

**ASYMMETRIC COMPOSITE MEMBRANES AND MODIFIED SUBSTRATES
USED IN THEIR PREPARATION**

FIELD OF INVENTION

The invention relates to a durable water permeable asymmetric composite
5 membrane with high levels of protein rejection, and substrates for use in
their preparation. In particular, the invention relates to a durable water
permeable asymmetric composite membrane consisting of a film of partially
cross-linked poly(ethanol) adhered to a hydrophilicized microporous sheet
of poly(ethylene).

BACKGROUND ART

It is well-known to use grafting to modify the surface of films, sheets and
moulded objects formed from polyolefins. For example, the publication of
Tazuke and Kimura (1978) discloses photografting onto poly(propylene),
poly(ethylene) and several other polymer films using benzophenone as a
15 sensitizer. In this publication the choice of solvent and sensitizer was
noted to be very important.

The publication of Ang et al (1980) discloses an irradiation procedure
where the sensitizer is dissolved in the monomer solution and can be used
for the photosensitized copolymerization in high yields of styrene, 4-vinyl
20 pyridine and methyl methacrylate to poly(propylene). Again, this
publication notes that the reaction was found to be very specific to
certain types of sensitizers.

The publication of Ogiwara et al (1981) discloses the photografting on
poly(propylene) and low-density poly(ethylene) (LDPE) films on which
25 sensitizers were coated beforehand. The sensitizers coated on films enabled
vinyl monomers, such as methyl methacrylate, acrylic acid and methacrylic
acid to graft easily with high yields. The hydrophilic monomers acrylic
acid and methacrylic acid were conveniently grafted using them in aqueous
solution in a liquid phase system.

30 The publication of Allmer et al (1988) discloses the modification of
surfaces of LDPE, high-density poly(ethylene) (HDPE) and polystyrene by
grafting with acrylic acid. The grafting is performed in the vapor-phase
and increased the wettability of the polymer. It was observed that acetone
was able to initiate grafting and was found to promote and direct grafting
35 to the surface. The later publication of Allmer et al (1989) discloses the
grafting of the surface of LDPE with glycidyl acrylate and glycidyl

methacrylate by photoinitiation. Acetone and ethanol were used as solvents, with acetone yielding slightly more grafting at the surface.

The publications of Yao and Ranby (1990a, 1990b and 1990c) disclose *inter alia* a process for the continuous photoinitiated graft copolymerization of acrylamide and acrylic acid onto the surface of HDPE tape film. The process is performed under a nitrogen atmosphere using benzophenone as the photoinitiator. It was noted that pre-soaking was very important for efficient photografting within short irradiation times. The application of this pre-soaking photografting method to poly(ethylene terephthalate) (PET) was also disclosed. In this context acetone was found to be a somewhat better solvent than methylethylketone and methylpropylketone. When applied to a continuous process for the photochemically induced graft polymerization of acrylamide and acrylic acid of poly(propylene) (PP) fibre surface under a nitrogen atmosphere, optimal concentrations of monomer and initiator in the pre-soaking solution were determined.

The publications of Kubota and Hata (1990a and 1990b) disclose an investigation of the location of methacrylic acid chains introduced into poly(ethylene) film by liquid and vapor-phase photografting and a comparative examination of the photografting behaviours of benzil, benzophenone and benzoin ethyl ether as sensitizers. In these latter studies poly(methacrylic acid) was grafted onto initiator-coated LDPE film.

The publication of Edge *et al* (1993) discloses the photochemical grafting of 2-hydroxyethyl methacrylate (HEMA) onto LDPE film. A solution phase method is used to produce a material with increased wettability.

The publication of Singleton *et al* (1993) discloses a method of making a polymeric sheet wettable by aqueous solvents and useful as an electrode separator in an electrochemical device. The polymeric sheet is formed from fibres which comprise poly(propylene) alone and is distinguished from a membrane formed from a microporous polymer sheet.

The publication of Zhang and Ranby (1993) discloses the photochemically induced graft copolymerisation of acrylamide onto the surface of PP film. Acetone was shown to be the best solvent among the three aliphatic ketones tested.

The publications of Yang and Ranby (1996a and 1996b) disclose factors affecting the photografting process, including the role of far UV radiation (200 to 300 nm). In these studies benzophenone was used as the photoinitiator and LDPE film as the substrate. Added water was shown to favour the photografting polymerisation of acrylic acid on the surface of

polyolefins, but acetone was shown to have a negative effect due to the different solvation of poly(acrylic acid) (PAA).

The publication of Hirooka and Kawazu (1997) discloses alkaline separators prepared from unsaturated carboxylic acid grafted poly(ethylene)-

5 poly(propylene) fibre sheets. Again, the sheets used as a substrate in these studies are distinguished from a membrane formed from a microporous polymer sheet.

The publication of Xu and Yang (2000) discloses a study on the mechanism of vapor-phase photografting of acrylic acid onto LDPE.

10 The publication of Shentu et al (2002) discloses a study of the factors, including the concentration of monomer, affecting photo-grafting on LDPE.

The publication of El Kholdi et al (2004) discloses a continuous process for the graft polymerisation of acrylic acid from monomer solutions in water onto LDPE. The publication of Bai et al (2011) discloses the
15 preparation of a hot melt adhesive of grafted low-density poly(ethylene) (LDPE). The adhesive is prepared by surface UV photografting of acrylic acid onto the LDPE with benzophenone as the photoinitiator.

The publication of Choi et al (2001) states that graft polymerisation is considered as a general method for modifying the chemical and physical
20 properties of polymer materials.

The publication of Choi (2002) discloses a method for producing an acrylic graft polymer on the surface of a polyolefin article comprising the steps of immersing the article in a solution of an initiator in a volatile solvent, allowing the solvent to evaporate, and then immersing the article
25 in a solution of an acrylic monomer before subjecting the article to ultraviolet irradiation in air or an inert atmosphere. Acrylic acid is used as the acrylic monomer in each one of the Examples disclosed in the publication, although the use of equivalent amounts of methacrylic acid, acrylamide and other acrylic monomers is anticipated.

30 The publication of Choi (2004) discloses the use of "ethylenically unsaturated monomers" in graft polymerisation. These other monomers are disclosed as monomers that are polymerizable by addition polymerisation to a thermoplastic polymer and are hydrophilic as a consequence of containing carboxyl (-COOH), hydroxyl (-OH), sulfonyl (SO₂), sulfonic acid (-SO₃H) or
35 carbonyl (-CO) groups. No experimental results concerning the chemical and physical properties of graft polymers prepared by a method using these other monomers is disclosed.

The publication of Choi (2005) discloses a non-woven sheet of polyolefin fibres where opposed surfaces of the sheet are hydrophilic as a consequence of an acrylic graft polymerisation. The properties of the sheet are asymmetric, the ion exchange coefficient of the two surfaces being different. The method used to prepare these asymmetric acrylic graft polymerised non-woven polyolefin sheets comprises the steps of immersing the substrates in a solution of benzophenone (a photoinitiator), drying and then immersing the substrate in a solution of acrylic acid prior to subjecting to ultraviolet (UV) irradiation. The irradiation may be performed when the surfaces are in contact with either air or an inert atmosphere.

The publication of Gao *et al* (2013) discloses a method of preparing a radiation cross-linked lithium-ion battery separator. In an example, a porous polyethylene membrane is immersed in a solution of benzophenone and triallyl cyanurate in dichloromethane. The immersed membrane is dried at room temperature before being immersed in a water bath at 30°C and irradiated on both sides using a high-pressure mercury lamp for three minutes.

The publication of Jaber and Gjoka (2016) discloses the grafting of ultra-high molecular weight polyethylene microporous membranes using monomers having one or more anionic, cationic or neutral groups. The publication states that the authors have discovered that molecules can be grafted on the surface of an asymmetric, porous ultra-high molecular weight polyethylene membrane using an ultraviolet radiation energy source. The grafted membranes are proposed for use in removing charged contaminants from liquids.

The objective of the majority of these prior art methods is to improve the adhesion, biocompatibility, printability or wettability of the surface of a substrate using photoinitiated polymerisation. These methods are to be distinguished from the use of UV-initiated grafting with an exogenously prepared preformed polymer to modify the permeability to water of a hydrophobic microporous polyolefin substrate.

The publication of Bolto *et al* (2009) reviews what is disclosed in publications concerning the cross-linking of poly(ethenol), i.e. PVA. These publications include those concerning cross-linking methods and the grafting of PVA onto support membranes, including porous hydrophobic membranes such as poly(ethylene) and poly(propylene).

The publication of Linder et al (1988) discloses semipermeable composite membranes comprising a film of modified PVA or PVA-copolymers on a porous support. Suitable support materials are required to be water insoluble and may be chosen, e.g. from polyacrylonitriles, polysulfones, polyamides,
5 polyolefins such as poly(ethylenes) and poly(propylenes), or cellulose.

The publication of Exley (2016) discloses an asymmetric composite membrane consisting of a film of cross-linked poly(ether ether ketone) adhered to a sheet of grafted microporous poly(ethylene). The microporous poly(ethylene) is obtained by photoinitiated grafting with an ethenyl monomer to provide a
10 hydrophilic sheet.

The publication of Craft et al (2017) discloses improvements in the asymmetric composite membranes disclosed in the publication of Exley (2016). The improved asymmetric composite membranes comprise of poly(vinyl alcohol) polymer crosslinked with a crosslinking agent (such as divinyl
15 benzene) coated on a film of cross-linked poly(ether ether ketone) adhered to a sheet of the grafted microporous poly(ethylene). The improvement is in the selectivity of the asymmetric composite membrane obtained.

It is an object of the present invention to provide an asymmetric composite membrane with improved levels of protein rejection while maintaining an
20 acceptable flux. It is an object of the present invention to provide a method to preparing the asymmetric composite membrane. It is an object of the present invention to provide a hydrophilicized sheet of microporous polyolefin particularly suited for use in the method of preparing the asymmetric composite membrane. It is an object of the present invention to
25 provide asymmetric composite membranes and hydrophilicized sheets of microporous polyolefin adaptable for use in extracting or recovering water from feed streams in the beverage and food processing industries, including dairy. These objects are to be read in the alternative with the object at least to provide a useful choice in the selection of such methods,
30 membranes and sheets.

STATEMENT OF INVENTION

In a **first** aspect the invention provides a hydrophilicized microporous sheet of polyolefin where the microporous polyolefin has been grafted with a preformed poly(4-ethenyl benzene sulfonic acid).
35 Preferably, the polyolefin is selected from the group consisting of: poly(ethylene), poly(propylene), poly(butylene) and poly(methylpentene). More preferably, the polyolefin is poly(ethylene) or poly(propylene). Most preferably, the polyolefin is poly(ethylene).

Preferably, the preformed poly(4-ethenyl benzene sulfonic acid) is equivalent to that provided in the working solution prepared according to Example 1.

In a **second** aspect the invention provides an asymmetric composite membrane comprising a film of partially crosslinked poly(ethenol) adhered to a hydrophilicized microporous sheet of polyolefin where the polyolefin has been grafted with a preformed poly(4-ethenyl benzene sulfonic acid) before adherence of the film of partially crosslinked poly(ethenol).

Preferably, the partially crosslinked poly(ethenol) is crosslinked to a degree in the range equivalent to that of the partially crosslinked poly(ethenol) provided in Vial 2 of Example 8 to that of the partially crosslinked poly(ethenol) provided in Vial 4 of Example 8. More preferably, the partially crosslinked poly(ethenol) is crosslinked to a degree substantially equivalent to that of the partially crosslinked poly(ethenol) provided in Vial 3 of Example 8.

Preferably, the polyolefin is selected from the group consisting of: poly(ethylene), poly(propylene), poly(butylene) and poly(methylpentene). More preferably, the polyolefin is poly(ethylene) or poly(propylene). Most preferably, the polyolefin is poly(ethylene).

In a preferred embodiment of the second aspect, the invention provides an asymmetric composite membrane consisting essentially of a film of partially crosslinked poly(ethenol) adhered to a hydrophilicized microporous sheet of poly(ethylene) where the polyolefin has been grafted with a preformed poly(4-ethenyl benzene sulfonic acid) before adherence of the film of partially crosslinked poly(ethenol).

In a most preferred embodiment of the second aspect, the invention provides an asymmetric composite membrane consisting essentially of a film of partially crosslinked poly(ethenol) adhered to a hydrophilicized microporous sheet of poly(ethylene) where the polyolefin has been grafted with a preformed poly(4-ethenyl benzene sulfonic acid) equivalent to that provided in the working solution prepared according to Example 1 before adherence of the film of partially crosslinked poly(ethenol) and the partially crosslinked poly(ethenol) is crosslinked to a degree substantially equivalent to that of the partially crosslinked poly(ethenol) provided in Vial 3 of Example 8.

An asymmetric composite membrane capable of providing at least 99.9% total protein rejection at a flux of 5 LMH with milk as a feed stream is provided.

In a **third** aspect the invention provides a method of preparing the hydrophilicized microporous sheet of polyolefin of the first aspect of the invention comprising the steps of:

1. Contacting a microporous sheet of polyolefin with a dispersion
5 comprising a preformed poly(4-ethenylbenzenesulfonic acid) in an aqueous solvent to provide a contacted microporous sheet;
2. Curing the contacted microporous sheet at a temperature and for a time
sufficient for at least a portion of the poly(4-ethenylbenzenesulfonic
acid) to be grafted onto the polyolefin substrate to provide a cured
10 microporous sheet; and then
3. Washing the cured microporous sheet to provide the hydrophilicized
microporous sheet of polyolefin.

Preferably, the polyolefin is selected from the group consisting of:
poly(ethylene), poly(propylene), poly(butylene) and poly(methylpentene).
15 More preferably, the polyolefin is poly(ethylene) or poly(propylene). Most preferably, the polyolefin is poly(ethylene).

Preferably, the aqueous solvent is acetone-water.

Preferably, the curing the contacted microporous sheet is by irradiating
with ultraviolet light at an intensity and at a temperature for a period of
20 time sufficient for at least a portion of the poly(4-ethenylbenzenesulfonic
acid) to be grafted onto the polyolefin.

Preferably, the irradiating is in the presence of a photoinitiator. More
preferably, the irradiating is in the presence of a photoinitiator selected
from the group consisting of: aceto-phenone, anthraquinone, benzoin,
25 benzoin ether, benzoin ethyl ether, benzil, benzil ketal, benzophenone,
benzoyl peroxide, n-butyl phenyl ketone, iso-butyl phenyl ketone,
fluorenone, propiophenone, n-propyl phenyl ketone and iso-propyl phenyl
ketone. Most preferably, the irradiating is in the presence of the
photoinitiator benzophenone.

30 Preferably, the ultraviolet light has a broad spectrum centred on 250 nm
and bandwidth limits of approximately 250 nm and 400 nm.

Preferably, the washing is with water.

In a preferred embodiment of the third aspect, the invention provides a method of preparing a hydrophilicized microporous sheet of poly(ethylene) comprising the steps of:

1. Polymerising 4-ethenylbenzenesulfonic acid in the presence of a radical initiator to provide a first dispersion in a first solvent of a poly(4-ethenylbenzenesulfonic acid);
 2. Contacting a microporous sheet of poly(ethylene) with a second dispersion in a second solvent of the poly(4-ethenylbenzenesulfonic acid) to provide a contacted microporous sheet of poly(ethylene);
 3. Curing the contacted microporous sheet at a temperature and for a time sufficient for at least a portion of the poly(4-ethenylbenzenesulfonic acid) to be grafted onto the polyolefin substrate; and then
 4. Washing the cured microporous sheet to provide the hydrophilicized microporous sheet of poly(ethylene),
- where the first solvent is water and the second solvent is acetone-water.

The 4-ethenylbenzenesulfonic acid may be provided in the form of a salt, e.g. as its sodium salt (SSS).

Preferably, the radical initiator is selected from the group consisting of: ammonium persulfate and sodium persulfate. More preferably, the radical initiator is sodium persulfate.

Preferably, the second solvent is 40 to 60% (v/v) acetone in water. Most preferably, the second solvent is 50% (v/v) acetone in water.

The second dispersion may be prepared by adding acetone to the first dispersion.

In a **fourth** aspect the invention provides a hydrophilicized microporous sheet of polyolefin prepared according to the method of the third aspect of the invention.

In a **fifth** aspect the invention provides a method of preparing the asymmetric composite membrane of the second aspect of the invention, comprising the steps of:

1. Contacting one side of the hydrophilicized microporous sheet of the first or fourth aspect of the invention with a solution in a first solvent of partially cross-linked poly(ethanol) in the presence of a radical initiator to provide a contacted sheet;

2. Drying the contacted sheet at a temperature and for a time sufficient to allow the partially cross-linked poly(ethanol) to adhere to the one side of the hydrophilicized microporous sheet of polyolefin and evaporate substantially all the solvent to provide a dried contacted sheet; and then
3. Washing the dried contacted sheet in a second solvent to provide the asymmetric composite membrane.

Preferably, the drying of the contacted sheet is by applying a positive thermal gradient across the thickness of the sheet from the contacted one side of the hydrophilicized microporous sheet to the other side.

In the description and claims of this specification the following abbreviations, acronyms, terms and phrases have the meaning provided: "comprising" means "including", "containing" or "characterized by" and does not exclude any additional element, ingredient or step; "consisting of" means excluding any element, ingredient or step not specified except for impurities and other incidentals; "consisting essentially of" means excluding any element, ingredient or step that is a material limitation; "crosslinking agent" means a material that is incorporated into the crosslinking bridge of a cross-linked polymer network; "flux" means the rate (volume per unit of time) of permeate transported per unit of membrane area; "graft polymer" means a polymer in which the linear main chain has attached to it at various points side chains of a structure different from the main chain; "homopolymer" means a polymer formed by the polymerization of a single monomer; "hydrophilic" means having a tendency to mix with, dissolve in, or be wetted by water and "hydrophilicity", "hydrophilicized" and "hydrophilicizing" have a corresponding meaning; "microporous" means consisting of an essentially continuous matrix structure containing substantially uniform small pores or channels throughout the body of the substrate (such as may be manufactured using a cast (wet) process technology) and specifically excludes a discontinuous matrix of woven or non-woven fibres; "partially crosslinked" means that only a portion of the available sites for cross-linking are utilised and the cross-linking reaction has been limited by reagents, temperature or period of time; "photoinitiator" means a photolabile compound which upon irradiation forms a radical; "poly(ethanol)" and "polyvinyl alcohol" are used synonymously; "post-treated polymer" means a polymer that is modified, either partially or completely, after the basic polymer backbone has been formed; "preformed" means formed beforehand, i.e. prior to treatment; "PSSS" or "pSSS" denotes the product of the polymerization of SSS, i.e. poly(4-ethenylbenzenesulfonic acid); "PVA" denotes poly(ethanol) (or

polyvinyl alcohol); "SSS" denotes sodium styrene sulfonate, i.e. the sodium salt of 4-ethenylbenzenesulfonic acid; "UVA" means electromagnetic radiation having wavelengths between 320 and 400 nm; "UVB" means electromagnetic radiation having wavelengths between 290 and 320 nm; "UVC" means electromagnetic radiation having wavelengths between 200 and 290 nm, and "xPVA" denotes PVA that is at least partially crosslinked.

The terms "first", "second", "third", etc. used with reference to elements, features or integers of the subject matter defined in the Statement of Invention and Claims, or when used with reference to alternative embodiments of the invention are not intended to imply an order of preference. The numbering of the Examples and the Comparative Examples (if any) is not intended to mean any pair of Example and Comparative Example is directly comparable. Where values are expressed to one or more decimal places standard rounding applies. For example, 1.7 encompasses the range 1.650 recurring to 1.749 recurring. Where concentrations or ratios of reagents or solvents are specified, the concentration or ratio specified is the initial concentration or ratio of the reagents or solvents. References to the use of 4-ethenylbenzenesulfonic acid encompass references to the use of salts of the acid, including SSS. In the absence of further limitation the use of plain bonds in the representations (if used) of the structures of compounds encompasses the diastereoisomers, enantiomers and mixtures thereof of the compounds.

The invention will now be described with reference to embodiments or examples and the figures of the accompanying drawings pages.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1. FTIR spectra of the monomer 4-ethenylbenzenesulfonic acid (SSS) and poly(4-ethenylbenzenesulfonic acid) (PSSS) prepared according to the method described in Example 1 (water) and Example 2 (DMSO).

Figure 2. FTIR spectra recorded for poly(4-ethenylbenzenesulfonic acid) (PSSS), the photoinitiator benzophenone (BP), no washing protocol (1), washed with water at a temperature of 45 to 50°C before drying (2), washed with acetone (3) and washed with water at a temperature of 45 to 50°C, dried and then washed with acetone (4).

Figure 3. Photograph of vials containing partially crosslinked poly(ethenol) (xPVA) prepared according the Example 8. From left to right: Vial 1, Vial2, Vial 3 and Vial 4.

Figure 4. Flux (LMH) (◆, broken line), total solids (%) (▲, dotted line) and protein rejection (%) (■, solid line) of a sample of an asymmetric composite membrane (030918Sii) prepared according to Example 9 during repeated clean-in-place (C-i-P) protocols.

5 **Figure 5.** Pressure series testing (0 to 20 bar) of a sample (030918Siii) of an asymmetric composite membrane prepared according to Example 9. Flux and protein rejection with milk as the feed stream were measured.

Figure 6. Comparison of the FTIR spectra (full range) recorded for samples (240818Si and 240818Sii) of an asymmetric composite membrane prepared
10 according to Example 9 and the poly(ethenol) (PVA) and cross-linked poly(ethenol) (xPVA) used in their preparation.

Figure 7. Comparison of the FTIR spectra (stretch mode region) recorded for samples (240818Si and 240818Sii) of an asymmetric composite membrane prepared according to Example 9 and the poly(ethenol) (PVA) and cross-
15 linked poly(ethenol) (xPVA) used in their preparation.

Figure 8. Comparison of the FTIR spectra (finger print region) recorded for samples (240818Si and 240818Sii) of an asymmetric composite membrane prepared according to Example 9 and the poly(ethenol) (PVA) and cross-linked poly(ethenol) (xPVA) used in their preparation.

20 **Figure 9.** Scanning electronmicrographs of the surface of samples of asymmetric composite membrane prepared according to Example 9 before and after being subjected to repeated clean-in-place (CIP) protocols.

DETAILED DESCRIPTION

The invention resides in part in the selection of a preformed polymer of 4-
25 ethenylbenzenesulfonic acid as the hydrophilicizing agent used in the preparation of hydrophilicized polyolefin substrates. This part of the invention is most advantageously applied to the hydrophilicization of preformed sheets of microporous poly(ethylene). Use of poly(4-ethenylbenzenesulfonic acid) as the hydrophilicizing agent has been found
30 to provide greater and more consistent hydrophilicization of the polyolefin substrate. This improvement is attributed at least in part to the reduced number of side reactions that may occur when compared with use of the monomer (cf. the method described in the publications of Exley (2016) and Craft et al (2017)). It is also anticipated that the use
35 increases the likelihood of the preformed polymer grafting to the

polyolefin substrate at multiple sites. A structurally distinct form of grafted polyolefin substrate may therefore be being obtained.

The improved performance of a hydrophilicized sheet of microporous poly(ethylene) prepared by the method of the present invention when
5 compared with that prepared by the method disclosed in the publications of Exley (2016) and Craft *et al* (2017) is demonstrated by a higher flux with water as the feed stream whilst retaining the desired durability including tolerance to chlorine and other cleaning agents. The hydrophilicized sheets of microporous poly(ethylene) prepared by the method of the present
10 invention also "wet out" at pressures lower than those previously required. The method of preparing the hydrophilicized sheets of microporous poly(ethylene) is also less wasteful of reagents, including the photoinitiator, and eliminates the need for the exclusion of oxygen during the preparation. The polymer of 4-ethenylbenzenesulfonic acid is
15 advantageously prepared as a dispersion (the 'working solution') that can be used directly without the need to isolate the polymer. This advantage is illustrated in the methods of the following Examples.

The invention also resides in part in the use of the hydrophilicized sheet of microporous polyolefin to prepare an asymmetric composite
20 membrane. Providing a hydrophilicized, i.e. wettable, sheet of microporous polyolefin facilitates the formation of the film of partially cross-linked poly(ethanol) (xPVA) on the surface and adherence to that surface. In contrast with the preparation of the asymmetric composite membranes disclosed in the publication of Craft *et al* (2017) persulfate is
25 used as a cross-linking agent. The high levels of protein rejection demonstrated for the asymmetric composite membranes is attributed in part to the selection of this crosslinking agent. A porosity providing a size exclusion reduced to an estimated 30 kDa from an estimated 160 kDa is believed to be achieved (and is supported by the increased levels of total
30 protein rejection of greater than 99.9%).

When drying the hydrophilicized microporous sheet of polyolefin contacted with the dispersion in water of partially cross-linked poly(ethanol) (xPVA) applying a positive thermal gradient across the thickness of the sheet from the contacted side to the other side is also believed to assist in
35 maintaining porosity of the hydrophilicized microporous sheet of polyolefin and thereby provide an asymmetric composite membrane with higher flux rates than might otherwise be achievable. In Example 9 the application of a positive thermal gradient is a consequence of the sheet being supported on a glass plate during the drying steps. The positive thermal

gradient is believed to limit the extent to which the dispersion in water may permeate the pores of the hydrophilicized microporous sheet.

The asymmetric composite membranes provided by the invention are therefore further distinguished from other membranes, e.g. those suggested in the publication of Linder *et al* (1988), where a superficial film of cross-linked PVA or PVA-copolymer is proposed to be coated on a hydrophobic, i.e. water repelling, sheet of microporous polyolefin.

MATERIALS AND METHODS

All microporous sheets used in the preparation of samples were prepared from virgin poly(ethylene), i.e. poly(ethylene) of high purity.

FTIR

Spectra of the samples were recorded using a Thermo Electron Nicolet 8700 FTIR spectrometer equipped with a single bounce ATR and diamond crystal. An average of 32 scans with a 4 cm⁻¹ resolution was taken for all samples.

Flux

Permeability was determined using a filter assembly (Sterlitech Corp.) by measuring the flux with deionized water as the feed stream at various pressures. Flux J_v was then graphed against effective pressure difference across the membrane, p_{eff} , and the slope of the permeability L_p .

$$L_p = \frac{J_v}{\Delta p_{eff}}$$

The samples were mounted in the filter assembly. Deionized water was fed into the rig at 2.5 L min⁻¹ and 4 to 8 °C. The time to collect a predetermined volume of permeate was noted. The flux rate (J) was calculated according to the following equation:

$$J = \frac{V}{t \times A}$$

where V is the permeate volume (L), t is the time (h) for the collection of V and A is area of the sample (m²) which was determined to be 0.014 m².

Salt rejection

Rejection was measured using a 2 g/L solution in water of sodium chloride with a feed pressure of 16 bar. The conductivities from the feed and permeate were compared.

$$\%R_{NaCl} = \left(1 - \frac{\sigma_p}{\sigma_f}\right) \times 100$$

where σ_p is the conductivity of permeate and σ_f is the conductivity of the feed.

Total solids rejection

- 5 Rejection for whole milk samples was measured by pouring 20 mL of sample from the feed in a petri dish and measuring the dry weight after 2 hours in a 100 °C oven.

$$\%R_{TS} = \left(1 - \frac{m_{p,TS}}{m_{f,TS}}\right) \times 100$$

- 10 where $m_{p,TS}$ is total milk solids in the permeate and $m_{f,TS}$ is the mass of milk total solids in the feed.

Protein concentrations

Total protein and total whey protein concentrations in permeate were calculated on the basis of HPLC analysis with UV absorbance monitoring.

'Clean-in-Place' (CIP) protocol

- 15 To mimic commercial processing operations samples of the asymmetric composite membrane was subjected to repeated *in situ* washing protocols) as described in Craft et al (2017). The intermediate and subsequent flux rates were determined to assess the likely durability of the membrane in commercial processing operations. The *in situ* washing protocol was based
20 on that employed in a commercial processing operation but modified in duration to compensate for the greater exposure of the membrane to the cleaning agents (caustic and acid) in the filter assembly. Prior to the washing steps the membrane was rinsed by circulating water at an initial temperature of 65°C through the filter assembly for a period of three
25 minutes before draining the system.

- The membrane was subjected to a first wash by circulating a 2% (w/v) sodium hydroxide solution ("caustic wash") through the filter assembly for a period of five minutes before draining and flushing the system by circulating water at an initial temperature of 65°C through the filter
30 assembly system for a period of five minutes. The membrane was subjected to a second wash by circulating a 2% (w/w) nitric acid solution ("acid wash") through the filter assembly system for a period of ten minutes before draining and flushing the system of circulating water at an initial

temperature of 65°C for a period of ten minutes. The membrane was subjected to a third wash (a "caustic wash") before flushing the system by circulating water at an initial temperature of 65°C for a period of five minutes before circulating chilled water for a period of five minutes to
5 cool the system. All rinsing and washing steps were performed with no pressure recorded on the pressure gauge of the filter assembly.

Preparation of poly(4-ethenylbenzenesulfonic acid)

EXAMPLE 1

A quantity of 50 g of the monomer 4-ethenylbenzenesulfonic acid as its
10 sodium salt (SSS) was dissolved in a volume of 100 mL of distilled water to provide a solution. A quantity of 0.5 g of the initiator sodium persulfate (SPS) was then dissolved in the solution and the initiator-monomer mixture heated with stirring at a temperature of 80 to 90°C for a time of about 20 minutes. A viscous solution was obtained having a total volume of about 125
15 mL. The viscous solution was diluted with the same volume of distilled water to provide 250 mL of a working solution of poly(4-ethenylbenzenesulfonic acid).

The polymer could be precipitated from this working solution by the addition of an excess volume of acetone, followed by collection of the
20 precipitate by filtration through a Buchner funnel and then washing with acetone to provide a light white solid that could be readily ground to a powder using a pestle and mortar.

EXAMPLE 2

A quantity of 5 g of the monomer 4-ethenylbenzenesulfonic acid as its
25 sodium salt (SSS) was dissolved in a volume of 20 mL of dimethylsulfoxide (DMSO) to provide a solution.

A quantity of 0.05 g of the initiator ammonium persulfate (APS) was then dissolved in the solution and the initiator-monomer mixture heated with stirring at a temperature of 80 to 90°C for a time of about 20 minutes. The
30 poly(4-ethenylbenzenesulfonic acid) was precipitated from the cooled solution by addition of an excess volume of acetone, collected by filtration through a Buchner funnel and washed with acetone to provide the same light white solid that could be readily ground to a powder obtainable in Example 1.

35 The Fourier transform infrared (FTIR) spectra of the powder obtained by the methods of preparation described in Example 1 (PSSS from water) and Example

2 (PSSS from DMSO) are compared with that of the FTIR spectrum of the monomer 4-ethenylbenzenesulfonic acid (SSS) in Figure 1. A comparison of the spectra was consistent with the polymerisation of the monomer in both methods of preparation. The polymer prepared by the method described in
5 Example 1, i.e. the working solution, was used as the hydrophilicizing agent in the preparation of hydrophilicized sheets of microporous poly(ethylene) according to the following examples.

Preparation of hydrophilicized sheets of microporous poly(ethylene)

EXAMPLE 3

10 A volume of 6 mL of the working solution obtained according to Example 1 was mixed with a volume of 5 mL of distilled water in a vial to provide a volume of initial solution containing 1.2 g of poly(4-ethenylbenzenesulfonic acid) (pSSS). A volume of 10 mL acetone was added to the volume of initial solution and allowed to become transparent before
15 adding and dissolving in the solution a quantity of 0.2 g of the photoinitiator benzophenone to provide a hydrophilicizing mixture. The surface of a sheet of microporous poly(ethylene) (TARGRAY™ wet process polyethylene separators, item no. SW320H (Targray, Kirkland QC, Canada)) dimensioned (13.5 cm x 18.5 cm) to fit the filter assembly (Sterlitech
20 Corp.) was contacted with the hydrophilicizing mixture and irradiated with ultraviolet (UV) light (broad spectrum centred on 320 nm) for a period of time of 2 minutes. The irradiated contacted sheets were then washed with cold tap water before being placed in a water bath maintained at a temperature of 45 to 50°C for a time of about 5 minutes. The washed sheets
25 were then air dried before testing or use in the preparation of an asymmetric composite membrane.

EXAMPLE 4

The method of preparation described in Example 3 was repeated with the volume of initial solution containing 1.7 g of poly(4-ethenylbenzenesulfonic acid). This quantity of the polymer was close to the
30 maximum that could be dissolved in the solvent system used.

EXAMPLE 5

A one step method of preparation including the monomer 4-ethenylbenzenesulfonic acid was evaluated.
35 A volume of 3 mL of the working solution obtained according to Example 1 was mixed with a volume of 8 mL of distilled water and a quantity of 0.6 g

of the monomer 4-ethenylbenzenesulfonic acid in a vial to provide a volume of initial solution containing 0.6 g of poly(4-ethenylbenzenesulfonic acid). A volume of 10 mL acetone was added to the volume of this initial solution and allowed to become transparent before adding a quantity of 0.4 g of the photoinitiator benzophenone to provide a hydrophilicizing mixture.

The surface of a sheet of microporous poly(ethylene) (TARGRAY™ wet process polyethylene separators, item no. SW320H (Targray, Kirkland QC, Canada)) dimensioned (13.5 cm x 18.5 cm) to fit the filter assembly (Sterlitech Corp.) was contacted with the hydrophilicizing mixture and irradiated with UV light (broad spectrum centred on 350 nm) for a period of time of 2 minutes before being washed with cold tap water and placed in a water bath maintained at a temperature of 45 to 50°C for about 5 minutes and then air dried.

15 **EXAMPLE 6**

A two-step method of preparation using only the monomer 4-ethenylbenzenesulfonic acid in the first of the two steps was evaluated.

In the first step a volume of 10 mL of distilled water followed by a volume of 10 mL of acetone was added to a foil wrapped vial containing a quantity of 2.4 g of the monomer and a quantity of 0.4 g of the photoinitiator benzophenone and the mixture shaken until all solids had dissolved. The surface of a sheet of microporous poly(ethylene) (TARGRAY™ wet process polyethylene separators, item no. SW320H (Targray, Kirkland QC, Canada)) dimensioned (13.5 cm x 18.5 cm) to fit the filter assembly of a test rig (Sterlitech Corp.) was contacted with the mixture and irradiated with ultraviolet (UV) light (broad spectrum centred on 350 nm) before washing with cold tap water and placing in a water bath maintained at a temperature of 45 to 50°C for a time of 5 minutes before being air dried.

In the second step a volume of 6 mL of the working solution obtained according to Example 1 was mixed with a volume of 5 mL of distilled water in a vial to provide a volume of initial solution containing 1.2 g of poly(4-ethenylbenzenesulfonic acid). A volume of 10 mL acetone was added to the volume of initial solution and allowed to become transparent before adding and dissolving in the solution a quantity of 0.2 of the photoinitiator benzophenone to provide a hydrophilicizing mixture. The surface of the air dried sheet obtained according to the first step was contacted with the hydrophilicizing mixture and irradiated with UV light (broad spectrum centered on 350 nm) for a period of time of 2 minutes

before washing with cold tap water and placing in a water bath maintained at a temperature of 45 to 50°C for a period of time of about 5 minutes and then air dried.

Observations

5 Grafting of the preformed poly(4-ethenylbenzenesulfonic acid) onto the sheet of microporous poly(ethylene) according to the methods of preparation described in Example 3, Example 4, Example 5 and Example 6 was confirmed by washing in acetone (solvent for the photoinitiator benzophenone) and water (solvent for poly(4-ethenylbenzenesulfonic acid)). Four washing protocols
10 (1, 2, 3 and 4) were adopted and the FTIR spectra recorded for samples of hydrophilicized sheets of microporous poly(ethylene) prepared according to the method described in Example 3 following application of these washing protocols are presented in Figure 2.

Preparation of asymmetric composite membrane

15 **EXAMPLE 7**

A series of preliminary experiments were performed to evaluate methods of preparing a film of cross-linked poly(ethenol) (xPVA) on a surface. A solution of the radical initiator sodium persulfate (SPS) was prepared by adding a quantity of 0.2 g of SPS to a volume consisting of 10 mL deionised
20 water and 10 mL acetone. The solution of radical initiator was applied onto the surface of each of three glass plates (Plate 1, Plate 2 and Plate 3). Plate 2 and Plate 3 were transferred to an oven and dried at a temperature of 60°C until all solvent had evaporated to leave a thin layer of the initiator deposited on the surface. Solutions of poly(ethenol) (PVA) were
25 prepared at a concentration of 1% (w/v) in either dimethyl sulfoxide (DMSO) or deionised water. The solution of poly(ethenol) (PVA) in DMSO was sprayed onto the wet surface of Plate 1 and the plate then transferred to an oven and dried at a temperature of 60°C. The solution of poly(ethenol) (PVA) in DMSO was also sprayed onto the dry surface of Plate 2 and the plate then
30 transferred to an oven and dried at a temperature of 60°C. The solution of poly(ethenol) in deionised water was sprayed onto the dry surface of Plate 3 and the plate then transferred to an oven and dried at a temperature of 60°C. The desired film of cross-linked poly(ethenol) was not formed on Plate 1. The failure attributed to the presence of acetone causing the
35 polymer to crash out of solution. The film formed on Plate 2 was too frangible to be useful as a rejection layer of an asymmetric composite membrane. A clear, peelable film formed on the surface of Plate 3. The film

was not brittle and this method of preparation was adopted for use in the preparation of the asymmetric composite membrane.

EXAMPLE 8

A series of preliminary experiments were performed to evaluate methods of preparing a film of partially cross-linked poly(ethenol) (xPVA) and thereby control the properties of the rejection layer of the asymmetric composite membrane. Volumes of 10 mL of a 1% (w/v) solution of poly(ethenol) (PVA) in deionised water containing a quantity of 0.1 g of SPS were dispensed into each four vials (Vial 1, Vial 2, Vial 3 and Vial 4). The solution in each vial was heated to a temperature of 75°C and maintained at this temperature with stirring until the following observations were made (and the vials then cooled):

- A yellow solid crashed out of solution (Vial 1; 3 to 4 minutes)
- A cloudy white solution with some precipitation formed (Vial 2, around 3 minutes)
- A cloudy white solution formed (Vial 3; 1.5 to 2 minutes)
- A cloudy solution started to form (Vial 4; 10 to 20 seconds)

The observations are also presented in Figure 3. The method of preparing partially cross-linked poly(ethenol) according to that formed in Vial 3 was adapted for use in the preparation of the membrane.

EXAMPLE 9

A volume of 20 mL of the solution of the radical initiator sodium persulfate (SPS) was prepared according to Example 7. A volume of the solution of partially cross-linked poly(ethenol) (xPVA) was prepared according to Example 8 (Vial 3).

The solution of the radical initiator was applied to one surface of a hydrophilicized sheet of microporous poly(ethylene) prepared according to Example 3. The sheet was then placed on a glass plate and transferred to an oven and dried at a temperature of 60°C. The solution of partially cross-linked poly(ethenol) was applied to the same surface of the dried sheet and the sheet then returned to the oven and dried at 60°C. The dried membrane was then washed with cool water and air dried before evaluation for flux, total solids and salts rejection with different feed streams (water and milk).

Evaluation of samples of asymmetric composite membrane

Replicate samples (240818Si, 240818Sii, 240818Siii, 030918Si, 030918Sii, 030918Siii) of membrane prepared according to Example 9 were evaluated. The results of this evaluation are summarised in Table 1. Following an initial wetting with 20% (v/v) isopropanol in water, fluxes in the range 7.8 to 10.9 litres per square meter per hour (LMH) were obtainable for a feed stream of water at a pressure of 10 bar. Similar, if not slightly greater fluxes were obtained for a solution of salts with salt rejection in excess of 20%. For a feed stream of whole milk, fluxes were reduced but provided in excess of 50% total solids rejection and well in excess of greater than 99% protein rejection.

Sample	Initial flux (LMH)	Salt flux (LMH)	Salt rejection (%)	Milk flux (LMH)	Total solids rejection (%)	Protein rejection (%)
240818Si	10.9 at 10 bar	11.7 at 10 bar	20.3	-	-	
240818Sii	7.8 at 10 bar	10.7 at 10 bar	21.3	-	-	
240818Siii	8.9 at 10 bar	10.3 at 10 bar	28.4	4.5 at 10 bar	63.0	99.95
030918Si	2.1 at 5 bar	-	-	1.3 at 10 bar	-	99.83
030918Sii	-	-	-	0.7 at 5 bar	62.4	99.99
030918Siii	-	-	-	0.6 at 5 bar	55.7	100.00

Table 1. Evaluation of samples of asymmetric composite membrane prepared according to Example 9. The sample (240818Siii) demonstrating the highest salt rejection was also evaluated along with two other samples (030918Sii and 030918Siii) for total solids and protein rejection with milk as a feed stream.

One of the samples (030918Sii) was further evaluated for its tolerance to clean-in-place (CIP) protocols. One of the samples (030918Siii) was also further evaluated in a pressure series test to see how the flux and protein rejection were affected. The results of these further evaluations are summarised in Tables 2 and 3 and Figures 4 and 5.

Number of CIPs	Milk flux (LMH)	Total solids rejection (%)	Protein rejection (%)
0	0.7	62.4	99.99
1	2.3	55.9	99.94
2	2.0	–	99.94
3	4.7	50.7	99.93
4	5.0	46.3	99.88
5	5.7	42.0	99.84
10	5.7	49.0	99.87

Table 2. Flux, total solids and protein rejection of a sample of an asymmetric composite membrane (030918Sii) prepared according to Example 9 during repeated clean-in-place (CIP) protocols.

Pressure	Milk flux (LMH)	Protein rejection (%)
0	–	99.99
5	0.6	99.94
10	3.3	99.94
15	5.1	99.93
20	7.1	99.88

Table 3. Pressure series testing (0 to 20 bar) of a sample (030918Siii) of an asymmetric composite membrane prepared according to Example 9. Flux and protein rejection with milk as the feed stream were measured.

Although the invention has been described with reference to embodiments or examples it should be appreciated that variations and modifications may be made to these embodiments or examples without departing from the scope of the invention. Where known equivalents exist to specific elements, features or integers, such equivalents are incorporated as if specifically referred to in this specification. In particular, variations and modifications to the embodiments or examples that include elements, features or integers disclosed in and selected from the referenced publications are within the scope of the invention unless specifically disclaimed. The advantages provided by the invention and discussed in the description may be provided in the alternative or in combination in these different embodiments of the invention.

INDUSTRIAL APPLICABILITY

A durable asymmetric composite membrane with high levels of protein rejection whilst maintaining a high flux with feed streams such as whole milk is provided.

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