

TITLE**Tubular Membrane, Method For Preparation Thereof, And
Tubular Membrane Module**5 TECHNICAL FIELD

The present invention relates to a tubular membrane, method
for preparation thereof, and tubular membrane module. In
particular, the invention relates to a tubular membrane
having incorporated aquaporin water channels for increased
10 flow rate of water and reduced cross-flow of solutes.

BACKGROUND

Tubular membrane modules comprise a plurality of tubular
membranes with porous walls. Tubular membrane modules work
15 through tangential cross-flow and are generally used to
process difficult feed streams such as those with high
content of dispersed solids or high content of suspended
solids, oil, grease, or fats. One example of use is for
concentrating wastewater that contains high amounts of
20 solids.

Production of tubular membranes is described in GB
1,325,672, in which the mandrel section contains two hollow
concentric tubes. The inner lumen of the central tube is
25 used to pump the casting solution to the end of the mandrel
where a polymer solution is extruded to form the membrane.
The other channel in the concentric tube arrangement is used
for passing a cooling material (for example cooled water) to

control the temperature of the casting solution and reduce the temperature caused by frictional drag of the tube along the mandrel section. In the final step involving the process of tube formation and the casting of a membrane inside this
5 tube, the tube is cut and immersed in water (preferably cold) to gel the liquid polymer film deposited on the inner portion of the nonwoven, thus forming a solid asymmetric membrane.

10 In order to mechanically strengthen tubes, the tubes may be wound on the external surface with one or more reinforcing filaments or tapes which are conveniently at least partially sealed to the nonwoven tube. These filaments or tapes are preferably made of thermoplastic materials. Glass filaments
15 may also be used.

U.S. Pat. Nos. 4,767,645, 4,833,014, and 4,259,183 disclose the process of casting a membrane within a tube, as the tube is continuously formed is through a piston or cylindrical
20 bob which is part of the mandrel upon which the tubular membrane is formed. This piston is at a slight clearance of the formed tube and is concentrically arranged within the nonwoven tube. The end of the piston has an opening through which the membrane casting solution emerges and coats the
25 tube. When the tube moves relative to the piston the membrane is framed between the outer side of the piston and the inner side of the tube.

U.S. pat. No. 6077376 discloses tubular membranes produced
30 by helical winding strips of fibrous material on a mandrel and then passing said strip through a heated section of said

mandrel during the helical winding thereof to flatten and smooth fibers protruding along the cross-sectional width of said strip, whereby a tube with a smooth inner bore along its entire length is formed.

5

WO17088975 discloses a tubular filter membrane element, which is produced by injection molding. The membrane element may be used for microfiltration.

10 Tubular membranes may be provided with two or more layers. Thus, US20140021128 discloses a membrane having two or more layers in which one layer is embedded in the membrane wall and the other layer abuts the membrane wall. CN201529497 discloses a tubular film comprising a transition layer and
15 an active separation membrane. The tubular film is formed by spirally winding a non-woven material and the active separation layer is a casted layer coating the inner side of the transition layer. US2010108599A discloses a membrane which comprises a tubular support, and a polymeric membrane
20 film on the support. The polymeric membrane film comprises three zones cast simultaneously from a single dope. The three zones include an inner zone on the support comprising macro-void pores, an intermediate zone on the inner zone comprising macro-void pores smaller than the macro-void
25 pores of the inner zone, and a skin on the intermediate zone comprising pores of less than 1 micron.

WO2013/043118 discloses thin film composite (TFC) membranes in which aquaporin water channels are incorporated in the
30 active layer of the membrane. In addition, it discloses a method of producing thin film composite membranes and their

uses in filtration processes, such as nanofiltration and osmotic filtration processes. The TFC membranes comprise lipid-AQP/copolymer-AQP vesicles that are incorporated in the TFC active layer. WO2010/146365 describes preparation of TFC-aquaporin-Z (AqpZ) filtration membranes that use an amphiphilic triblock copolymer as a vesicle forming substance for incorporating immobilised AQPs. WO2014/108827 discloses a hollow fiber (HF) module having fibers modified with a thin film composite (TFC) layer comprising aquaporin water channels in which the aquaporin water channels are incorporated in lipid or block copolymeric vesicles before incorporation into the TFC layer.

In the prior art a tubular membrane comprising a TFC layer incorporating a vesicle comprising a transmembrane protein has not been disclosed. Thus, it has hitherto been difficult or not possible to dewater highly viscous liquids or liquids with a high solid or oily content using membrane technologies. The present invention aims at solving this long felt need.

SUMMARY

The present invention relates to a tubular membrane comprising on a surface thereof a Thin Film Composite (TFC) layer incorporating a vesicle comprising an amphiphilic diblock copolymer of the PMOXA_{a-b}-PDMS_{c-d} type as vesicle membrane forming material, a reactive end group functionalised PDMS_{e-f} as an additive, and a transmembrane protein.

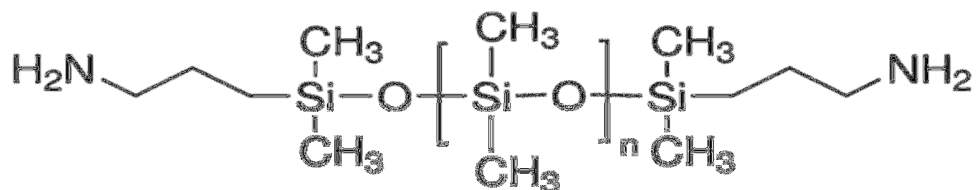
The present invention relates to the use of PMOXA-PDMS

diblock copolymers (poly(2-methyloxazoline)-block-poly(dimethyl siloxane) diblock copolymer), to form self-assembled vesicles with transmembrane proteins, such as aquaporin water channels. The aquaporin vesicles may then be used in the production of separation membranes in which the transmembrane proteins are incorporated or immobilised and active, for example for allowing water molecules to pass through the membrane. For example, for the production of tubular membranes comprising the transmembrane proteins, the vesicles may be added to an aqueous liquid composition comprising an aromatic amine, such as a diamine or triamine, e.g., 1,3-diaminobenzene (MPD) applied to the surface of the support tubular membrane, which, when brought into contact with a solution of an acid halide in an organic solvent, will participate in an interfacial polymerization reaction to form a thin film composite active or selective layer on said support, thus forming a separation membrane wherein said vesicles have become immobilized or incorporated.

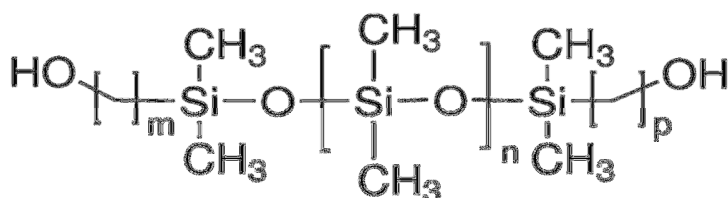
In a certain aspect, the $\text{PMOXA}_a\text{-b-PDMS}_{c\text{-d}}$ of the vesicle is selected from the group consisting of $\text{PMOXA}_{10\text{-}40}\text{-PDMS}_{25\text{-}70}$ and mixtures thereof. To increase the robustness of the vesicle it may be preferred to use a mixture comprises at least a first amphiphilic diblock copolymer of the general formula $\text{PMOXA}_{10\text{-}28}\text{-PDMS}_{25\text{-}70}$ and a second amphiphilic diblock copolymer of the general formula $\text{PMOXA}_{28\text{-}40}\text{-PDMS}_{25\text{-}70}$. The weight proportion between the first and the second amphiphilic diblock copolymer is usually in the range of 0.1:1 to 1:0.1. The concentration of amphiphilic diblock copolymer in the liquid composition is generally in the

range of 0.1 to 50 mg/ml, such as 0.5 to 20 mg/ml, and preferably 1 to 10 mg/ml.

The reactive end group functionalised PDMS_{e-f} (reactive end
 5 group functionalized poly(dimethyl siloxane)) of the vesicle
 is usually present in a concentration of from about 0.05% to
 about 1% v/v of a liquid composition comprising the vesicle.
 The reactive end group functionalised PDMS_{e-f} may be
 functionalized with one, two or more of amine, carboxylic
 10 acid, and/or hydroxy groups. Suitably, the integer e is
 selected in the range of 20 to 40, such as 30 and the
 integer f is selected from the range of 40 to 80, such as
 50. In a certain aspect of the invention the reactive end
 group functionalised PDMS_{e-f} is bis(amino alkyl),
 15 bis(hydroxyalkyl), or bis(carboxylic acid alkyl) terminated
 PDMS_{e-f}, such as poly(dimethyl siloxane), bis(3-aminopropyl)
 or poly(dimethyl siloxane), bis(3-hydroxypropyl).
 Furthermore, the reactive end group functionalised PDMS_{e-f}
 may be selected from the group consisting of H₂N-PDMS₃₀₋₅₀,
 20 HOOC-PDMS₃₀₋₅₀, and HO-PDMS₃₀₋₅₀ and mixtures thereof.
 Examples of said end-functionalised PDMS_{e-f}, where e-f
 represents the range of from 30 to 50, are bis(aminopropyl)
 terminated poly(dimethyl siloxane) having the formula shown
 here below where (CAS Number 106214-84-0, Aldrich product
 25 No. 481246, average Mn ~5,600 or CAS Number 106214-84-0,
 product No. 481696 Aldrich, average Mn ~27,000:



and bis(hydroxyalkyl) terminated poly(dimethyl siloxane) having the formula shown here below where n is approximately 30 to 50 and m and p are both integers between 2 and 5, such as 3 or 4, (CAS Number 156327-07-0, Aldrich product No. 481246, average Mn ~5,600):



- 10 The vesicle of the invention may further contain about 1 % v/v to about 12 % v/v of triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type to increase its integrity. Typically, said vesicle comprises from about 8 % v/v to about 12 % v/v of triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type.
- 15 The triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type is typically selected from PMOXA₁₀₋₂₀-PDMS₂₅₋₇₀-PMOXA₁₀₋₂₀.

The vesicle in the liquid formulation of the invention may further comprise a flux improving agent to increase either the water flux or decrease the reverse salt flux or both. The flux improving agent may be selected among a large group of compounds but is generally preferred as alkylene glycol monoalkyl ether alkylat, beta cyclodextrin, or polyethylene

glycol (15)-hydroxystearate. The flux increasing agent is usually present in an amount of 0.1% to 1% by weight of the liquid composition.

5 While any transmembrane protein may be incorporated in the membrane material disclosed in the present invention, it is generally desired to use transmembrane protein that transport ions (ion channels) or water (aquaporin water channels). Ion channels include chloride channels and metal
10 ion transporters. Chloride channels in addition to the chloride ion also conduct HCO_3^- , I^- , SCN^- , and NO_3^- in some transmembrane proteins. The metal ion transporters include magnesium transporters, potassium ion channels, sodium ion channels, calcium channels, proton channels etc.

15

In a preferred embodiment of the invention, the transmembrane protein is an aquaporin water channel. Aquaporin water channels facilitate the transport of water in or out of a cell. In an industrial membrane, the
20 aquaporin water channels ensure the flow of water by osmosis, while other solutes in the solution are rejected.

The vesicle of the invention may be present in a liquid composition before immobilization in a membrane, such as a
25 TFC layer provided on a support membrane. The liquid composition may comprise a buffer to stabilize the vesicles. Before the transmembrane protein, such as aquaporin, is mixed with the other constituents, suitably the transmembrane protein is solubilized in a detergent. The
30 solubilization of the transmembrane protein in a detergent prevent or ameliorate the tendency of the transmembrane

protein to precipitate in the aqueous solution. Thus, the vesicles in the liquid composition may further comprise a detergent or a surfactant. The detergent may be selected from the group consisting of lauryl dimethylamine N-oxide (LDAO), octyl glucoside (OG), dodecyl maltoside (DDM) or combinations thereof.

Without wishing to be bound by any particular theory, it is believed that the vesicles containing free available reactive groups on the surface will be not only physically incorporated or immobilised in (adsorbed), but, in addition, chemically bound in the TFC layer, because the reactive free end groups, such as amino groups, hydroxyl groups and carboxyl groups, will participate in the interfacial polymerization reaction with the acyl halide, such as trimesoyl chloride (TMC). In this way, it is believed that vesicles will be covalently bound in the TFC layer, leading to relatively higher vesicle loading and thus higher water flux through the membranes. In addition, it is believed that the covalent coupling of vesicles in the TFC layer results in higher stability and/or longevity of the AQPs and AQP-vesicles when incorporated in the selective membrane layer.

The vesicles may be prepared in a liquid composition incorporating a transmembrane protein comprising the step of stirring a mixture of a solution of an amphiphilic diblock copolymer of the $\text{PMOXA}_{a-b}\text{-PDMS}_{c-d}$ type, a reactive end group functionalised PDMS_{e-f} , and a transmembrane protein. To obtain the best result, the stirring is continued for 12-16 hours.

The present invention provides novel tubular membranes having AQPs incorporated in the active layer to facilitate water transport, where the AQPs are incorporated in amphiphilic polymeric bilayer membrane vesicles. The tubular
5 membranes may be used as both forward osmosis membranes and reverse osmosis membranes.

The porous support tubular membrane may be formed by a number of materials. The specific choice of material is not
10 essential as long as the support membrane is able sufficiently to support the TFC layer and to withstand decomposition during operation condition, i.e. able to withstand the pressure and/or the chemical environment on either side of the membrane. In certain aspects provided
15 herein the support tubular membrane is made of porous polymeric material such as polyethylene (PE), high density polyethylene (HDPE), Ultra-high-molecular-weight polyethylene (UHMWPE), polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride
20 (PVDF), ethylvinylacetate (EVA), polycarbonate, nylon 6, thermoplastic urethane (TPU), polyethersulfone (PES), polysulfone (PS), or combinations thereof. Support tubular membranes are commercially available from e.g. Berghof Membranes as 5mm or 8mm membrane modules (Hyperflux I5 or
25 I8) prepared of PES or PVDF. Other examples are Seprolyn® Tubular modules from Microdyn Nadir, Tubular Ultrafiltration Membranes from Spintek®, and the Compact series from Pentair®.

30 Tubular membranes offer several advantages. The relatively large inside diameters allows for feed flows with high

solids content and large particles. Tubular membranes also enable good control over fouling by reducing concentration polarization. High flow velocities do the cleaning job at a lower pressure drop than other membrane types.

5

In some embodiments of the support tubular membrane the molecular weight cut-off value is at least 200 D, such as at least 400 D, such as at least 1000 D, such as least 5 kD, such as at least 10 kD, such as at least 25 kD. In some
10 embodiments of the support tubular membrane the molecular weight cut-off value is not higher than 500 kD, such as not higher than 200 kD, such as not higher than 100 kD, such as not higher than 75kD. In a preferred aspect of the invention, the cut-off value of the support tubular membrane
15 is 50 kD.

The support tubular membrane may be symmetrical or asymmetrical. In case the porous support membrane is asymmetrical, the TFC layer is suitably formed on the skin
20 layer face. The support tubular membrane may further be supported by a woven or non-woven mechanical support in some embodiments to increase the mechanical construction and reduce the risk of fractures during operation.

25 The support tubular membrane may e.g. be of the micro filter (MF) or ultra filter (UF) type. When coated with the TFC layer of the invention, the membrane will allow primarily water to pass through and reject solutes in the feed.

30 In some embodiments, the support tubular membrane has an internal diameter of about 2 mm to about 20 mm, about 3 mm

to about 15 mm, or about 4 mm to about 12 mm. In some
embodiments, each of the tubular porous membranes has an
internal diameter of $2\text{ mm} \pm \frac{1}{2}\text{ mm}$, $3\text{ mm} \pm \frac{1}{2}\text{ mm}$, $4\text{ mm} \pm \frac{1}{2}\text{ mm}$, 5
5 $\text{mm} \pm \frac{1}{2}\text{ mm}$, $6\text{ mm} \pm \frac{1}{2}\text{ mm}$, $7\text{ mm} \pm \frac{1}{2}\text{ mm}$, $8\text{ mm} \pm \frac{1}{2}\text{ mm}$, $9\text{ mm} \pm \frac{1}{2}$
11 $\text{mm} \pm \frac{1}{2}\text{ mm}$, $12\text{ mm} \pm \frac{1}{2}\text{ mm}$, $13\text{ mm} \pm \frac{1}{2}\text{ mm}$, $14\text{ mm} \pm \frac{1}{2}\text{ mm}$, 15
 $\pm \frac{1}{2}\text{ mm}$, $16\text{ mm} \pm \frac{1}{2}\text{ mm}$, $17\text{ mm} \pm \frac{1}{2}\text{ mm}$, $18\text{ mm} \pm \frac{1}{2}\text{ mm}$, $19\text{ mm} \pm \frac{1}{2}$
mm or $20\text{ mm} \pm \frac{1}{2}\text{ mm}$.

10 The thickness of the support tubular membrane is usually
above $50\mu\text{m}$, such as above $100\mu\text{m}$ to ensure physical integrity
during the preparation and the operation of the separation
process. Usually, the thickness is not above 2mm, such as
not above 1mm to prevent possible issues with concentration
15 polarization in support membrane pores. The thickness of the
TFC layer is usually about 50nm to 500nm.

In certain embodiments of the tubular membrane module, the
plurality of tubular porous support membranes are enclosed
20 within a shell. In some embodiments the shell has a diameter
of about 20 mm to about 300 mm or about 30 mm to about 200
mm. In some embodiments, the shell has a diameter of $50\text{ mm} \pm$
 5 mm or $90\text{ mm} \pm 5\text{ mm}$. The shell usually have a diameter up
to 10 cm for a pilot scale unit and up to 30 cm for a
25 commercial unit.

The TFC layer may be provided on the inner side, the outer
side, or both of the tubular support membrane. In a certain
embodiment, the TFC layer is provided on the inside of the
30 tubular membrane to allow the feed solution or suspension to
pass through the lumen of the tubular membrane.

In a certain aspect the invention also relates to a tubular membrane module comprising a bundle of tubular membranes as disclosed above. The bundle of tubular membranes is generally surrounded by a shell, wherein an inlet for passing a first solution is connected to the lumen of the tubes in one end of the bundle and an outlet is connected to the lumen in the other end of the bundle, and an inlet is provided in the shell for passing a second solution outside the bundle of tubular membranes to an outlet provided at another location of the shell.

The invention also relates to the preparation of a tubular membrane. The method comprises the steps of providing a mixture of vesicles in an aqueous liquid composition and a di-amine or tri-amine compound, said vesicles comprising an amphiphilic diblock copolymer of the $\text{PMOXA}_{a-b}\text{-PDMS}_{c-d}$ type as vesicle membrane forming material, a reactive end group functionalised PDMS_{e-f} as an additive, and a transmembrane protein, covering a surface of a porous tubular membrane support with the mixture, applying a hydrophobic solution comprising an acyl halide compound, and allowing the di-amine or tri-amine compound of the aqueous solution and the acyl halide compound of the hydrophobic solution to perform an interfacial polymerization reaction to form the Thin Film Composite (TFC) layer.

In a certain embodiment of the invention, the hydrophobic solution further comprises a TFC layer modifying agent in an amount of 0.1 to 10% by volume. The TFC layer modifying agent has the purpose to increase the water flow and/or the

rejection of solutes. In a suitable embodiment, the TFC layer modifying agent is a C3 to C8 carbonyl compound or mesitylene. As an example, the TFC layer modifying agent is selected among the group consisting of diethylene ketone, 2-
 5 pentanone, 5-pentanone, cyclopentanone and/or mesitylene.

The di-amine compound may be selected among a range of compounds including for example, phenylenediamines, such as *m*-phenylenediamine, *p*-phenylenediamine, 2,5-dichloro-*p*-phenylenediamine, 2,5-dibromo-*p*-phenylenediamine, 2,4,6-trichloro-*m*-phenylenediamine, 2,4,6-tribromo-*m*-phenylene-
 10 diamine, etc; diaminobiphenyls, such as 2,2'-diaminobiphenyl, 4,4'-diaminobiphenyl, 3,3'-dichloro-4,4'-diaminobiphenyl, 3,5,3',5'-tetrabromo-4,4'-diaminobiphenyl, etc;
 15 diaminodiphenylmethanes, such as 4,4'-diaminodiphenylmethane, 3,3'-diaminodiphenylmethane, 2,2'-diaminodiphenylmethane, 3,3'-dichloro-4,4'-diaminodiphenylmethane, 2,2'-dichloro-4,4'-diaminodiphenylmethane, 3,5,3',5'-tetrachloro-4,4'-diaminodiphenylmethane, 3,5,3',5'-tetrabromo-4,4'-
 20 diaminodiphenylmethane, etc.; diaminobibenzyls, such as 4,4'-diaminobibenzyl, 3,5,3',5'-tetrabromo-4,4'-diaminobibenzyl, etc.; 2,2-bisaminophenylpropanes, such as 2,2-bis(4'-aminophenyl)propane, 2,2-bis(3',5'-dichloro-4'-aminophenyl)propane, 2,2-bis(3',5'-dibromo-4'-aminophenyl)-
 25 propane, etc.; diaminodiphenylsulfones, such as 4,4'-diaminodiphenylsulfone, 3,5,3',5'-tetrachloro-4,4'-diaminodiphenylsulfone, 3,5,3',5'-tetrabromo-4,4'-diaminodiphenylsulfone, etc.; diaminobenzophenones, such as 4,4'-diaminobenzophenone, 2,2'-diaminobenzophenone, 3,3'-dichloro-4,4'-
 30 diaminobenzophenone, 3,5,3',5'-tetrabromo-4,4'-diaminobenzophenone, 3,5,3',5'-tetrachloro-4,4'-diaminobenzo-

phenone, etc.; diaminodiphenyl ethers, such as 3,3'-diaminodiphenyl ether, 4,4'-diaminodiphenyl ether, 3,3'-dibromo-4,4'-diaminodiphenyl ether, etc. piperazine, N-phenylbenzene-1,3 diamine, melanine, and mixtures of such
5 compounds. In a preferred aspect the diamine is selected as *m*-phenylenediamine (MPD) also known as 1,3-diaminobenzene.

The tri-amine compound may be selected among a range of compounds including for example, diethylene triamine,
10 dipropylene triamine, phenylenetriamine, bis(hexamethylene)triamine, bis(hexamethylene)triamine, bis(3-aminopropyl)amine, hexamethylenediamine, N-tallowalkyl dipropylene, 1,3,5-triazine-2,4,6-triamine, and mixtures of these compounds.

15

The acyl halide compound usually has two or three acyl halide groups available for reaction with the di- or triamine compound. Suitable examples of diacyl halide or triacyl halide compounds include trimesoyl chloride (TMC),
20 trimesoyl bromide, isophthaloyl chloride (IPC), isophthaloyl bromide, terephthaloyl chloride (TPC), terephthaloyl bromide, adipoyl chloride, cyanuric chloride and mixtures of these compounds.

25 The amine groups of the di-amine or tri-amine compound and the reactive end group of PDMS_{e-f} will compete with the acid chloride groups of the acyl halide compound for reaction. Generally, the proportion by weight of the di-amine or tri-amine compound to acyl halide compound is from 0:1 to 30:1.
30 When a high density of vesicles on the surface is required the amount of di-amine or tri-amine groups is usually in the

lower part of the range, i.e. 0:1 to 1:1, such as between 0:1 to 0.5:1. In other embodiments of the invention, a more rigid TFC layer is desired and a selection of the reactants are in the higher end of the range, such as 1:1 to 30:1, preferably 1:1 to 5:1.

The method of the invention may make use of a hydrophobic solution comprising the acid halide further comprises a TFC layer modifying agent in an amount of 0.1 to 10% by volume. Suitably, the TFC layer modifying agent is a C3 to C8 carbonyl compound or mesitylene. In a preferred aspect the TFC layer modifying agent is selected among the group consisting of diethylene ketone, 2-pentanone, 5-pentanone, and cyclopentanone.

In a suitable embodiment of the method according to the invention the inner surface of the porous tubular membrane support is covered with the mixture to provide the TFC layer on the lumen side.

The method of the invention is usually implemented with the reactive end group functionalised PDMS_{e-f} being present in a concentration of from about 0.05% to about 1% v/v of the aqueous liquid composition comprising the vesicle. The PMOXA_{a-b}-PDMS_{c-d} is suitably selected from the group consisting of PMOXA₁₀₋₄₀-PDMS₂₅₋₇₀ and mixtures thereof. In some embodiments the mixture comprises at least a first amphiphilic diblock copolymer of the general formula PMOXA₁₀₋₂₈-PDMS₂₅₋₇₀ and a second amphiphilic diblock copolymer of the general formula PMOXA₂₈₋₄₀-PDMS₂₅₋₇₀. The weight proportion between the first and the second

amphiphilic diblock copolymer may be in the range of 0.1:1 to 1:0.1. The concentration of amphiphilic diblock copolymer in the liquid composition may be in the range of 0.1 to 50 mg/ml, such as 0.5 to 20 mg/ml, and preferably 1 to 10
 5 mg/ml.

The method of the invention is usually implemented with the reactive end group functionalised PDMS_{e-f} being functionalized with one or more of amine, carboxylic acid, and/or hydroxy groups, and wherein e is 30 and f is 50. Thus, the reactive end group functionalised PDMS_{e-f} is suitably selected from the group consisting of H₂N-PDMS₃₀₋₅₀, HOOC-PDMS₃₀₋₅₀, and HO-PDMS₃₀₋₅₀ and mixtures thereof. In a certain embodiment, the reactive end group functionalised
 10 PDMS_{e-f} is poly(dimethylsiloxane), bis(3-aminopropyl).

The method may be implemented with the liquid composition comprising the vesicle further comprising from about 1 % v/v to about 12 % v/v of triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type. Suitably, said triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type is selected from PMOXA₁₀₋₂₀-PDMS₂₅₋₇₀-PMOXA₁₀₋₂₀.
 20

The method may be applied using the liquid composition comprising the vesicle further comprises a flux improving agent. Suitably, the flux improving agent is an alkylene glycol monoalkyl ether alkylat, beta cyclodextrin, or polyethylene glycol (15)-hydroxystearate. The flux
 25

increasing agent may suitably be present in an amount of 0.1% to 1% by weight of the liquid composition.

5 The method further provides an embodiment in which the vesicle prior to incorporation in the TFC layer is present in a liquid composition comprising a buffer. In addition, the liquid composition may further comprise a detergent or a surfactant. The detergent may e.g. be selected from the group consisting of lauryldimethylamine N-oxide (LDAO),
10 octyl glucoside (OG), dodecyl maltoside (DDM) or combinations thereof.

Suitably, the porous tubular membrane support comprises a bundle of tubular membranes. The bundle may be surrounded by
15 a shell prior to the covering of a surface of the tubular membrane support with the mixture of vesicles in an aqueous liquid composition and a di-amine or tri-amine compound. After interfacial reaction of the di-amine or tri-amine compound, a tubular membrane module is provided having
20 tubular membranes modified with a selective layer comprising the vesicles of the present invention. Conveniently, the selective layer comprises a thin film composite (TFC) layer on the inside surface of the tubular membranes, although in certain embodiments, the TFC layer may be formed on the
25 outside of the fibers.

In a related aspect, the present invention provides a method of preparing a tubular membrane module comprising a bundle of tubular membranes surrounded by a protective shell,
30 wherein the tubular membranes are modified with a selective layer comprising the vesicles comprising an amphiphilic

diblock copolymer of the $\text{PMOXA}_{a-b}\text{-PDMS}_{c-d}$ type as vesicle membrane forming material, a reactive end group functionalised PDMS_{e-f} as an additive, and a transmembrane protein. The method comprises contacting the lumen of the tubular membranes with a mixture of the vesicles in an aqueous liquid composition and a di-amine or tri-amine compound, for a time sufficient for absorbing the mixture in the pores of the support tubular membranes. Optionally, the absorption may be assisted by a minor pressure difference, i.e. the pressure on the shell side is smaller than on the lumen side of the tubular membranes. The absorption may be allowed to proceed until the pores of the support tubular membranes have been fully saturated with the mixture. After the absorption step, excess mixture is removed by draining.

The aqueous mixture present in the pores may be dried subsequent to the draining. Usually, the drying is performed with dried compressed air with low humidity (less than 10% humidity). The drying is usually initiated by directing the dried compressed air to the lumen of the tubular membrane at a relatively high flow rate for a relative short period of time to entrain possible droplets, followed by a more steady drying by directing the dried compressed air to the lumen of the tubular membrane at a relatively lower flow rate to a relatively longer time to evaporate the water in the absorbed mixture. Finally, the dried compressed air is directed to the shell side module to evaporate the water in the mixture from the exterior side of the tubular membrane.

In a subsequent step the inner surface of the tubular membrane module is reacted with an acyl halide in an

interfacial polymerization reaction to form the selective layer comprising the vesicles. The acyl halide present in an organic solvent is pumped through the lumen of the tubular membrane for a time sufficient for the interfacial reaction to occur. Subsequently, excess organic solution is drained off and dried using dry compressed air. As a final step, the module is rinsed with water on both lumen and shell side.

The module may be subjected to a post-treatment to improve the performance. In a certain post-treatment step, the lumen of the tubular membrane is subjected to a citric acid solution at a concentration of 5% to 20%, preferably 10% to 15%. The temperature may be elevated to a temperature above 50°C. Preferably, the temperature of the post-treatment does not exceed 90°C.

In tubular membranes modules, the protective shell typically has an elongate form, with a bundle of tubes longitudinally arranged inside the protective shell.

20

The tubular membrane or the tubular membrane module as disclosed herein may be used for the concentration of a product solution by forward osmosis. In a forward osmosis configuration, the TFC layer is provided on the inside of the tubular membrane and the feed solution is directed to the lumen thereof. A draw solution is passed on the shell side to provide for an osmotic pressure drawing the water out of the feed solution and into the draw solution.

Examples**Example 1:****Preparation of Aquaporin Stock Solution**5 ***Recombinant Production of Aquaporin Z***

All types and variants of aquaporin water channel proteins, including aquaglyceroporins, may be used in the manufacture of membranes and compositions according to this invention, cf. methods described in WO2010/146365. Representative
10 examples include the spinach aquaporin SoPIP2;1 protein and the bacterial aquaporin-Z from *E. coli*.

Functional aquaporin-Z was overproduced in *E. coli* strain BL21(DE3) bacterial cultures as His-tagged protein with a
15 tobacco etch virus cleavage site. The fusion protein has 264 amino acid and a Mw of 27234 Da. Genomic DNA from *E. coli* DH5 was used as a source for amplifying the AqpZ gene. The AqpZ gene was amplified using gene specific primers with the addition of a tobacco etch virus cleavage site (TEV);
20 ENLYFQSN at the N-terminus of AqpZ. The amplified AqpZ was digested with the enzyme NdeI and BamHI and then ligated to the similarly digested 6-His tagged expression pET28b vector DNA. The positive clones were verified by PCR-screening. The authenticity of the constructs was then confirmed by DNA
25 sequencing.

The *E. coli* strain BL21(DE3) was used for expression of the protein. Luria Broth cultures containing 50 µg/ml kanamycin were incubated for 13-16 hours at 37C, diluted 100-fold into
30 fresh LB broth and propagated to a density of about 1.2-1.5 (OD at 600 nm). Expression of recombinant protein was

induced by addition of 1 mM IPTG for 3 hour at 35°C before centrifugation. Harvested cells were resuspended in ice-cold binding buffer (20 mM Tris pH 8.0, 50 mM NaCl, 2 mM β -mercaptoethanol, 10% glycerol) in the presence of 0.4 mg/ml lysozyme, 50 units Bensonase and 3% n-octyl β -D-Glucopyranoside. The sample was subjected to five times lysis cycles in a microfluidizer at 12,000 Pa. Insoluble material was pelleted by 30 minutes centrifugation at 40,000 x g. The supernatant was passed through a Q-Sepharose fast flow column (Amersham Pharmacia), and the flow through was collected. The flow through fraction was topped up with NaCl to 300 mM before loaded onto a pre-equilibrated Ni-NTA column. The column was washed with 100 column volumes of a wash buffer (20 mM Tris pH 8.0, 300 mM NaCl, 25 mM imidazole, 2 mM β -mercaptoethanol, 10% glycerol) to remove non-specifically bound material. Ni-NTA agarose bound material was eluted with five bed volumes of elution buffer (20 mM Tris pH 8.0, 300 mM NaCl, 300 mM imidazole, 2 mM β -mercaptoethanol, 10% 15 glycerol, containing 30 mM n-octyl β -D-Glucopyranoside). AqpZ was further purified with anion exchange chromatography; monoQ column (GE healthcare). The sample mixture was diluted and concentrated to bring the salt and imidazole concentration to approximately 10 mM with Amicon concentrator, membrane cut off 10,000 Da before loading to MonoQ column. The buffer used during anion exchange chromatography were (A) 20 mM Tris pH 8.0, 30 mM OG, 10% glycerol and (B) 20 mM 20 Tris pH 8.0, 1 M NaCl, 30 mM OG, 10% glycerol. The eluted peak fractions containing AqpZ from the ion exchange column was pooled. The purified AqpZ extract was kept frozen at -80°C.

Procedure for Purification of Aquaporin Protein

A batch of frozen extract of aquaporin protein, such as aquaporin Z, AQPZ, e.g. from an *E. coli* fermentation, was obtained and treated as follows for use in the experiments
5 to produce and characterise membranes comprising protein-PAI nanostructures of the present invention.

One day before the purification experiment, the AQP extract (stored at -80 °C freezer) was thawed on ice or in a 4°C
10 refrigerator. Portions of the buffers and ddH₂O were readied at 4°C. The AQP extract was stirred in an adequate chilled beaker on ice bath by a magnetic stick to dissolve any precipitate. 1.5 volumes of pre-chilled LDAO-free AQP binding buffer was gradually added into 1 volume of the
15 solubilized extract (using a further 0.5 volume buffer for rinsing the extract tubes and filtration cup), mixed well and filtered through a sterile 0.45 µM vacuum filter cup. Vacuum was applied to the filter cup to avoid excess foaming and the filtrate was placed on ice to use within 2 hours.

20

A Histrap column was equilibrated with sterile water followed by AQP Binding buffer at RT. The flow rate was set at 1ml/min (for 1 mL prepacked column) or 2.5 ml/min (for 5 ml prepacked column and self-packed column). The 3 times
25 diluted extract (on ice water bath) was loaded onto the Histrap column using ÄKTA program. The flow rate was set at 1 ml/min (for 1 mL prepacked column) or 2.5 ml/min (for 5 mL prepacked column and self-packed column). The loading volume was less than 30 ml/ml resin. The extract flow-
30 through on ice-water bath was collected and stored at 4°C for further use. The column was washed with 10 CV (column

volume) ice cold AQP binding buffer. The flow rate was set at 2.5 ml/min (for 5 ml preppacked column and self-packed column) or set at 1 ml/min for 1 ml preppacked column. The AQP protein was eluted with ice cold AQP elution buffer (10
5 column volume) at flow rate 2.5 ml/min using ÄKTA program. The fraction volume was set to 10 ml and collection started in 15 mL PP tubes after 0.5 - 1CV.

Eluted fractions were capped and stored on ice or 4 °C. The
10 AQP purity and conformation was examined by denaturing and native PAGE analysis respectively. Protein concentration was measured by Nanodrop. The extract flow-through may be processed a second and a third time as needed to produce an AQP composition of suitable quality.

15 When AQP quality analyses are passed, the protein concentration may be adjusted to 5 mg/ml by adding ice cold imidazole-free AQP binding buffer containing 2% LDAO. Finally the AQP was sterilized by filtration through 0.45 µm sterilized cup and stored at 4°C in refrigerator for use
20 within a month or else stored at -80°C in a freezer.

Example 2

Preparation of water filtration membrane using vesicles.

Main vesicle forming materials:

25 Poly(2-methyloxazoline)-block-poly(dimethylsiloxane) diblock copolymer (PDMS₆₅PMOXA₂₄ - DB1) purchased as a viscous white liquid used as received.

Poly(2-methyloxazoline)-block-poly(dimethylsiloxane) diblock copolymer (PDMS₆₅PMOXA₃₂ - DB2) purchased as a viscous white
30 liquid used as received.

Additives:

Poly(2-methyloxazoline)-block-poly(dimethylsiloxane)-block-poly-(2-methyloxazoline) triblock copolymer PMOXA₁₂PDMS₆₅PMOXA₁₂ (TB) purchased as a viscous white liquid used as received as a hydrophobicity agent, and bis(3-aminopropyl) terminated poly(dimethylsiloxane) having a molecular weight of 2500 Da purchased as a liquid from Sigma Aldrich used as received as a cross-linking agent.

Phosphate buffer 10 mM (PBS) (pH 7.2, 136 mM NaCl, 2.6 mM KCl) was prepared by dissolving 8 g NaCl, 0.2 g KCl, 1.44 g Na₂HPO₄ and 0.24 g of KH₂PO₄ in 800 mL MiliQ purified H₂O, adjusting the pH to 7.2 with HCl and completing the volume to 1 L. Further detergent additives were N,N-Dimethyldodecylamine N-oxide BioXtra (Lauryldimethylamine N-oxide - LDAO) was purchased from Carbosynth, and Kolliphor® HS 15 (polyethylene glycol (15)-hydroxystearate (KHS)). AqpZ 5 mg/mL in 0.2% LDAO in the stock (purified as described above).

Preparation method of the aqueous solution (MPD solution):

1. Prepare a 0.5% by weight KHS solution by dissolving 5 g KHS in 1 l PBS.
2. Prepare a 0.05% by weight LDAO solution in PBS by dissolving 0.05 g LDAO in 100 mL PBS.
3. In the preparation vessel, weigh DB1 to reach a concentration of 0.5 g DB1/L of prepared formulation.
4. In the same preparation vessel weigh DB2 to reach a concentration on 0.5 g DB2/L of prepared formulation. (1:1 weight ratio DB1 and DB2).
5. In the same preparation vessel, add TB hydrophobicity additive to reach a concentration of 0.12 g TB/L of

prepared formulation.

6. Add LDAO 0.05% prepared in step 2 in the proportion 100 mL/L of prepared formulation

7. Add the bis(3-aminopropyl) terminated
5 poly(dimethylsiloxane) to reach a final concentration of 0.1%.

8. Add AqpZ stock solution to reach a concentration of 5 mg/L of prepared formulation and a 1/400 protein:polymer ratio.

10 9. Add KHS 0.5% solution prepared in step 1 in accordance with table 2 below, to reach the desired volume of prepared formulation subtracting the volumes of LDAO, bis(3-aminopropyl) terminated poly(dimethylsiloxane) and AQPZ added in step 6 and 8.

15 10. Stir the mixture from step 9 overnight at 170 rotations per minute (not more than 20 hours) at room temperature to achieve the formulation.

11. Next morning take the prepared Ex. 2 formulation obtained in the sequence of steps 1 to 10 and filter it
20 through 200 nm pore size filters to sterilize it, put it in a closed sealed bottle and keep it at room temperature for not more than 12 months.

The vesicle formulation was tested for size, water
25 permeability and zeta potential by DLS, Zeta potential and stopped flow measurements in 0.5 M NaCl. The results are measured 5 times for 5 different batches.

Table 1: Vesicle formulation properties

Dh / nm (DLS)	306 nm $\pm$ 20 (40% $\pm$ 4%)
	86 nm $\pm$ 10 (40% $\pm$ 4%)

	14 nm $\pm$ 4 (20% $\pm$ 2%)
Zeta potential / mV	1.73 $\pm$ 0.25
Ki / s ⁻¹	2561 $\pm$ 300 s ⁻¹

Table 2: Formulation tested on LPRO hand-made membranes

% KHS solution	Jw/bar (L/m ² h)/bar	Rejection NaCl (%)	Applied pressure, bar
0	4.03 $\pm$ 0.08	97.9 $\pm$ 0.8	5
3%	4.75 $\pm$ 0.08	98.2 $\pm$ 0.1	5
5%	5.23 $\pm$ 0.09	96.5 $\pm$ 1.7	5

- 5 The results reported in table 2 indicates that the flux is improved by the addition of KHS to the coating aqueous solution in all the tested concentrations. Furthermore, the salt rejection initially increases by the addition of 3% KHS, but it decreases when further amounts of KHS are added.
- 10 Thus, a concentration of 3% say KHS appears to be the optimal concentration in which the water flux improves, without sacrificing the salt rejection.

15 The interfacial polymerization of the TFC layer using the formulation comprising 3% KHS in the aqueous phase is further changed by modifying the organic phase with diethylketone (DEK) and mesitylene (Mes).

Table 3: Formulation tested on LPRO hand-made membranes

% KHS solution	% TFC Modifier	Jw/bar (L/m ² h)/bar	Rejection NaCl (%)	Applied pressure, bar
0	0	5.2	97.5	5
3%	0	6.11	97.2	5
3%	3% DEK	7.47	96.3	5
3%	0.9% Mes	6.21	98.1	5
3%	1.8% Mes	6.42	98.3	5

The results of the experiments reported in table 3 show that a flux increase of 22% can be obtained by the addition of 3% DEK to the organic phase. Thus, a total of 43% increase in the flux can be obtained by the addition of 3% KHS to the aqueous phase and 3% DEK to the organic phase without substantially sacrificing the salt rejection.

The addition of Mes to the organic phase does not substantially increase the water flux further, however the salt rejection is increased. Thus, for applications where a high salt rejection is of importance Mes can be added to the organic phase and for applications where a high water flux is of importance DEK can be added to the organic phase.

Example 3:

A tubular membrane module covered with a TFC layer on the inside of the tubes:

The support membrane was prepared of PES polymer of the type 37.50 and had a molecular weight cut-off value of 50 kD. The

PEG100k retention was 94% and the water permeability was 244 LMH/bar.

The inner diameter of the individual tubes in the module was 5.3 mm. 115 tubes were assembled into a module having an exterior diameter of 90mm. The membrane length in the module including the epoxy potting was 125 cm (effective membrane length: 119 cm). The total membrane area of the lumen side of the membrane tubes was 2,27 m², based on membrane length excluded epoxy potting. Similar properties of a support membrane module may be obtained from Hyperflux I5 of the Berghof HyperFlux module program.

An aqueous solution as prepared in example 2 above in which the concentration of MPD was 3% and the concentration of the KHS solution was 3% were prepared. The organic solution was prepared containing 0.17% TMC and 1.7% DEK.

Coating protocol:

- a. Coating is done on a dry module,
- b. The aqueous solution is pumped bottom-up approximately at 1.5LPM through the lumen of the tubes in the module for 3 minutes, recirculated for 10 minutes and drained for 3 minutes to obtain pores in the membrane saturated with the aqueous solution,
- c. The aqueous solution that permeates through to shell side is manually drained off,
- d. The aqueous solution is dried via 3 separate steps (top-down), with <10% humidity dry compressed air:

- i. High flow, high pressure flushing using a rate of 750LPM and a pressure of 1.5 bar for 0.5 minutes,
- 5 ii. Low flow, low pressure drying on lumen side using a rate of 110 LPM and a pressure of 0-0.1 bar for 9.5 minutes, and
- 10 iii. Low flow, low pressure drying on shell side using a rate of 110 LPM and a pressure of 0-0.1 bar for 17 minutes,
- e. The organic solution was pumped bottom-up approximately at 0.5LPM through the lumen of the tubes of the module for 7 minutes, recirculated for 5-10 minutes and drained for 7 minutes,
- 15 f. The organic solution drying step is done via 2 separate steps (top-down), with <10% humidity dry compressed air:
 - i. Low flow, low pressure drying on lumen side using a rate of 110 LPM and a pressure of 0-0.1 bar for 2-5 minutes, and
 - 20 ii. Low flow, low pressure drying on shell side using a rate of 110 LPM and 0-0.1 bar for 2-5 minutes,
 - g. The module was rinsed on both lumen and shell side with RO/DI water
 - 25 h. The module was post-treated with 10-15% citric acid solution at 70⁰C, which was recirculated for 10 minutes, and
 - i. The module was subsequently rinsed on both lumen and shell side with RO/DI water.

30

Results for the tubular modules:

5 modules prepared as above were tested in a forward osmosis co-current configuration, in which a feed solution was directed to the lumen side of the tubes and the draw solution was directed to the shell side of the module. The feed solution was RO water and the draw solution was 1M NaCl in RO water.

The test conditions and the results of the tests are indicated in table 4 below.

Table 4:

Module No.	1	2	3	4	5
Feed in rate (LPM)	12	10	12	12	12
Draw in rate (LPM)	1.5	1.5	1.5	1.5	1.5
Feed in pressure (bar)	0.37	0.39	0.31	0.29	0.26
Feed pressure drop (bar)	0.24	0.24	0.26	0.23	0.20
Draw in pressure (bar)	0.14	0.14	0.05	0.05	0.02
Draw pressure drop (bar)	0.03	0.04	0.04	0.03	0.02
Average TMP	0.13	0.15	0.15	0.14	0.15
Duration (hr)	3.5	3.5	3.4	2.9	3.5
Water flux (LMH)	4.19	3.95	4.58	3.79	4.59
Reverse salt flux (gMH)	0.66	0.48	0.34	0.31	0.36

The average performance of the 5 modules tested shows that the water flux is around 4 LMH and the reverse salt flux is around 0.5 gmh.

5 The various aspects and implementations has been described
in conjunction with various embodiments herein. However,
other variations to the disclosed embodiments can be
understood and effected by those skilled in the art in
practicing the claimed subject-matter, from a study of the
10 drawings, the disclosure, and the appended claims.

CLAIMS

1. A tubular membrane comprising on a surface thereof a Thin Film Composite (TFC) layer incorporating a vesicle comprising an amphiphilic diblock copolymer of the PMOXA_{a-b}-
 5 PDMS_{c-d} type as vesicle membrane forming material, a reactive end group functionalised PDMS_{e-f} as an additive, and a transmembrane protein.

2. The tubular membrane according to claim 1, wherein the
 10 reactive end group functionalised PDMS_{e-f} is present in a concentration of from about 0.05% to about 1% v/v of a liquid composition comprising the vesicle.

3. The tubular membrane according to claim 1 or 2, wherein
 15 the TFC layer is provided on the inside of the tubular membrane.

4. The tubular membrane according to any one of the claims 1 to 3, wherein the internal diameter of the tubular membrane
 20 is between 2mm to 10mm, such as 3mm to 15mm.

5. The tubular membrane according to any one of the claims 1 to 4, wherein said PMOXA_{a-b}-PDMS_{c-d} is selected from the group consisting of PMOXA₁₀₋₄₀-PDMS₂₅₋₇₀ and mixtures thereof.

25

6. The tubular membrane according to claim 5, wherein a mixture comprises at least a first amphiphilic diblock copolymer of the general formula PMOXA₁₀₋₂₈-PDMS₂₅₋₇₀ and a second amphiphilic diblock copolymer of the general formula
 30 PMOXA₂₈₋₄₀-PDMS₂₅₋₇₀.

7. The tubular membrane according to claim 6, wherein the weight proportion between the first and the second amphiphilic diblock copolymer is in the range of 0.1:1 to 1:0.1.

5

8. The tubular membrane according to any of the claims 1 to 7, wherein the concentration of amphiphilic diblock copolymer in the liquid composition is in the range of 0.1 to 50 mg/ml, such as 0.5 to 20 mg/ml, and preferably 1 to 10 mg/ml.

10

9. The tubular membrane according to any one of the claims 1 to 8, wherein said reactive end group functionalised PDMS_{e-f} is functionalized with one or more of amine, carboxylic acid, and/or hydroxy groups, and wherein e is 30 and f is 50.

15

10. The tubular membrane according to any one of the claims 1 to 9, wherein the reactive end group functionalised PDMS_{e-f} is poly(dimethylsiloxane), bis(3-aminopropyl).

20

11. The tubular membrane according to any one of the claims 1 to 10, wherein the reactive end group functionalised PDMS_{e-f} is selected from the group consisting of H₂N-PDMS₃₀₋₅₀, HOOC-PDMS₃₀₋₅₀, and HO-PDMS₃₀₋₅₀ and mixtures thereof.

25

12. The tubular membrane according to any one of the claims 1 to 11, wherein the transmembrane protein is an aquaporin water channel.

30

13. The tubular membrane according to any one of the claims
1 to 12, wherein the liquid composition comprising the
vesicle further comprises from about 1 % v/v to about 12 %
v/v of triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b}
5 type.

14. The tubular membrane according to any one of the claims
1 to 13, wherein said triblock copolymer of the PMOXA_{a-b}-
PDMS_{c-d}-PMOXA_{a-b} type is selected from PMOXA₁₀₋₂₀-PDMS₂₅₋₇₀-
10 PMOXA₁₀₋₂₀.

15. The tubular membrane according to any one of the claims
1 to 14, wherein the liquid composition comprising the
vesicle further comprises a flux improving agent.
15

16. The tubular membrane according to claim 15, wherein the
flux improving agent is an alkylene glycol monoalkyl ether
alkylat, beta cyclodextrin, or polyethylene glycol (15)-
hydroxystearate.
20

17. The tubular membrane according to claim 15 or claim 16,
wherein the flux increasing agent is present in an amount of
0.1% to 1% by weight of the liquid composition.

25 18. The tubular membrane according to anyone of the claims 1
to 17, wherein the vesicle prior to incorporation in the TFC
layer is present in a liquid composition comprising a
buffer.

19. The tubular membrane according to claim 18, wherein the liquid composition further comprises a detergent or a surfactant.

5 20. The tubular membrane according to claim 18 or 19, wherein the detergent is selected from the group consisting of lauryldimethylamine N-oxide (LDAO), octyl glucoside (OG), dodecyl maltoside (DDM) or combinations thereof.

10 21. A tubular membrane module comprising a bundle of tubular membranes according to any of the claims 1 to 20.

22. The tubular membrane module according to claim 21, wherein the bundle of tubular membranes is surrounded by a shell, wherein an inlet for passing a first solution is connected to the lumen of the tubes in one end of the bundle and an outlet is connected to the lumen in the other end of the bundle, and an inlet is provided in the shell for passing a second solution outside the bundle of tubular
15 membranes to an outlet provided at another location of the shell.
20

23. A method for preparing a tubular membrane comprising

Providing a mixture of vesicles in an aqueous liquid composition and a di-amine or tri-amine compound, and a transmembrane protein,
25

Covering a surface of a porous tubular membrane support with the mixture,

Applying a hydrophobic solution comprising an acyl halide compound, and
30

Allowing the di-amine or tri-amine compound of the aqueous solution and the acyl halide compound of the hydrophobic solution to perform an interfacial polymerization reaction to form the Thin Film Composite (TFC) layer.

24. The method according to claim 23, wherein the di-amine compound is 1,3-diaminobenzene.

25. The method according to claims 23 or 24, wherein the proportion by weight of the di-amine or tri-amine compound to acyl halide compound is from 0:1 to 30:1 by weight.

26. The method according to anyone of the claims 23 to 25, wherein the hydrophobic solution further comprises a TFC layer modifying agent in an amount of 0.1 to 10% by volume.

27. The method according to claim 26, wherein the TFC layer modifying agent is a C3 to C8 carbonyl compound or mesitylene.

28. The method according to anyone of claims 26 or 27, wherein the TFC layer modifying agent is selected among the group consisting of diethylene ketone, 2-pentanone, 5-pentanone, and cyclopentanone.

29. The method according to anyone of the claims 23 to 28, wherein the porous support tubular membrane is formed by a polysulfone or a polyethersulfone polymer.

30. The method according to any of the claims 23 to 29, wherein the inner surface of the porous tubular membrane support is covered with the mixture to provide the TFC layer on the lumen side.

5

31. The method according to any of the claims 23 to 30, wherein said vesicles comprising an amphiphilic diblock copolymer of the $\text{PMOXA}_{a-b}\text{-PDMS}_{c-d}$ type as vesicle membrane forming material, a reactive end group functionalised PDMS_{e-f} as an additive.

10

32. The method according to any one of the claims 23 to 31, wherein the reactive end group functionalised PDMS_{e-f} is present in a concentration of from about 0.05% to about 1% v/v of the aqueous liquid composition comprising the vesicle.

15

33. The method according to any one of the claims 23 to 32, wherein the internal diameter of the porous tubular membrane is between 2mm to 10mm, such as 3mm to 8mm.

20

34. The method according to any one of the claims 23 to 33, wherein said $\text{PMOXA}_{a-b}\text{-PDMS}_{c-d}$ is selected from the group consisting of $\text{PMOXA}_{10-40}\text{-PDMS}_{25-70}$ and mixtures thereof.

25

35. The method according to claim 34, wherein a mixture comprises at least a first amphiphilic diblock copolymer of the general formula $\text{PMOXA}_{10-28}\text{-PDMS}_{25-70}$ and a second amphiphilic diblock copolymer of the general formula $\text{PMOXA}_{28-40}\text{-PDMS}_{25-70}$.

30

36. The method according to claim 35, wherein the weight proportion between the first and the second amphiphilic diblock copolymer is in the range of 0.1:1 to 1:0.1.

5 37. The method according to any of the claims 23 to 36, wherein the concentration of amphiphilic diblock copolymer in the liquid composition is in the range of 0.1 to 50 mg/ml, such as 0.5 to 20 mg/ml, and preferably 1 to 10 mg/ml.

10

38. The method according to any one of the claims 23 to 37, wherein said reactive end group functionalised PDMS_{e-f} is functionalized with one or more of amine, carboxylic acid, and/or hydroxy groups, and wherein e is 30 and f is 50.

15

39. The method according to any one of the claims 23 to 38, wherein the reactive end group functionalised PDMS_{e-f} is poly(dimethylsiloxane), bis(3-aminopropyl).

20

40. The method according to any one of the claims 23 to 40, wherein the reactive end group functionalised PDMS_{e-f} is selected from the group consisting of H₂N-PDMS₃₀₋₅₀, HOOC-PDMS₃₀₋₅₀, and HO-PDMS₃₀₋₅₀ and mixtures thereof as cross-linking agent.

25

41. The method according to any one of the claims 23 to 40, wherein the transmembrane protein is an aquaporin water channel.

42. The method according to any one of the claims 23 to 41, wherein the liquid composition comprising the vesicle further comprises from about 1 % v/v to about 12 % v/v of triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type.

5

43. The method according to any one of the claims 23 to 42, wherein said triblock copolymer of the PMOXA_{a-b}-PDMS_{c-d}-PMOXA_{a-b} type is selected from PMOXA₁₀₋₂₀-PDMS₂₅₋₇₀-PMOXA₁₀₋₂₀.

10

44. The method according to any one of the claims 23 to 43, wherein the liquid composition comprising the vesicle further comprises a flux improving agent.

15

45. The method according to claim 44, wherein the flux improving agent is an alkylene glycol monoalkyl ether alkylat, beta cyclodextrin, or polyethylene glycol (15)-hydroxystearate.

20

46. The method according to claim 44 or claim 45, wherein the flux increasing agent is present in an amount of 0.1% to 1% by weight of the liquid composition.

25

47. The method according to anyone of the claims 23 to 46, wherein the vesicle prior to incorporation in the TFC layer is present in a liquid composition comprising a buffer.

48. The method according to claim 47, wherein the liquid composition further comprises a detergent or a surfactant.

30

49. The method according to claim 48, wherein the detergent is selected from the group consisting of lauryldimethylamine N-oxide (LDAO), octyl glucoside (OG), dodecyl maltoside (DDM) or combinations thereof.

5

50. The method according to claim 23, wherein the porous tubular membrane support comprises a bundle of tubular membranes.

10 51. The method according to any of the claim 23 to 50, wherein the mixture of vesicles in an aqueous liquid composition and a di-amine or tri-amine compound, and a transmembrane protein is contacted with a surface of the porous tubular membrane support for at least 7 min to
15 saturate the porous tubular membrane support.

52. The method according to any of the claims 23 to 51, wherein the mixture is dried in 2 or more steps using different pressures of the drying air.

20

53. The method according to any of the claims 23 to 52, wherein a first initial drying step uses a pressure of the drying air, which is at least 2 times higher than the pressure in the subsequent step.

25

54. The method according to claim 53, wherein the first initial drying step uses a pressure of the drying air, which is the least 3 times, such as 4 times, such as 5 times higher than the pressure in the subsequent step.

30

55. The method according to any of the claims 23 to 54, wherein the total time for drying the mixture is at least 15 minutes and preferably 20 minutes.

- 5 56. Use of the tubular membrane according to any one of the claims 1 to 20, or the tubular membrane module according to claims 21 or 22, for the concentration of a product solution by forward osmosis.