

ASYMMETRIC MEMBRANES FOR USE IN NANOFILTRATION

Field of the Invention

The present invention relates to asymmetric membranes for nanofiltration, particularly nanofiltration of solutes dissolved in organic solvents, and particularly the nanofiltration of solutes dissolved in strongly basic and acidic organic solvent environments.

Background to the Invention

Membrane processes are well known in the art of separation science, and can be applied to a range of separations of species of varying molecular weights in liquid and gas phases (see for example “Membrane Technology and Applications” 2nd Edition, R.W.Baker, John Wiley and Sons Ltd, ISBN 0-470-85445-6).

Nanofiltration is a membrane process utilising membranes whose pores are generally in the range 0.5-5 nm, and which have molecular weight cut-offs in the region of 200-2,000 Daltons. Molecular weight cut-off of a membrane is generally defined as the molecular weight of a molecule that would exhibit a rejection of 90% when subjected to nanofiltration by the membrane. Nanofiltration has been widely applied to filtration of aqueous fluids, but due to a lack of suitable solvent stable membranes has not been widely applied to the separation of solutes in organic solvents. This is despite the fact that organic solvent nanofiltration (OSN) has many potential applications in manufacturing industry including solvent exchange, catalyst recovery and recycling, purifications, and concentrations. US Pat. Nos. 5,174,899 5,215,667; 5,288,818; 5,298,669 and 5,395,979 disclose the separation of organometallic compounds and/or metal carbonyls from their solutions in organic media. UK Patent No. GB2373743 describes the application of OSN to solvent exchange; UK Patent No. GB2369311 describes the application of OSN to recycle of phase transfer agents, and; EP1590361 describes the application of OSN to the separation of synthons during oligonucleotide synthesis. However, there are no reports to date describing the application of OSN in strongly basic or acidic organic solvent

environments.

Polyimides have been used widely to form membranes used in separation processes, particularly gas separations, and also for separations of liquids. US 5,264,166 and US 6,180,008 describe processes for the production of integrally skinned asymmetric polyimide membranes. These membranes are prepared as flat sheet membranes on a supporting substrate using a phase inversion technique, which results in an ultra-thin top layer of the asymmetric membrane characterised by pore sizes below 5 nm in diameter. After formation, the membranes are treated with a non-volatile conditioning agent dissolved in solvent. The conditioning agent maintains membrane properties for nanofiltration of low molecular weight solutes from organic solvents, and allows the membrane to be processed, stored and handled in a dry state. The application of these membranes to solvent recovery from lube oil filtrates are described in US Patent Nos 5,360,530; 5,494,566; and 5,651,877. GB 2,437,519 reports membranes formed by phase inversion of polyimide solutions, followed by crosslinking of the resulting polyimide membrane, and then treatment with a non-volatile conditioning agent dissolved in solvent. However integrally skinned polyimide membranes formed by phase inversion are not stable in all solvents, even when crosslinked according to GB 2,437,519. In particular, they are not stable in strongly basic or acidic organic environments.

Polybenzimidazole membranes have been widely reported for use in gas separations and processing of aqueous fluids. US 3,699,038, US 3,720,607, US 3,841,492, US 4,448,687 and US 4,693,824 report the formation of integrally skinned polybenzimidazole membranes formed by phase inversion from a dope solution. US 3,737,402 reports the formation of polybenzimidazole membranes by phase inversion from a dope solution, followed by annealing at temperatures of at least 135°C to improve the reverse osmosis performance of the membranes. US 4,693,825 reports the production of polybenzimidazole membranes from a dope solution containing benzyl alcohol as an additive.

It has been reported that crosslinking of polybenzimidazole (PBI) membranes improves their chemical resistance. US 4,666,996, US 6,986,844, US 4,734,466, and US 4,020,142

all disclose methods for the crosslinking PBI. However, these methods are known to lead to a dramatic increase in the brittleness of the membranes, making them difficult to manufacture and use.

Summary of the Invention

The present invention provides asymmetric polybenzimidazole nanofiltration membranes which are particularly suitable for use in organic solvents.

In a first aspect, the invention provides a membrane for nanofiltration of a feed stream solution comprising a solvent and dissolved solutes and showing preferential rejection of the solutes at ambient temperature, comprising an integrally skinned asymmetric polybenzimidazole membrane which is impregnated with a conditioning agent.

In a particular embodiment, the polybenzimidazole is crosslinked so as to improve the chemical resistance of the membrane.

In yet a further aspect, the present invention provides the use of a polybenzimidazole membrane as defined herein for the nanofiltration of a feed stream, wherein the feed stream comprises a solvent which is strongly acidic or strongly basic and/or the feed stream comprises one or more strongly acidic or strongly basic compounds present in the solvent.

In yet another aspect, the present invention provides a method of separating dissolved solutes from a feed stream by nanofiltration, said feed stream comprising a solvent which is strongly acidic or strongly basic and/or the feed stream comprises one or more strongly acidic or strongly basic compounds present in the solvent; wherein said method comprises passing the feed through a polybenzimidazole membrane as defined herein.

In another aspect, the invention provides a process for forming an integrally skinned asymmetric polybenzimidazole membrane for solvent nanofiltration, comprising the steps of:

- (a) preparing a polybenzimidazole dope solution comprising:
 - (i) a polybenzimidazole polymer, and (ii) a solvent system for said polybenzimidazole which is water miscible;
- (b) casting a film of said dope solution onto a supporting substrate;
- (c) allowing the dope solution to evaporate over an evaporation period and then immersing the film cast on the substrate into a coagulating medium;
- (d) optionally, treating the resulting asymmetric membrane with a solvent comprising one or more crosslinking agents for polybenzimidazole; and
- (e) treating the asymmetric membrane with a wash bath or baths comprising a conditioning agent.

In a further aspect the present invention provides a membrane obtainable by any one of the methods defined herein.

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In a further aspect the present invention provides a membrane directly obtained by any one of the methods defined herein.

Membranes of the invention can be used for nanofiltration operations in organic solvents. In particular, they can be used for nanofiltration operations in solvents in which the base polybenzimidazole is soluble. This is advantageous with respect to many of the prior art asymmetric solvent nanofiltration membranes, which lose structure and dissolve in typical dope solvents such as dimethylacetamide (DMAc), and exhibit low or no flux in some chlorinated solvents such as dichloromethane. Further, membranes of the present invention can be employed in a feed stream for nanofiltration in which the solvent is strongly acidic or basic, or in which the feed stream contains components which are strongly acidic or basic. This is advantageous with respect to the prior art asymmetric solvent nanofiltration membranes, which lose structure and dissolve under strongly acidic or basic conditions. Membranes of the present invention however are stable in these solvents, offering acceptable flux and rejections. Yet a further advantage of the

membranes of the present invention is that they may exhibit higher fluxes than known membranes when mixtures of water and organic solvent are being processed.

Brief Description of the Drawings

Figure 1 shows the intrinsic viscosity of synthesised polybenzimidazole measured in dimethylacetamide at 30°C.

Figure 2 shows flux for various polybenzimidazole membranes at 30 bar with a nanofiltration feed stream comprising acetone as a solvent and with polystyrene oligomers as solutes.

Figure 3 shows flux and rejection data for various polybenzimidazole membranes prepared from a dope solution containing 17wt% polybenzimidazole at 30 bar with a nanofiltration feed stream comprising acetone as a solvent and with polystyrene oligomers as solutes.

Figures 4(a) and 4(b) show flux and rejection data for a various polybenzimidazole membranes prepared from a dope solution containing 15wt% polybenzimidazole at 30 bar with a nanofiltration feed stream comprising acetone as a solvent and with polystyrene oligomers as solutes.

Figure 5 shows the flux and molecular weight cut off (MWCO) curves of polybenzimidazole membranes prepared from 15 and 17 wt% dope solutions with DMAc as a solvent. Nanofiltration of a feed solution comprising polystyrene oligomers dissolved in THF has been performed at 30 bar and 30°C.

Figure 6 shows the flux and MWCO curves of polybenzimidazole membranes prepared from 15 and 17 wt% dope solutions with a mixture of DMAc:THF at a ratio 4:1 as a solvent. Nanofiltration of a feed solution comprising polystyrene oligomers dissolved in THF has been performed at 30 bar and 30°C (% R on the y-axis means % rejection).

Figure 7 shows the flux and MWCO curves of polybenzimidazole membranes prepared from 15 and 17 wt% dope solutions with DMAc as a solvent. Nanofiltration of a feed solution comprising polystyrene oligomers dissolved in dichloromethane has been performed at 30 bar and 30°C.

Figure 8 shows the flux and MWCO curves of polybenzimidazole membranes prepared from 15 and 17 wt% dope solutions with a mixture of DMAc:THF at a ratio 4:1 as a solvent. Nanofiltration of a feed solution comprising polystyrene oligomers dissolved in dichloromethane has been performed at 30 bar and 30°C (% R on the y-axis means % rejection).

Figure 9 shows the flux and MWCO curves of crosslinked polybenzimidazole membranes prepared from 17 wt% dope solutions with a DMAc as a solvent. Nanofiltration of feed solutions comprising polystyrene oligomers dissolved in THF and DMF has been performed at 30 bar and 30°C (% R on the y-axis means % rejection).

Figure 10 shows the flux versus time for crosslinked polybenzimidazole membranes prepared from 17 wt% dope solutions with a DMAc as a solvent. Nanofiltration of feed solutions comprising polystyrene oligomers dissolved in DMF has been performed at 30 bar and 30°C.

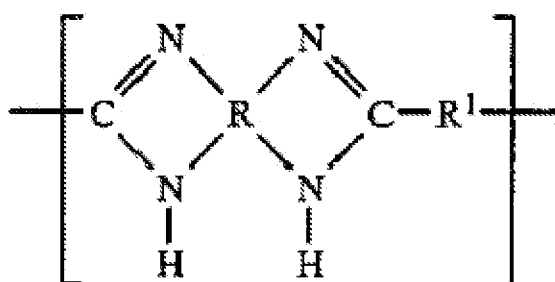
Description of Various Embodiments

Asymmetric membranes will be familiar to one of skill in this art and include an entity composed of a dense ultra-thin top "skin" layer over a thicker porous substructure of the same material, i.e. as being integrally skinned. Typically, the asymmetric membrane is supported on a suitable porous backing or support material.

Polybenzimidazole membranes of the invention can be produced from a number of polybenzimidazole polymer sources. The identities of such polymers are presented in the prior art, including US 3,699,038, US 3,720,607, US 3,737,402, US 3,841,492, US 4,448,687, US 4,693,824 and US 4,693,825. Processes for producing suitable

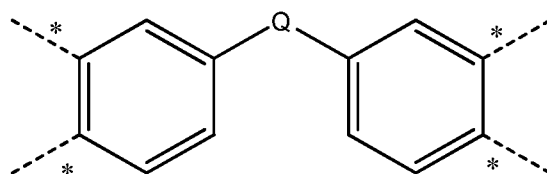
polybenzimidazoles are known to those skilled in the art and include those described in US Pat.2,895,948, US Patent No Re 26,065, US 3,313,783, US 3,509,108, US 3,555,389, US 3,433,772, US 3,408,336, US 3,549,603, US 3,708, 439, US 4,154, 919, 4,312,976, US 5,410,012, US 5,554,715 and in the Journal of Polymer Science, Vol 50, pages 511-539 (1961).

A preferred class of polybenzimidazole polymer useful to prepare the membranes of the invention has the following general repeat structure I shown below:



where R is a tetravalent aromatic nucleus, typically symmetrically substituted, with the nitrogen atoms forming the benzimidazole rings being paired upon adjacent carbon atoms of the aromatic nucleus, and R¹ is a divalent substituent selected from aliphatic, alicyclic and aromatic radicals.

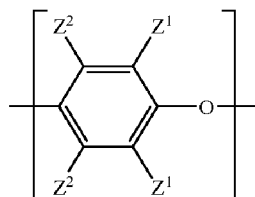
Suitably, the R group in the general repeat structure I shown above has the structure shown below:



wherein Q is a direct bond between the adjacent rings or an alkylene linker and * marks the point of attachment with the N atoms of the fused imidazole rings.

In an embodiment, Q is a direct bond.

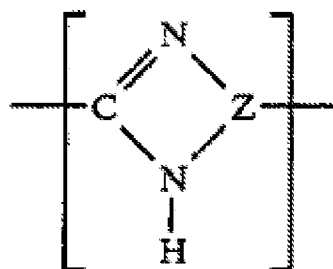
The R^1 substituents in the general repeat structure I can include (1) an aromatic ring, (2) an arylene group, (3) an alkylene group, (4) an arylene-ether group, and (5) a heterocyclic ring. A suitable example of an aromatic ring is phenyl. A suitable example of an arylene group is phenylene. The term “alkylene group” includes (1-20C) alkylene groups. In an embodiment, an alkylene group is a (1-6C) alkylene group. An arylene-ether group is suitably a group of the general formula III



(III)

wherein each Z^1 or Z^2 group is hydrogen or a hydrocarbyl substituent group (suitably a (1-6C)hydrocarbyl group. When R^1 is a heterocyclic ring, it is suitably a saturated, unsaturated or partially saturated monocyclic or bicyclic ring containing 4 to 12 atoms of which 1, 2, 3 or 4 ring atoms are chosen from nitrogen, sulphur or oxygen, which ring may be carbon or nitrogen linked, wherein a $-CH_2-$ group can optionally be replaced by a $-C(O)-$; and wherein a ring nitrogen or sulphur atom is optionally oxidised to form the N-oxide or S-oxide(s). Particular examples of heterocyclic rings include pyridine, pyrazine, furan, quinoline, thiophene, or pyran.

A further preferred class of polybenzimidazole polymers useful to prepare the membranes of the invention has the following general repeat structure II shown below:

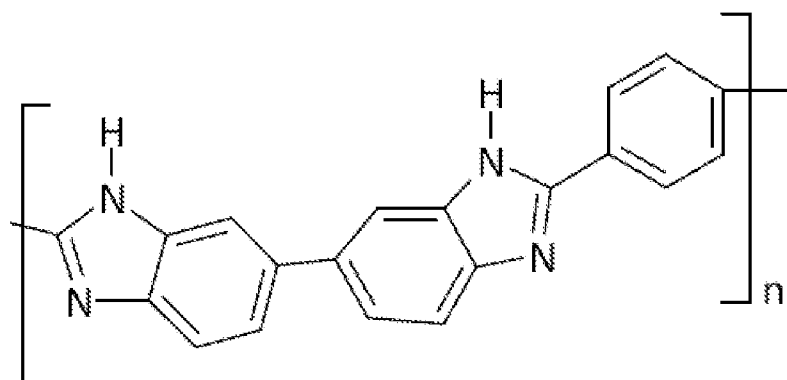


Where Z is an aromatic nucleus having the nitrogen atoms forming the benzimidazole ring paired upon adjacent carbon atoms of the aromatic nucleus. Further

polybenzimidazoles useful in the invention are mixtures of polymers with structure I and polymers with structure II.

Suitably Z is a fused phenyl ring.

A preferred polybenzimidazole for forming the membranes of the invention is poly(2,2'-[m-phenylene])-5,5'-bis-benzimidazole which has the formula shown below:



wherein n is an integer.

Suitably, n is an integer within the range of 10 to 5000, more typically 20 to 3000 and even more typically 50 to 2000.

Membranes of the invention can be made by dissolving the desired polybenzimidazole polymer in a solvent together with optional viscosity enhancers, optional void suppressors, and optionally discrete particles of an immiscible matrix, to give a viscous, polymer dope solution, spreading the solution upon a porous support to form a film, partially evaporating the solvent, and quenching the film in water. This precipitates the polymer and forms an asymmetric membrane by the phase inversion process.

The invention includes a process for forming an integrally skinned asymmetric crosslinked polybenzimidazole solvent nanofiltration membrane, comprising the steps of:

(a) preparing a polybenzimidazole dope solution consisting essentially of:

(i) a polybenzimidazole polymer present in amounts of 5 to 30% by weight of said dope solution,

- (ii) a solvent system for said polybenzimidazole which is water miscible,
 - (iii) optionally, a viscosity enhancer present in amounts less than 5 wt% of said dope solution,
 - (iv) optionally, a void suppressor present in amounts of less than 10% by weight of said dope solution,
 - (v) optionally, a surfactant present in amounts of less than 5% by weight of said dope solution,
 - (vi) optionally, a discrete inorganic or organic matrix suspended in the dope solution at an amount of less than 20% by weight of the said dope solution;
- (b) casting a film of said dope solution onto a supporting substrate;
- (c) allowing the dope solution to evaporate over an evaporation period, and then immersing the film cast on the substrate into a coagulating medium;
- (d) optionally, treating the resulting asymmetric membrane with a solvent comprising one or more crosslinking agents for polybenzimidazole; and;
- (e) treating the asymmetric membrane with a conditioning agent.

Optionally, the membranes may be dried as a further step (f) following step (e).

The polybenzimidazole polymer dope solution may be prepared by dissolving the polybenzimidazole polymer in one or a mixture of organic solvents, including the following water-miscible solvents: N,N-dimethylacetamide, also referred to as DMAc, N-methyl-2-pyrrolidone, hereinafter referred to as NMP, tetrahydrofuran, hereinafter referred to as THF, N,N-dimethylformamide, hereinafter referred to as DMF, dimethylsulfoxide, 1,4 dioxane, gamma.-butyrolactone, water, alcohols, ketones, and formamide.

The weight percent of the polybenzimidazole polymer in solution may range from 5% to 30% in the broadest sense, although a 12% to 20% range is preferable and 14% to 18% range is even more preferred.

Additives such as viscosity enhancers may be present in amounts up to 10% by weight of the said polybenzimidazole polymer dope solution and these include polyvinyl

pyrrolidones, polyethylene glycols and urethanes. Additionally additives such as void suppressors may be used in amounts up to 5% of the weight of said polybenzimidazole polymer dope solution, including maleic acid. Additives such as surfactants, which influence the pore structure, may be used in amounts up to 5% of the weight of said polybenzimidazole polymer dope solution, for example Triton X-100 (available from Sigma-Aldrich UK Ltd. (octylphenoxy-polyethoxyethanol)).

Organic or inorganic matrices in the form of powdered solids may be present at amounts up to 20wt% of the said polymer dope solution. Carbon molecular sieve matrices can be prepared by pyrolysis of any suitable material as described in US Pat.No. 6,585,802. Zeolites as described in US Pat. No. 6,755,900 may also be used as an inorganic matrix. Metal oxides, such as titanium dioxide, zinc oxide and silicon dioxide may be used, for example the materials available from Evonik Degussa AG (Germany) under their Aerosol and AdNano trademarks. Mixed metal oxides such as mixtures of cerium, zirconium, and magnesium may be used. Preferred matrices will be particles less than 1.0 micron in diameter, preferably less than 0.1 microns in diameter, and preferably less than 0.01 microns in diameter. In some cases it may be advantageous to disperse the matrices in a separate solution from the dope solution, preferably an organic solvent solution, and then subsequently add this solution to the dope solution containing the polymer. In a preferred embodiment crystals or nanoparticles of an inorganic matrix, for example zeolites or metal oxides, may be grown to a selected size in a separate solution from the dope solution, and this dispersion solution subsequently added to the dope solution containing the polymer. This separate solution may comprise water or an organic solvent with nanoparticles dispersed in the continuous liquid phase. In yet a further preferred embodiment, the solvent in which the matrix is dispersed may be volatile, and it may be removed from the dope solution prior to membrane casting by evaporation.

Once the polybenzimidazole polymer is dissolved in the solvent system described, and optionally organic or inorganic matrices are added into the dope solution so that the matrices are well dispersed, it is cast onto a suitable porous support or substrate. The support can take the form of an inert porous material which does not hinder the passage of permeate through the membrane and does not react with the membrane material, the

casting solution, the gelation bath solvent, or the solvents which the membrane will be permeating in use. Typical of such inert supports are metal mesh, sintered metal, porous ceramic, sintered glass, paper, porous nondissolved plastic, and woven or non-woven material. Preferably, the support material is a non-woven polymeric material, such as a polyester, polyethylene, polypropylene, polyetherether ketone (PEEK), polyphenylene sulphide (PPS), Ethylene-ChloroTriFluoroEthylene (Halar[®] ECTFE), or carbon fibre material.

Following the casting operation, a portion of the solvent may be evaporated under conditions sufficient to produce a dense, ultra-thin, top "skin" layer on the polybenzimidazole membrane. Typical evaporation conditions adequate for this purpose include exposure to air for a duration of less than 100 seconds, preferably less than 30 seconds. In yet a further preferred embodiment, air is blown over the membrane surface at 15°C to 25 °C for a duration of less than 30 seconds.

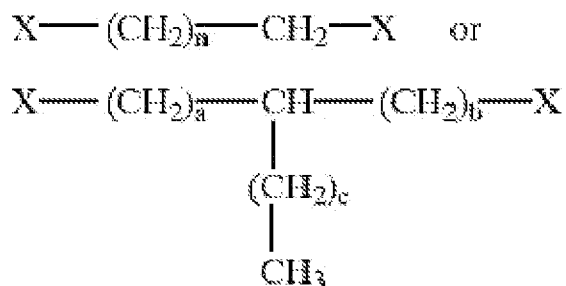
The coagulating or quenching medium may consist of water, alcohol, ketones or mixtures thereof, as well as additives such as surfactants, e.g., Triton® X-100 (available from Sigma-Aldrich UK Ltd (octylphenoxy-polyethoxyethanol)). The conditions for effecting coagulation are well known to those skilled in the art.

The asymmetric polybenzimidazole membranes formed can be washed according to the following techniques. Typically a water-soluble organic compound such as low molecular weight alcohols and ketones including but not limited to methanol, ethanol, isopropanol, acetone, methylethyl ketone or mixtures thereof and blends with water can be used for removing the residual casting solvent (e.g. DMAc) from the membrane. Alternatively the membrane may be washed with water. Removal of the residual casting solvent may require successive wash blends in a sequential solvent exchange process. Both membrane efficiency (solute rejection) and permeate flow rate can be enhanced by the proper solvent exchange process.

Suitable crosslinking agents for treating the polybenzimidazole polymer described in US 4,666,996, US 6,986,844, US 4,734,466, and US 4,020,142, and all are incorporated

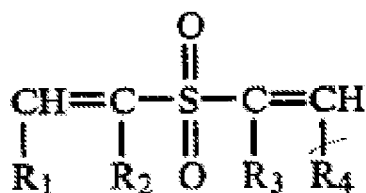
herein. These include multifunctional alkyl halides, divinyl sulfones, and strong polyfunctional organic acids.

Multifunctional alkyl halides include those containing at least two halide substituents, and with the general structure:



where X is Br or Cl, n is 1 to 11, a is 1 to 10, b is 0 to 4, and c is 0 to 6. A preferred class of difunctional alkyl halides comprises straight chain, terminally di-substituted compounds having the structure $\text{X}-(\text{CH}_2)_n-\text{CH}_2-\text{X}$ where X and n are as defined above. A most preferred difunctional alkyl halide is dibromobutane (DBB). The alkyl halide may also contain three or more halide substituents. Exemplary alkyl halides with three or more halide substituents include tribromopropane, trichloropropane, pentaerythrityl tetrabromide, and pentaerythrityl tetrachloride.

Further suitable crosslinking agents include divinylsulfones with the general formula:



wherein each of R_1 - R_4 is the same or different and is selected from H or C_1 - C_3 alkyl.

Strong polyfunctional organic acids suitable for use in the present invention include

carboxylic acids, sulfonic acids, sulphuric acid or phosphoric acid. Representative examples are perfluoroglutaric acid, benzene hexacarboxylic acid, benzene pentacarboxylic acid, 1,2,3,4-benzenetetracarboxylic acid, 1,2,3,5-benzenetetracarboxylic acid, 1,2,4,5-benzenetetracarboxylic acid, 1,3,5-benzenetricarboxylic acid, dibromosuccinic acid, polyacrylic acid, 1,4,5,8-naphthalenetetracarboxylic acid, 2,6-naphthalenedisulfonic acid, aryl-sulfonic acids, aryl-sulfinic acids, aryl-phosphinic acids, aryl-phosphonic acids. Suitable solvents for crosslinking polybenzimidazole using strong polyfunctional organic acids are known to those skilled in the art and include glacial acetic acid.

The crosslinking agent may be dissolved in a solvent to form a crosslinking solution. The solvent can be an organic solvent chosen from ketones, ethers, alcohols, acids or any solvent that dissolves the crosslinking agent. In a preferred embodiment, the solvent in the crosslinking solution will also swell the asymmetric membrane to allow good penetration of the crosslinking agent into the membrane.

The solvent used to dissolve the alkyl halide should not react with the alkyl halide and should not dissolve the uncrosslinked PBI membrane. Preferred solvents include ketones, such as acetone, methyl isobutyl ketone (MIBK), methyl ethyl ketone (MEK), and pentanone; and ethers, such as isopropyl ether and butyl ether.

The solvent used to dissolve the divinylsulfone may optionally also comprise a strong base catalyst, including alcohol metal hydroxides such as sodium and potassium hydroxide, alcohol metal alkoxides having from one to six alkyl carbon atoms such as sodium methoxide, sodium ethoxide, and alkyl aryl amine hydroxides such as particularly preferred benzyl trimethyl ammonium hydroxide. The base catalyst is generally added in amounts ranging from about 5 percent to 150 percent based upon the total weight of the divinylsulfone which is added. The preferred range is about 25 to about 50 percent by weight.

The concentration of crosslinking agent in the crosslinking solution can be adjusted with respect to the quantity of polybenzimidazole asymmetric membrane to be added per

volume of solution, in order to control the extent of crosslinking that takes place, so that the ratio between reactive groups in the crosslinking agent and polybenzimidazole amine hydrogen groups in the membrane treated is in the range 0.01 to 100, preferably in the range 0.01 to 10 and yet more preferably in the range 0.1 to 5.

The time for crosslinking can be varied between 0.01 and 120 hours, more preferably between 0.5 and 60 hours. The temperature of the crosslinking can be varied between 0°C and the boiling point of the solvent, preferably between 0°C and 150°C, yet more preferably between 50°C and 120°C.

The asymmetric membrane is then conditioned by contacting the membrane with a conditioning agent dissolved in a solvent to impregnate the membrane. The conditioning agent is a low volatility organic liquid. The conditioning agent may be chosen from synthetic oils (e.g., polyolefinic oils, silicone oils, polyalphaolefinic oils, polyisobutylene oils, synthetic wax isomerate oils, ester oils and alkyl aromatic oils), mineral oils (including solvent refined oils and hydroprocessed mineral oils and petroleum wax isomerate oils), vegetable fats and oils, higher alcohols (such as decanol, dodecanol, heptadecanol), glycerols, and glycols or derivatives thereof (such as polypropylene glycols, polyethylene glycols, polyalkylene glycols or derivatives thereof). Suitable solvents for dissolving the conditioning agent include alcohols, ketones, aromatics, hydrocarbons, or mixtures thereof. The use of a conditioning agent in accordance with the invention allows a suitable pore structure to be maintained in a dry state, and produces a flat sheet membrane with improved flexibility and handling characteristics. Prior to use, the conditioning agent must be flushed from the membrane, i.e. the conditioning agent of this invention serves the purpose of maintaining the desired membrane structure to preserve the performance characteristics when the membrane is in the dry state, and it is not a component of the functional membrane when used for the purpose of solvent nanofiltration. This contrasts the conditioning agents of the present invention from agents that become part of the functional membrane.

Following treatment with the conditioning agent, the membrane is typically dried in air at ambient conditions to remove residual solvent.

Heat treatment may also be used to increase the membrane rejection of solutes. After the conditioning step, the membrane may be heated to between 150°C and 300°C for between 1 minute and 2 hours.

Membranes of the invention can be used for nanofiltration operations, particularly in organic solvents. By the term “nanofiltration” it is meant a membrane process which will allow the passage of solvents while retarding the passage of larger solute molecules, when a pressure gradient is applied across the membrane. This may be defined in terms of membrane rejection R_i , a common measure known by those skilled in the art and defined as:

$$R_i = \left(1 - \frac{C_{P,i}}{C_{R,i}} \right) \times 100\% \quad (1)$$

where $C_{P,i}$ = concentration of species i in the permeate, permeate being the liquid which has passed through the membrane, and $C_{R,i}$ = concentration of species i in the retentate, retentate being the liquid which has not passed through the membrane. It will be appreciated that a membrane is selectively permeable for a species i if $R_i > 0$. It is well understood by those skilled in the art that nanofiltration is a process in which at least one solute molecule i with a molecular weight in the range 200-2,000 g mol⁻¹ is retained at the surface of the membrane over at least one solvent, so that $R_i > 0$. Typical applied pressures in nanofiltration range from 5 bar to 50 bar.

The term “solvent” will be well understood by the average skilled reader and includes an organic or aqueous liquid with molecular weight less than 300 Daltons. It is understood that the term solvent also includes a mixture of solvents.

By way of non-limiting example, solvents include aromatics, alkanes, ketones, glycols, chlorinated solvents, esters, ethers, amines, nitriles, aldehydes, phenols, amides, carboxylic acids, alcohols, furans, and dipolar aprotic solvents, water, and mixtures thereof.

By way of non-limiting example, specific examples of solvents include toluene, xylene, benzene, styrene, anisole, chlorobenzene, dichlorobenzene, chloroform, dichloromethane, dichloroethane, methyl acetate, ethyl acetate, butyl acetate, methyl ether ketone (MEK), methyl iso butyl ketone (MIBK), acetone, ethylene glycols, ethanol, methanol, propanol, butanol, hexane, cyclohexane, dimethoxyethane, methyl tert butyl ether (MTBE), diethyl ether, adiponitrile, N,N dimethylformamide, dimethylsulfoxide, N,N dimethylacetamide, dioxane, nitromethane, nitrobenzene, pyridine, carbon disulfide, tetrahydrofuran, methyltetrahydrofuran, N-methyl pyrrolidone, acetonitrile, water, and mixtures thereof.

The membranes of the present invention are particularly suited to nanofiltration operations in which the solvent is strongly acidic or basic, or in which the feed stream contains components which are strongly acidic or basic.

The term “strongly acidic” is used herein to refer to a compound which has a pKa of less than 5. The term “strongly basic” is used herein to refer to a compound which has a pKa of greater than 9. The strongly acidic or basic compound may be a solvent and/or a compound dissolved in a solvent.

By way of non-limiting example, specific strongly basic solvents include amines, in particular alkanolamines, alkyl amines, and polyamines, such as alkyl diamines, alkyl triamines, piperidine and derivatives including alkylated piperidine, pyridine and alkyl pyridines including alkyl, dialkyl and trialkyl pyridines, and including and including ethyl amine, ethylenediamine, diethylenetriamine, triethylenetetramine, monomethylamine, dimethylamine, trimethylamine, monoethylamine, diethylamine, triethylamine, isopropylamine, diisopropylamine, mono-n-propylamine, di-n-propylamine, tri-n-propylamine, di-n-butylamine, tri-n-butylamine, cyclohexylamine, dicyclohexylamine, dimethylcyclohexylamine, pentamethyldiethylenetriamine, pentamethyldipropylenetriamine, tetramethyldipropylenetriamine, benzyl dimethylamine, tetramethylbis(aminoethyl)ether, N,N-dimethyl-2(2-aminoethoxy)ethanol, 3-amino propanol, N-ethylmethylamine, 2-ethoxy ethylamine, N,N-diethylhydroxylamine, N-ethyl-N-(1,2-dimethylpropyl)amine, diisopropylmethylamine, 2-ethylhexylamine,

dimethylbutyl amine, 3-methoxypropylamine, 3-(2-ethylhexoxy)-1-propanamine, methylaminopropylamine, dimethylaminopropylamine, methoxypropylamine, 3-ethoxy propylamine, N,N-diisopropylethylamine, dimethylisopropylamine, bis-2-ethylhexylamine, diethylmethylamine, N-methylisopropylamine, dibenzyl hydroxyl amine, monoethanolamine, diethanolamine, triethanolamine, dimethylethanolamine, N-methyldiethanolamine, monomethylethanolamine, 2-(2-aminoethoxy)ethanol, polyoxyalkyleneamines, monopropanol amines, morpholine;, N-methylmorpholine, N-ethylmorpholine, N-methylmorpholine oxide, aminopropylmorpholine, quinoline, and solutions of alcohol metal alkoxides having from one to six alkyl carbon atoms such as sodium methoxide, sodium ethoxide, and alkyl aryl amine hydroxides such as particularly preferred benzyl trimethyl ammonium hydroxide.

By way of non-limiting example, specific strongly acidic solvents include carboxylic acids and their derivatives, incorporating trifluoroacetic acid and acetic acid.

Solvent can be understood to mean solvents, acidic solvents or basic solvents and mixtures thereof.

The term “solute” will be well understood by the average skilled reader and includes an organic molecule present in a liquid solution comprising a solvent and at least one solute molecule such that the weight fraction of the solute in the liquid is less than the weight fraction of the solvent, and where the molecular weight of the solute is at least 20 g mol^{-1} higher than that of the solvent.

The membrane of the present invention can be configured in accordance with any of the designs known to those skilled in the art, such as spiral wound, plate and frame, shell and tube, and derivative designs thereof.

The following Examples illustrate the invention.

In Examples 1-4, a laboratory scale cross-flow nanofiltration unit was used with 4 cross flow cells. Membrane discs, of active area 14 cm^2 , were cut out from flat sheets and

placed into 4 cross flow cells in series. A feed solution consisting of <1 wt % of test solutes was charged into a 5 L feed tank and re-circulated at a flow rate of 1.5 L min⁻¹ using a diaphragm pump (Hydra-Cell, Wanner, USA). Pressure in the cells was generated using a backpressure regulator which was located down-stream of a pressure gauge. The pressure drop across the 4 cells was measured to be less than 0.5 bar. The re-circulating liquid was kept at 30°C by a heat exchanger. During start-up, the conditioning agent was removed by re-circulating pure solvent for an hour without applying any pressure and discarding the initial permeate. During operation, permeate samples were collected from individual sampling ports for each cross-flow cell and the retentate sample was taken from the feed tank. Pre-conditioning of the membranes was necessary to reduce the effects of compaction to achieve steady state fluxes and rejections. The solvent flux N_v was calculated from the equation:

$$N_v = \frac{V}{At} \quad (2)$$

Where V = volume of a liquid sample collected from the permeate stream from a specific cross-flow cell, t = time over which the liquid sample is collected, A= membrane area.

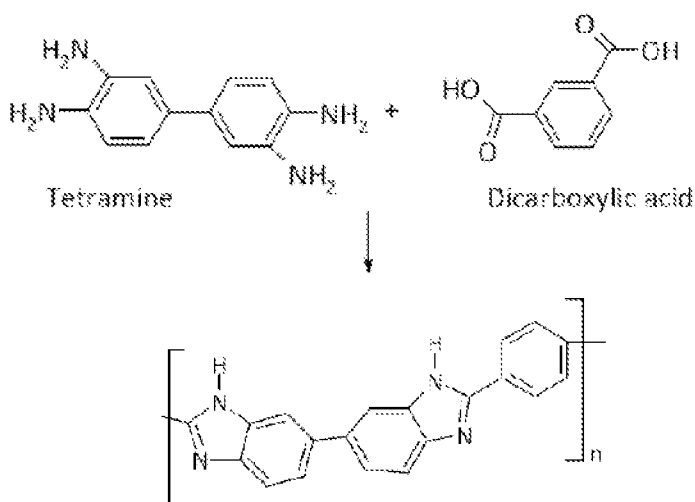
A feed solution consisting of a homologous series of styrene oligomers was used to obtain the MWCO curve during nanofiltration with polystyrene solutes. The styrene oligomer mixture contained a mixture of 1 g of PS580 and PS1050 (purchased from Polymer Labs, UK) and 0.1 g of α -methylstyrene dimer (purchased from Sigma Aldrich, UK). The styrene oligomers were all fully soluble in the tested solvents at this concentration

EXAMPLE 1

Polybenzimidazole polymer was synthesised as follows.

625 gm of Polyphosphoric acid (PPA) was weighted in a 1 liter 3 neck round bottom flask at room temperature followed by the fixing of flask to the overhead stirring assembly equipped with oil bath. The oil was heated to 155 °C, at around 125 °C the addition of tetra-amine was started under the constant flow of dry nitrogen. The addition was very slow in such a way that it lasted for more than 15 minutes. After the completion of

tetraamine addition the temperature was further raised to 170 °C and kept constant for 45 minutes flowed by diacid addition. The reaction was further kept stirring for next 4 hrs at 170 °C. After 4 hrs the reaction temperature was further raised to 210 °C for next 2.5 hrs followed by 230 °C for 2 hrs. At the end of reaction the viscous polymer solution was poured in large excess of water in the form of fine continuous fiber.



The crude PBI fibers were crushed in to fine pieces and further processed with sodium bicarbonate solution to neutralise the phosphoric acid. The fine chopped fibers were crushed in mixture to make fine powder. The fine powder of the polymer was washed further with water followed by acetone and dried in vacuum oven overnight. The dry polymer was further purified by dissolving the polymer in hot dimethylacetamide (DMAc) followed by centrifuge and precipitation in large excess of water. The precipitated polymer was washed with water for 3 times and crushed in to fine powder. The fine powder of the polymer was soaked into acetone to replace water absorbed in the polymer followed by drying in vacuum oven at 120 °C overnight.

The polymer which had been synthesised was characterised as follows:

The synthesised PBI was characterised by GPC for molecular weight determination, as shown below in Table 1:

Table 1

Entry No.	% yield	Mw	Mn	Polydispersity (Mw/Mn)	IV (dl.g-1)**
Batch 1*	93	324889	190578	1.7	1.08

The intrinsic viscosity of the polymer was determined by the dilute solution method using DMAc as a solvent at 30°C, and is shown in Figure 1.

Membranes were fabricated from the polybenzimidazole polymer as follows:

Membranes were formed using the prepared polymer. The dope solution composition was as given in Table 2. The high molecular weight of the starting polymer limited the dope solution concentration to 15 wt.-17wt% % of polymer. The weighed quantity of the DMAc was taken in flask and heated to 80 °C first, once the temperature of the solvent attained desired temperature the purified polymer was added to the flask. The dissolution of the polymer at high temperature resulted in a highly viscous polymer solution without any residue. After the complete dissolution of the polymer the heating was removed to cool the dope solution. Once the dope solution was cooled it was transferred to a 50 ml centrifuge tube to centrifuge the dope solution at 7000 rpm for 30 minutes. The dope solution was allowed to stand overnight to allow disengagement of any air bubbles. The details of membrane casting conditions are also given in Table 2.

Table 2

Entry No.	Polymer (Wt.%)	Solvent used	Volatile non-solvent used	Solvent/non-solvent ratio	Evaporation time (Sec)	Membrane code
1	17	DMAc	-	1/0	60	17PBI-1/0-0-UX-0- Mem.1
2	17	DMAc	THF	4.09/1	60	17PBI-4.09/1-0-UX-0- Mem.1
3	15	DMAc	-	1/0	60	15PBI-1/0-0-UX-0-Mem.2
4	15	DMAc	THF	4.09/1	60	15PBI-4.09/1-0-UX-0- Mem.1

The coding used to designate the membranes were as follows, i.e **15PBI-1/0-0-UX-0** stands for

Polymer Wt.%	Solvent/Non-solvent ratio	Annealing Temp. (°C)	UX-uncrosslinked X- crosslinked	Temperature used crosslinking
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The dope solution was used to cast films 250 µm thick on a polypropylene backing material using an adjustable casting knife on an automatic film applicator (Braive Instruments). Solvent was allowed to evaporate from the surface of the film at controlled

time intervals after which the film was immersed, parallel to the surface, into a precipitation water bath at room temperature. The membranes were subsequently immersed in solvent exchange baths of isopropanol, to remove residual DMAc and water. Following this, the membrane was immersed into a bath of IPA/polyethylene glycol 400 (40/60, v/v %) to prevent drying out. The membranes were then air dried to remove excess solvent.

The membranes were then tested for flux and rejection in crossflow nanofiltration. The data from these tests are shown in Figures 2-8.

EXAMPLE 2

Membranes were formed as in Example 1 above and then crosslinked as follows.

The membranes were immersed into a bath of methyl isobutyl ketone and crosslinker (dibromobutane) for 12 hrs. at 60 °C temperature. The membrane was then removed from the crosslinking bath and washed with IPA to remove any residual crosslinker. Following this, the membrane was immersed into a bath of IPA/polyethylene glycol 400 (40/60, v/v %) to prevent drying out. The membranes were then air dried to remove excess solvent. The dried membrane was fixed to the glass plate with the help of PVC tape and heated in oven at 100 °C for 1 hr.

These crosslinked membranes were then tested for flux and rejection as described above. The data from these tests is shown in Figures 9 and 10.

EXAMPLE 3

Crosslinked polybenzimidazole membranes were prepared as per Example 3 and were immersed into undiluted solutions of monoethanolamine and trifluoroacetic acid and held at 30°C. The membranes were monitored for stability over 4 weeks. No change in the membranes appearance or properties was observed.

EXAMPLE 4

Crosslinked polybenzimidazole membranes were prepared as per Example 2. These were used to test nanofiltration of a solution containing a photoresist material supplied by TOKYO OHKA KOGYO EUROPE B.V catalogue number TFR 970 dissolved at 1 g L^{-1} in a mixture of Butyl diglycol: Monoethanolamine:Water (60:20:20). The membranes showed a positive rejection for the Photoresist (PR) as shown in Table 3 below:

Table 3. Performance evaluation of crosslinked PBI membranes for separation of PR in
BDG:MEA:Water

Entry No	Membrane used	Flux at 4 hrs ($\text{lm}^{-2}\text{h}^{-1}$)	PR rejection (%)	MWCO*
1	PBI-15-Crosslinked (YB)	15 (at day 3)	70 (at day 3)	395
2	PBI-17-Crosslinked (YB)	10.5 (at day 1)	85.2 (at day 1)	236

* MWCO of the membrane based on standard PS rejection analysis after 24 hrs of filtration

CLAIMS

1. A process for forming an integrally skinned asymmetric crosslinked polybenzimidazole membrane for solvent nanofiltration, comprising the steps of:

(a) preparing a polybenzimidazole dope solution comprising:

(i) a polybenzimidazole polymer, and (ii) a solvent system for said polybenzimidazole which is water miscible;

(b) casting a film of said dope solution onto a supporting substrate;

(c) allowing the dope solution to evaporate for an evaporation period, and then immersing the film cast on the substrate into a coagulating medium;

(d) treating the resulting asymmetric membrane with a solvent comprising one or more of a multifunctional alkyl halide, a divinyl sulfone, a strong polyfunctional organic acid;

(e) treating the asymmetric membrane with a conditioning agent.

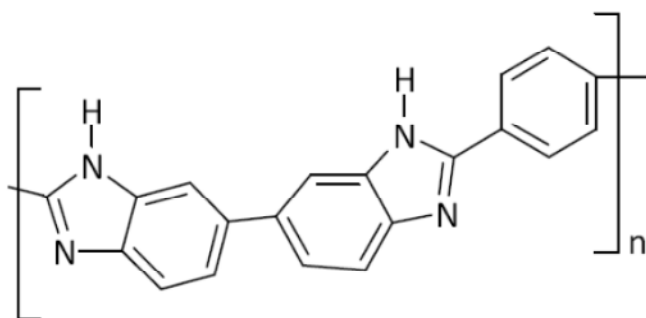
2. A process according to claim 1, wherein the polybenzimidazole polymer is present in amounts of 5 to 30% by weight of said dope solution.

3. A process according to claim 1 or claim 2 wherein the multifunctional alkyl halide is a mono-,di-,tri- functional alkyl halide.

4. A process according to any one of claims 1, 2, or 3, further comprising (f) drying the membrane;

and/or optionally wherein the process further comprises a step of heating the membrane to about 150°C or higher, preferably for up to 3 hours.

5. A process according to any preceding claim, wherein the polybenzimidazole has the following formula:



optionally wherein the polybenzimidazole dope solution comprises solvents chosen from N-methyl-2-pyrrolidone, tetrahydrofuran, N,N-dimethylformamide, dimethylsulfoxide, N,N-dimethylacetamide, 1,4 dioxane, gamma.-butyrolactone, water, alcohols, ketones, and formamide.

6. A process according to any preceding claim, wherein the polybenzimidazole dope solution further comprises a viscosity enhancer in amounts of up to 10% by weight of said dope solution;

optionally wherein the polybenzimidazole dope solution further comprises a viscosity enhancer chosen from polyvinyl pyrrolidones, polyethylene glycols and urethanes added to the polybenzimidazole dope solution at amounts up to 10% by weight of said dope solution.

and/or optionally wherein the polybenzimidazole dope solution further comprises a void suppressor used in amounts up to 5% of the weight of said polybenzimidazole dope solution.

7. A process according to any preceding claim, wherein the polybenzimidazole dope solution further comprises a discrete organic or inorganic matrix dispersed in the polybenzimidazole dope solution at amounts up to 20 % by weight of said dope solution;

optionally wherein the average particle size of the discrete matrix is less than 0.1 micron;

and/or optionally wherein the discrete matrix is first dispersed in a solvent and subsequently added to the dope solution;

optionally wherein the solvent used to disperse the discrete matrix is removed from the polybenzimidazole dope solution by evaporation.

8. A process according to any preceding claim, wherein the crosslinking agent is chosen from multifunctional alkyl halides, divinyl sulfones, strong polyfunctional organic acids;

optionally wherein the crosslinking agent is chosen from alkyl halides (including dibromobutane, tribromopropane, trichloropropane, pentaerythrityl tetrabromide, and pentaerythrityl tetrachloride), divinyl sulfones, perfluoroglutaric acid, benzene hexacarboxylic acid, benzene pentacarboxylic acid, 1,2,3,4-benzenetetracarboxylic acid, 1,2,3,5-benzenetetracarboxylic acid, 1,2,4,5-benzenetetracarboxylic acid, 1,3,5-benzenetricarboxylic acid, dibromosuccinic acid, polyacrylic acid, 1,4,5,8-naphthalenetetracarboxylic acid, 2,6-naphthalenedisulfonic acid, aryl-sulfonic acids, aryl-sulfinic acids, aryl-phosphinic acids, aryl-phosphonic acids;

and/or optionally wherein the crosslinking agent is dissolved in a solvent;

optionally wherein the crosslinking agent is dissolved in a solvent chosen from ketones, ethers, carboxylic acids and alcohols

9. A process according to any preceding claim, wherein the quantity of crosslinking agent used to treat the polybenzimidazole membrane is adjusted so that the reactive groups in the crosslinking agent and polybenzimidazole amine hydrogen groups in the membrane treated is in the range 0.01 to 100;

optionally wherein the quantity of crosslinking agent used to treat the polybenzimidazole membrane is adjusted so that the reactive groups in the crosslinking agent and polybenzimidazole amine hydrogen groups in the membrane treated is in the range 0.1 to 10.

10. A process according to any preceding claim, wherein the time for crosslinking is chosen from between 0.1 and 120 hours;

and/or optionally wherein the temperature of crosslinking solution is held between 20 and 150°C.

11. A process according to any preceding claim, wherein the conditioning agent is a non-volatile liquid;

optionally wherein the conditioning agent is selected from one or more of synthetic oils (including polyolefinic oils, silicone oils, polyalphaolefinic oils, polyisobutylene oils, synthetic wax isomerate oils, ester oils and alkyl aromatic oils), mineral oils (including solvent refined oils and hydroprocessed mineral oils and petroleum wax isomerate oils), vegetable fats and oils, higher alcohols (such as decanol, dodecanol, heptadecanol), glycerols, and glycols (such as polypropylene glycols, polyethylene glycols, polyalkylene glycols).

12. A process according to any preceding claim, wherein the resulting membrane is configured as spiral wound, plate and frame, shell and tube, or derivative designs thereof.

13. A membrane obtainable by the method of any preceding claim.

14. Use of a membrane according to claim 13 for nanofiltration of a feed stream solution comprising an organic solvent and dissolved solutes, wherein the feed stream comprises at least one strongly basic or strongly acidic solvent.

15. A membrane for nanofiltration of a feed stream solution comprising an organic solvent and dissolved solutes and showing preferential rejection of the solutes at ambient temperature, comprising an integrally skinned asymmetric polybenzimidazole cast film membrane, wherein the membrane is impregnated with a conditioning agent that maintains the pore structure of the membrane prior to its use for nanofiltration.