compaction resistance. Another possibility is that the presence of PVP leads to delayed mixing during the immersion precipitation process thereby suppressing the formation of macrovoids and forming a spongy substructure with a dense separation layer.

More notably, the addition of PVP maintains the highly ordered self-assembled selective separation layer of the film with an open macrovoid structure underneath supported on a woven/non-woven fabric. This result counters conventional knowledge in the art and is therefore a surprising result, as in theory, the probability of self-assembly getting disrupted is higher if the molecular weight of the additive is substantially higher than the molecular weight of the precursor polymer. Another surprising result is that the addition of a high molecular weight PVP tends to favorably decrease the viscosity of the casting solution, as opposed to what is documented in the literature. As shown in Figure 1, the viscosity of solutions at the same wt% of ISV polymer shows a nearly 20% decrease in viscosity with the addition of 5% PVP-K90. Specifically, measurements taken at room temperature and as similar shear conditions, show that the ISV solution with no additive was measured at 1473 cP, while adding 5% PVP-K90 to the solution decrease the viscosity to 1180 cP. As disclosed herein, the flux decline (% loss as a function of time) of films casted from neat ISV polymers (i.e. ISV polymers without PVP) is in the range 60-70%, while that of films produced from casting solutions containing high molecular weight additives is 5-30%, depending on the type of solvent system. The protein adsorption of film with PVP is ~35% less compared to film from neat ISV polymer. This might be due to

higher molecular weight additive getting entrapped in the polymer matrix and imparting hydrophilic character to the film. These films have excellent selectivity for proteins with ~3 fold difference in size. For example, only 56% of bovine serum albumin (7 nm) was rejected by the novel films disclosed, compared to 96% for thyroglobulin (20 nm). Additionally, the pore size of the BCP film can be tuned by changing the solvent system. For example, an ISV polymer film incorporating 5% PVP-K90 in dioxane/tetrahydrofuran solvent system showed a 47% increase in permeability, while the same film showed a 60% decrease in permeability under similar casting conditions in a dioxane/acetone solvent system. *See* FIG. 7D, discussed in further detail below. A method for forming an isoporous block copolymer (BCP) film comprises the steps of: formulating a polymer solution by mixing at least one block copolymer with at least one solvent and at least one high molecular weight hydrophilic polymer; forming the polymer solution into a film; evaporating a portion of the solvent(s); immersing the film into a coagulation bath; and optionally, rinsing the BCP film with water. The solvent for the polymer solution BCP film casting solution solvent comprises at least one of: Acetaldehyde, Acetic acid, Acetone, Acetonitrile, Benzene, Chloroform, Cyclohexane, Dichloromethane, Dimethoxyethane, Dimethyl sulfoxide, Dimethylacetamide, Dimethylformamide, 1,4-Dioxane, Ethanol, Ethyl acetate, Formic acid Hexane, Methanol, N-Methyl-2-pyrrolidone, Propanol Pyridine, Sulfolane, Tetrahydrofuran, or Toluene.

[0010] One embodiment of the aforementioned method may be performed as follows. The first step of the process is the creation of a composite structure. This process involves the formulation of a polymer solution comprising: (1) a block copolymer such as poly(isoprene-b-styrene-b-4-vinyl-pyridine) (ISV) (molar mass 50-500 kg/mol); (2) a solvent such as 1,4-dioxane and, optionally, tetrahydrofuran (THF) or acetone, onto a woven/non-woven microporous

substrate such as polyester, thereby embedding a highly porous fabric into the liquid solution. It will be readily apparent to one of ordinary skill in the art that other known block copolymers may be substituted for the ISV polymer disclosed herein. The ISVs described herein have molecular weights as follows: ISV22: 94,000 Da; ISV28: 124,000 Da; ISV29: 91,000 Da; ISV43: 53,000 Da.

[0011] This step is followed by allowing the solvent in the extruded BCP film to evaporate (for 60-160 seconds). The BCP film is then immersed into a coagulation water bath, preferably at a temperature between 5 °C and 45 °C. The solution coagulates and forms a solid separation layer through the well-known immersion precipitation process. The porous composite that results exhibits a thin, self-assembled isoporous top layer with pore sizes ranging from ~5-50 nm residing above a porous substructure. The porous composite formed results in ultrafiltration sized (approximately 5 to 25 nm) pores.

[0012] FIG. 1 shows a comparison of viscosities in BCP films formed with only ISV29 versus BCP films formed with ISV29 and 5% PVP-K90. Viscosity was calculated in centipoise (cP) and measurements were taken at room temperature under similar shear conditions. As shown in FIG. 1, the generic ISV29 film exhibited a viscosity of 1473 cP, while the ISV29 film with 5% PVP-K90 demonstrated a viscosity of 1180 cP, approximately 20% less. This decrease in viscosity upon addition of PVP-K90 is a surprising, favorable result that impacts the improved compaction resistance of the films of the present invention.

[0013] FIG. 2A and 2B show preliminary research into the use of high molecular weight additives in the casting of BCP films. In addition to the use of PVP-K90 as disclosed in the

subsequent figures and related disclosure, 30% PEG-150K (polyethylene glycol with an average molecular weight of 150,000 Da) was tested for use in neat ISV29 BCP films. As shown in FIG. 2A, the use of PEG-150K, while introducing defects in the film due to likely solubility issues, was successful in demonstrating that self-assembly of the film was unaffected by the introduction of the additive. More notably, as shown in FIG. 2B, microscopic analysis of the 30% PEG-150K ISV29 BCP film showed the presence of macrovoids in the substructure of the formed film, a favorable characteristic that was absent in the ISV29 BCP films without an additive.

[0014] FIG. 3 shows microscopic scans of the top surfaces of ISV BCP films with and without the high molecular weight additive in different solvent systems. The images show the surprising result that the self-assembly of the ISV BCP films was not disrupted after the addition of 5% PVP K90, in both the DOX/THF and DOX/Ace solvent solutions. Because the self-assembly of the films is not disrupted, the films form uniformly sized micelles in the casting solution, which in turn, provide a highly ordered isoporous structure on the films' surfaces. The highly ordered uniformly sized pores give a very sharp molecular weight cut-off and provide excellent selectivity for separating molecules of differing size.

[0015] FIG. 4 shows the performance of films disclosed by the present invention compared to generic BCP films. In particular, FIG. 4 compares the performance of a "neat" ISV polymer film previously known in the art against novel ISV polymer films comprising poly(vinylpyrrolidone) ("PVP") and poly(ethylene glycol) ("PEG"). In the chart shown, four films are compared for their flux decline. Flux decline is used to measure the performance of a film, as a better-performing film will demonstrate a lesser decrease in flux over time. In FIG. 4,

flux (pure water permeation) was measured as $[(\text{Liter}/\text{m}^2/\text{h})/\text{bar g}]$, commonly annotated as LMH/bar. This flux measurement of the films tested is shown on the y-axis of the chart. The x-axis is a measurement of time, in minutes. FIG. 4 thus shows how the flux of the film changes over time. The first film tested was ISV28, a poly(isoprene-b-styrene-b-4-vinyl-pyridine) film previously known in the art (a “neat” ISV polymer film), which does not incorporate any PVP. The second film tested was the ISV28 film with 1.3% PVP360K-1, poly(vinylpyrrolidone) with an average molecular weight of 360,000 Da. The third film tested was the ISV28 film with 1.3% PVP360K-2, poly(vinylpyrrolidone) with an average molecular weight of 360,000 Da. The fourth film tested was the ISV29 film with 1% PEG58K, polyethylene glycol with an average molecular weight of 58,000 Da. Flux was then measured over 250 minutes.

[0016] The generic ISV film, the ISV28 BCP film, initially exhibited a flux of approximately 650 LMH/bar. However, over the 250-minute time period, the ISV28 film exhibited a flux decline to below 300 LMH/bar. This flux decline is primarily due to film compaction as the solution is passed through, and established the baseline against which the performance of the novel fabricated films could be compared. The second and third films tested represented ISV BCP films with a high molecular weight PVP incorporated. Unlike the ISV28 BCP film, the ISV28 film with 1.3% PVP360K-1 maintained a flux of approximately 300 LMH/bar, while the ISV28 film with 1.3% PVP360K-2 maintained a flux of approximately 200 LMH/bar across the 250-minute time interval. The fourth film tested, an ISV29 film with 1% PEG58K, exhibited a reduced flux decline over time to the ISV28 film, decreasing from an initial flux of approximately 480 LMH/bar to approximately 300 LMH/bar after 250 minutes. FIG. 4 is demonstrative of two points. First, that the incorporation of a high molecular weight PVP results

in a surprising improvement in protecting the ISV film against flux decline due to compaction. Second, FIG. 4 shows that these surprising effects are particularly pronounced with high molecular weight PVP, as compared to the alternative high molecular weight additive, PEG.

[0017] FIG. 5 shows additional data, calculating the flux decline percentage of various fabricated films embodying the invention. In all of the tested films, an ISV BCP is used to form the film. The various embodiments then incorporate between 0.5% and 5% by weight of PVP-K90, a high molecular weight PVP with an average molecular weight of 360,000 Da. Various solvent systems were used in the embodiments, as disclosed in FIG. 3, including a 70:30 mix of dioxane and acetone (DOX/Ace), and a 70:30 mix of dioxane and tetrahydrofuran (DOX/THF).

[0018] In FIG. 6, a flux decline pattern was charted for some of the embodiments disclosed in FIG. 5 as well as ISV BCP with low-molecular weight PEG400 additive. Then, the percentage flux decline, indicative of the compaction resistance of the film was calculated as follows: $(1 - \text{average of last 4 data points} / \text{average of first four data points}) * 100$. FIG. 6 shows the flux decline over a 70-minute time interval for four ISV22 BCP films (Film IDs: L160520 and L160422) identical except for their incorporation of high molecular weight PVP K90 or low molecular weight PEG400. The film incorporating PVP-K90 exhibited significantly less flux decline than the films with small molecular weight PEG400.

[0019] In FIG. 6, the films incorporating PVP-K90 show a distinctly greater compaction resistance than those that incorporate PEG400. The film incorporating PEG400 and PEG400 start with initial fluxes of approximately 750 LMH/bar and 690 LMH/bar, respectively. After 70 minutes, their fluxes decrease markedly, to approximately 450 LMH/bar and 350 LMH/bar, or 40% and 49%, respectively. This decline in flux is indicative of limited compaction resistance.

The decline in film flux of the ISV BCP films incorporating PEG is thus highly similar to those of ISV BCP films previously known in the art. By contrast, the ISV BCP films incorporating PVP-K90 demonstrate a strong compaction resistance over the measured time interval. The film incorporating 1A-PVP-K90 retained a flux of approximately 500 LMH/bar across the 70-minute time interval, while the film incorporating 3B-PVP-K90 retained its flux of approximately 480 LMH/bar for the duration of the time interval, demonstrating that the incorporation of PVP-K90 has a markedly positive effect on the compaction resistance of ISV BCP films. Together, FIGs. 5 and 6 show that the surprising compaction resistance of PVP-K90 incorporation in ISV BCP films is particularly significant when PVP-K90 is incorporated at between 0.5% and 5% by weight.

[0020] The favorable characteristics of the novel films disclosed are not limited to compaction resistance. As shown in FIGs. 7A through 7D, the novel films disclosed exhibit a lesser degree of fouling, and demonstrate a high level of reproducibility in fabrication, such that the permeability of the film may be modulated to tune the pore size of the film based on the solvent systems used. FIG. 7A demonstrates the lesser degree of film fouling that occurs in the novel films of the present invention. The protein adsorption of a neat polymer film, ISV29, is compared to an embodiment of the present invention, the ISV29 BCP film, further incorporating PVP-K90 (Film ID L160729JS-2B). In the ISV29 film, IgG antibodies collected at an amount of 261 ug/cm² over the time interval, while only collecting at an amount of 171 ug/cm² over the same time interval on the film incorporating PVP-K90, thus demonstrating approximately 35% less adsorption (and film fouling).

[0021] FIG. 7B demonstrates the high level of selectivity for permeation of particulate matter in the novel films of the present invention. The same fabricated film, an ISV28 BCP film

incorporating 1.3% PVP-K90 was tested for permeability (LMH/bar) for BSA (~7 nm) and thyroglobin (~20 nm). Using that permeability, a rejection percentage for the BSA and thyroglobin were calculated. The film was tested first with BSA, cleaned with 0.1N NaOH, soaked in deionized water for more than 48 hours, and then tested with thyroglobin. As shown in FIG. 7B, the film showed a permeability of 157 LMH/bar for BSA and a rejection percentage of 56%. However, at the larger particle diameter, the film showed a permeability of only 95 LMH/bar for thyroglobin and a rejection percentage of 96%.

[0022] FIG. 7C provides a summary of the reproducibility of the methods and novel BCP films disclosed. PVP-K90 as an additive significantly improves the reproducibility of films cast from ISV polymers, with ISV films with no additive exhibiting pure water permeabilities averaged over five separate films of 218 ± 195 LMH/bar and ISV films with 5% PVP-K90 exhibiting pure water permeabilities averaged over eight films of 451 ± 24 LMH/bar. FIG. 7C thus demonstrates that reproducibility is superior in the BCP films of the present invention compared to those not containing a high molecular weight additive.

[0023] FIG. 7D shows how the novel films incorporating PVP-K90 are affected by changes to the solvent system used during filtration. The neat ISV28 BCP film was compared to a ISV28 BCP film incorporating 5% PVP-K90. The permeability of the films was tested in DOX/THF (70/30) and DOX/Ace (70/30) solvent environments. While the ISV28 BCP film demonstrated a minor change in permeability, increasing from 445 LMH/bar to 537.5 LMH/bar, the ISV28 BCP film incorporating 5% PVP-K90 exhibited a marked decrease in permeability, from 658 LMH/bar to 217 LMH/bar. Because permeability is proportional to pore size, using those permeability measures in conjunction with known data such as that disclosed in FIG. 7B may be

used to tune the pore size of films incorporating PVP-K90 based on the solvent system used.

[0024] In FIG. 8, the films incorporating 5% (by mass) PVP-K90 relative to BCP show a distinctly greater compaction resistance than those without PVP-K90. The ISV43 film without PVP-K90 has an initial flux of approximately 202 LMH/bar. After 270 minutes, its flux decreases markedly, to approximately 135 LMH/bar, a 33% decline. This decline in flux is indicative of significant compaction. By contrast, the ISV43 BCP film incorporating PVP-K90 demonstrates a strong compaction resistance over the measured time interval. The film incorporating PVP-K90 retained a flux of approximately 267 LMH/bar across the 270-minute time interval, a decline of only 6%. The incorporation of PVP-K90 has a markedly positive effect on the compaction resistance of ISV BCP films.

[0025] FIG. 9 is a chart demonstrating a flux increase of films through the inclusion of PVP-K90 in ISV43 BCP films. The average flux of six ISV43 films with no high molecular weight additive was 203 ± 16 LMH/bar. The average flux of six ISV43 films with 5% (by mass) PVP-K90 relative to BCP was 355 ± 59 LMH/bar, an 82% increase compared to the films without PVP-K90.

[0026] Exposure of films/membranes to glycerol solutions to prevent pore collapse (and thus loss of flux) upon drying is well known in the art. The ISV43 films with PVP-K90 retain more of their flux upon drying after exposure to a 1:1 (by mass) glycerol:water, compared to the ISV43 films without PVP-K90. The average flux of two undried ISV43 films without PVP-K90 had an average flux of 199 LMH/bar; the average flux of four ISV43 films without PVP-K90 dried after exposure to 1:1 glycerol:water was 168 LMH/bar, a flux retention of 85%. The

average flux of two undried ISV43 films with PVP-K90 had an average flux of 279 LMH/bar; the average flux of four ISV43 films with PVP-K90 dried after exposure to 1:1 glycerol:water was 268 LMH/bar, a flux retention of 96%. This result shows the inclusion of the hydrophilic high molecular weight polymer increases the flux retention upon drying after exposure to a glycerol solution. This effect may be due to the hydrophilicity of the additive, which could aid the retention of glycerol. This effect, along with the flux increase and compaction resistance, demonstrates the unexpected benefits of the inclusion of the high molecular weight hydrophilic polymer additive in isoporous BCP films.

[0027] In some embodiments, the film is used in a separation or filtration application.

[0028] In some embodiments, the film is packaged as a syringe filter, capsule, cartridge, flat sheet, spiral wound, or hollow fiber.

[0029] In some embodiments, the block copolymer comprises a complex architecture. A complex architecture is defined as: possessing non-linear block arrangement, i.e., architecture with more than one chemistry/configuration/structure in or adjacent to at least one block.

[0030] Although this invention has been described in connection with specific forms and embodiments thereof, it will be appreciated that various modifications other than those discussed above may be resorted to without departing from the spirit or scope of the invention. For example, other high molecular weight additives could include a poly(acrylate), poly(methacrylate), poly(acrylic acid), poly(acrylamide), poly(vinylpyridine), poly(vinyl alcohol), poly(vinylpyrrolidone), naturally-derived polymers (including but not limited to cellulose, chitosan, complex carbohydrates), poly(ether), poly(maleic anhydride), poly(styrene

sulfonate), poly(allylamine hydrochloride), poly(sulfone), poly(ethersulfone), poly(ethylene glycols), or substituted equivalent of the above. The high molecular weight additives could have a molecular weight of at least 50% block copolymer molecular weight. Moreover, other elements may be substituted for those specifically shown and described, certain features may be used independently of other features, and in certain cases, particular locations of elements may be reversed or interposed, all without departing from the spirit or scope of the invention as defined in the appended Claims.