

Chemical Modification of Polyimides

The present invention relates to the chemical modification of polyimide membranes. In particular it relates to the chemical modification of polyimide membranes which form one layer (preferably the outer-layer) of dual-layer hollow fibres.

Polyimides are attractive membrane materials for gas separations because of their good gas separation and physical properties. Extensive work, including tailoring the chemical structures and performing cross-linking modifications by different methods such as thermal treatment, chemical treatment and UV irradiation, has been carried out aimed at obtaining polyimide membranes with better gas separation properties. Among all these efforts, cross-linking modification is expected to be the most promising approach to obtain better membranes which can be used under complex and harsh environments because it can impart polyimide membranes with anti-plasticisation properties and improved chemical resistance.

Most commercial membranes are in the form of hollow fibres because they offer a higher surface to volume ratio. Each hollow fiber membrane usually has an asymmetric cross-section morphology which consists of a thin dense selective layer and a porous supporting substrate. The asymmetric morphology gives the advantage of high flux which is required for practical applications of such membranes. US 5,085,676 discloses a process for preparing dual-layer hollow fibre gas separation membranes which structurally consist of a thin selective layer (usually the outer-layer) and a porous supporting substrate (usually the inner-layer). Not only do these dual-layer membranes have high flux advantages as for other asymmetric membranes, they

- 2 -

also optimise materials performance and reduce materials costs.

However, most polyimides suffer plasticization or
5 chemical attack induced by the sorption of CO₂, H₂S or other chemicals. Almost all the reported cross-linking modifications of polyimides to enhance chemical resistance and anti-plasticization characteristics have been conducted on thick and flat dense films,
10 which may have very limited applications for the modification of hollow fibre membranes. For example, US 4,717,393 presents photo-chemical methods for the cross-linking modification of particular polyimides containing benzophenone groups and hydrogen donor
15 groups such as methyl groups. Although this method produces cross-linked polyimides with high gas permselectivity, the gas permeability of these cross-linked polyimides is too low. US 4,981,497 describes a process to modify polyimide membranes with amino
20 compounds. The modification results in lower gas permeation rates as compared to the uncross-linked membranes but is limited to thick dense polyimide films and requires thermal treatment in order to complete the reaction. US 4,931,182 discloses a class
25 of polyimide membranes containing copolymerizable, surface-modifiable units containing both aromatic diamines and alkenylated diamines having a vinyl or vinylaryl group preferably positioned ortho to an amine functionality. The polyimide membranes can be
30 cross-linked by treatment with an activating force such as high energy electromagnetic irradiation or with a free radical source to impart high selectivity to the membranes with a large decrease in composite permeance. Unfortunately, hollow fibres from these
35 kinds of polyimides cannot be easily fabricated.

Therefore, it is essential to investigate new and practical cross-linking modification technologies for polyimide membranes, in particular with the aim of finding processes which can be suitably applied to the manufacture of hollow fibres.

Accordingly, the present invention provides a process for chemically modifying a dual-layer hollow fibre, wherein said fibre comprises a first layer consisting essentially of a polyimide and a second layer consisting essentially of a polymer which is substantially unaffected by the chemical modification process, which process comprises contacting said polyimide layer with a polyamine.

As used herein the term "polyimide" includes blends of two or more different polyimides.

As used herein the term "polymer" includes copolymers and blends of two or more different polymers and/or copolymers.

As used herein, the term "substantially unaffected by the chemical modification process" when used to qualify the nature of the polymer, means that the physical and/or chemical properties of the polymer which make it suitable for use as a support layer for the polyimide remain unaffected by the chemical modification process or are only affected to an extent which does not significantly affect its performance as a support layer for the polyimide.

In a preferred embodiment, the polyimide forms the outer-layer of the dual-layer hollow fibre and the polymer which is substantially unaffected by the chemical modification process forms the inner-layer of the dual-layer hollow fibre.

- 4 -

In one embodiment of the invention, the polyamine may contact only one side of the polyimide layer.

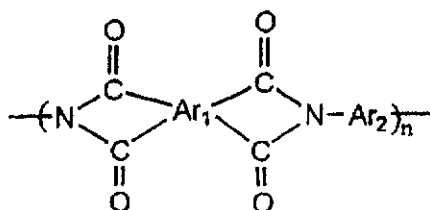
Preferably, the polyimide layer is contacted with the polyamine at a temperature in the range of from 5°C to 50°C, more preferably in the range of from 15°C to 30°C.

In one embodiment of the invention, the polyamine is contacted with the polyimide layer in the form of a solution in a suitable solvent. In this case, contact may be effected by simply dipping the dual-layer hollow fibre in the solution. When a solution of polyamine is used the polyimide layer is preferably washed with the solvent after contact with the polyamine solution. Preferred solvents include water and alcohols which are liquid at ambient temperature, such as methanol. Methanol is particularly preferred.

In a preferred embodiment, at the end of the process, the dual-layer hollow fibre is dried at a temperature in the range of from 5°C to 80°C, more preferably at a temperature in the range of from 15°C to 40°C.

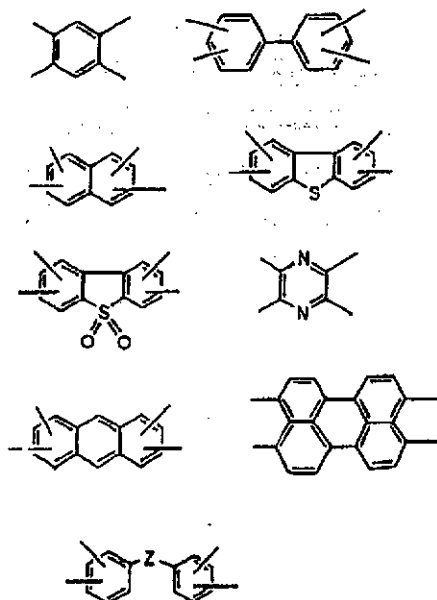
Whilst the process of the present invention could be applied to many types of polyimide, a preferred polyimide for use in the polyimide layer is an aromatic polyimide membrane.

Preferably the polyimide layer consists essentially of the following structural units:



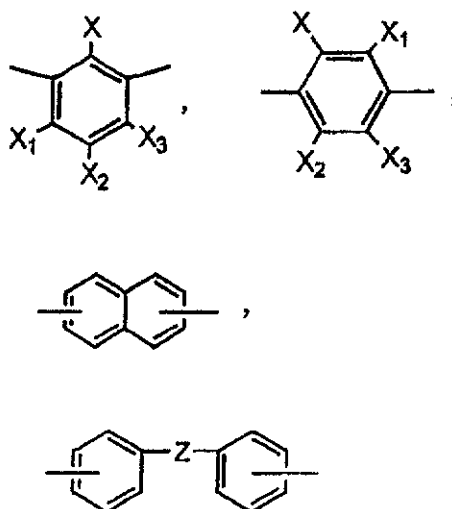
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where each of the n Ar_1 groups is a quadrivalent aromatic moiety independently selected from the group consisting of:



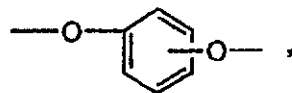
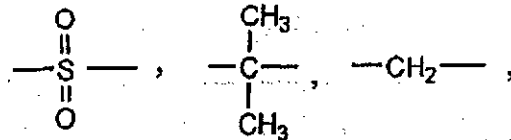
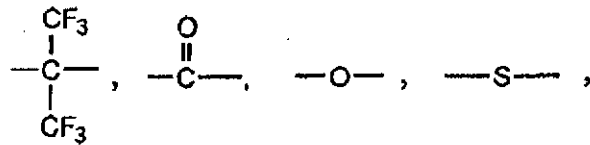
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and where each of the n Ar_2 groups is a bivalent aromatic moiety independently selected from the group consisting of:



- 6 -

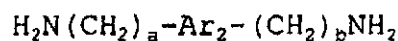
where Z is selected from the group consisting of:



and where X, X₁, X₂ and X₃ are each independently selected from hydrogen, C₁₋₅alkyl, C₁₋₅alkoxy, phenyl or phenoxy.

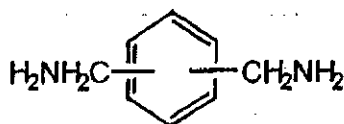
The value of n must be sufficient to provide a viable polymer membrane for use as the polyimide layer of a dual layer hollow fibre. Preferably, n is a number sufficient that said polymer has an inherent viscosity of at least 0.3 dL/g as measured at 25°C on a 0.5% by weight solution in N-methylpyrrolidinone.

In a preferred embodiment of the present invention, the polyamine is an aliphatic-aromatic polyamine. More preferably, the polyamine is an aliphatic-aromatic diamine. Even more preferably, the polyamine is an aliphatic-aromatic diamine having the general structure:



- 7 -

where Ar₂ is as defined above and a and b are each independently selected from the range 1 to 6. Still more preferably, the polyamine is an aliphatic-aromatic diamine having the general structure:



Most preferably, the polyamine is selected from m-xylylenediamine or p-xylylenediamine.

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As previously mentioned, the polyamine may be used in the form of a solution. In a preferred embodiment of the process, the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 2wt% to 50wt% based on the total weight of the solution. More preferably, the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 2wt% to 20wt% based on the total weight of the solution. Most preferably, the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 5wt% to 10wt% based on the total weight of the solution.

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The identity of the inert (or non-crosslinked) layer material is not critical to the present invention. It is simply necessary that it remain substantially unaffected by the modification process. Suitable polymers for forming the inert layer may be selected from polyesters, polysulfone, polycarbonate, polyetherketone, polyetheretherketone, polyethersulfone, polyetherimide, polyacrylonitrile,

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- 8 -

polyamide and polyolefin. Polyethersulfone and polysulfone are particularly preferred.

5 The present invention also provides for a chemically modified dual-layer hollow fibre obtainable by a process as previously described.

10 The present invention also provides for a process for separating at least one gas from a mixture of two or more gases, which process comprises bringing a pressurised mixture of said gases into contact with a dual-layer hollow fibre obtainable by a process as previously described. The gas mixtures for separation may be selected from mixtures of He and N₂, H₂ and N₂, O₂ and N₂, CO₂ and CH₄, CO₂ and H₂S and CH₄, and CO₂ and H₂S and CH₄ and C₂-C₄ hydrocarbons. The dual-layer hollow fibre obtainable by a process as previously described is particularly useful for separation of a mixture of CO₂ and CH₄ or a mixture of CO₂ and H₂S and CH₄.

25 In another aspect, the present invention also provides a process for chemically modifying a polyimide membrane, which process comprises contacting said membrane with an alcoholic solution of an aliphatic-aromatic polyamine.

30 Alcohols suitable for use as the solvent include any alcohol which is liquid at ambient temperature and is capable of solubilising the aliphatic-aromatic polyamine. Methanol is a particularly preferred solvent.

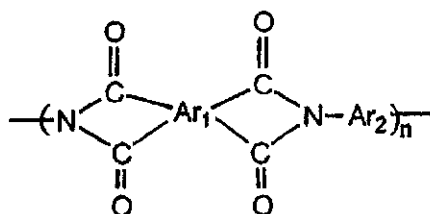
35 Preferably, the membrane is contacted with the solution at a temperature in the range of from 5°C to 50°C, more preferably at a temperature in the range of from 15°C to 30°C.

- 9 -

In a preferred embodiment of the process, the membrane is washed with the alcoholic solvent after contact with the solution.

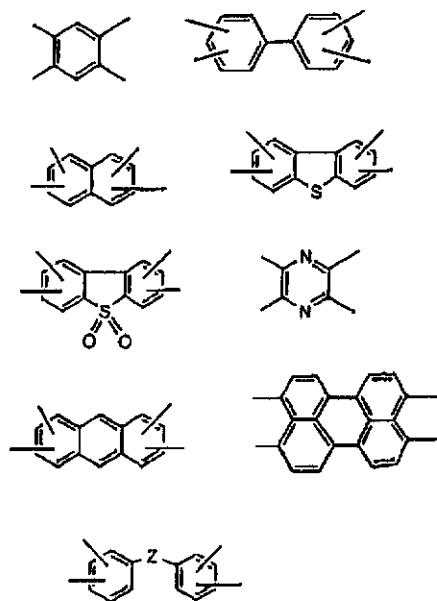
- 5 In another preferred embodiment of the process, after contact with the solution or after being washed with the alcoholic solvent, the membrane is dried at a temperature in the range of from 5°C to 80°C, more preferably at a temperature in the range of from 15°C
10 to 40°C.

In a preferred embodiment of the process, the polyimide membrane is an aromatic polyimide membrane. More preferably, the polyimide membrane consists
15 essentially of the following structural units:

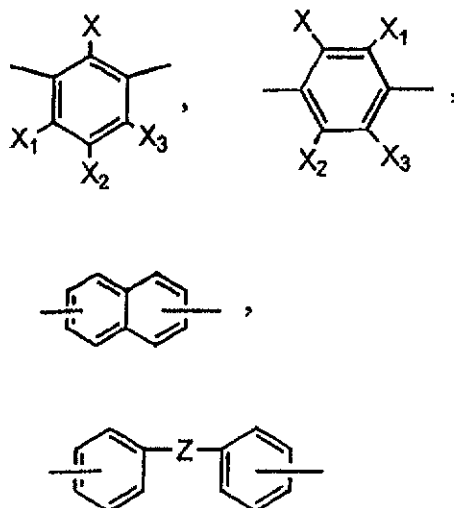


where each of the n Ar₁ is a quadrivalent aromatic moiety independently selected from the group
20 consisting of:

- 10 -

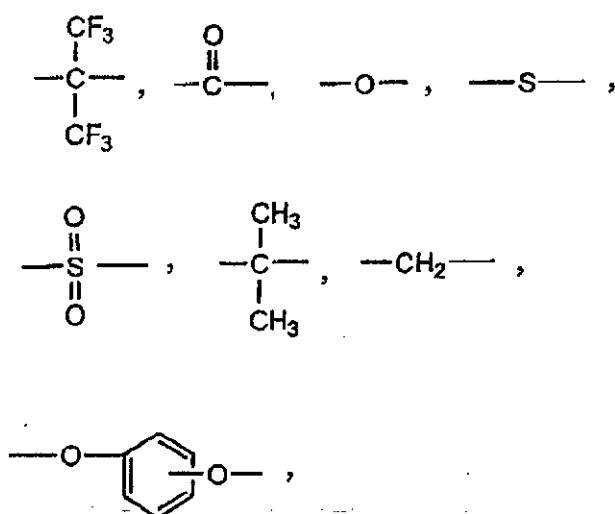


and where each of the n Ar_2 groups is a bivalent aromatic moiety independently selected from the group consisting of:



where Z is selected from the group consisting of:

- 11 -



and where X, X₁, X₂ and X₃ are each independently selected from hydrogen, C₁₋₅alkyl, C₁₋₅alkoxy, phenyl or phenoxy.

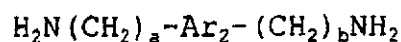
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The value of n must be sufficient to provide a viable polymer membrane. Preferably, n is a number sufficient that said polymer has an inherent viscosity of at least 0.3 dL/g as measured at 25°C on a 0.5% by weight solution in N-methylpyrrolidinone

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In a preferred embodiment of the process, the aliphatic-aromatic polyamine is an aliphatic-aromatic diamine. More preferably, the aliphatic-aromatic polyamine is an aliphatic-aromatic diamine having the general structure:

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where Ar₂ is as defined above and a and b are each independently selected from the range 1 to 6. Still more preferably, the aliphatic-aromatic polyamine is

- 12 -

an aliphatic-aromatic diamine having the general structure:



5 Most preferably, the aliphatic-aromatic polyamine is selected from m-xylylenediamine or p-xylylenediamine.

10 Preferably, the aliphatic-aromatic polyamine is present in the solution in a concentration of from 2wt% to 50wt% based on the total weight of the solution. More preferably the aliphatic-aromatic polyamine is present in the solution in a concentration of from 2wt% to 20wt% based on the total weight of the solution. Most preferably, the aliphatic-aromatic polyamine is present in the solution in a concentration of from 5wt% to 10wt% based on the total weight of the solution.

20 In a preferred embodiment, the polyimide membrane is in the form of a hollow fibre.

In a particularly preferred embodiment, the polyimide membrane is the selective layer of a dual-layer hollow fibre, the support layer of said dual-layer hollow fibre comprising a polymer which is substantially unaffected by the chemical modification process. Most preferably, the polyimide membrane forms the outer layer of said dual-layer hollow fibre.

30 The novelty of the present invention resides in the use of alcoholic (preferably methanolic) solutions of rigid aliphatic-aromatic diamines such as p-xylene diamines as a chemical cross-linking reagent for polyimides and in particular for dual-layer hollow fibres with polyimides as the selective layer.

Advantageously, the modification can be performed at ambient temperature, and adopting inert materials as the support layer of dual-layer hollow fibre membranes helps to reduce the side effects of chemical
5 modification which often makes such processes unsuitable for application to dual-layer hollow fibres. This invention provides a feasible method for the production of high-selectivity and anti-plasticisation dual-layer hollow fibres for gas
10 separation and also provides an improved general method of chemical modification of polyimides (which may be in the form of single or dual-layer hollow fibres for gas separation).

15 The processes of this invention can produce high-selectivity and anti-plasticisation single-layer and dual-layer hollow fibres containing a chemically cross-linked polyimide layer for gas separation. The gas mixtures include the mixtures of H_2/N_2 , CO_2/CH_4 and
20 O_2/N_2 . Also the membranes fabricated can be used for separation of volatile organic mixtures.

Figure 1 shows scanning electron micrograph (SEM) pictures of the cross-section of
25 polyimide/polyethersulfone(PES) dual-layer hollow fibre membranes.

Figure 2 shows typical FTIR spectra of the outer-layers of unmodified and cross-linked dual-layer
30 hollow fibres.

Figure 3 shows FTIR spectra of the PES inner-layers of unmodified and cross-linked dual-layer hollow fibres.

35 Figure 4 shows the effect of feed pressure on N_2 permeances of virgin and cross-linked polyimide/PES dual-layer hollow fibres.

Figure 5 shows the effect of feed pressure on CO₂ permeances of virgin and cross-linked polyimide/PES dual-layer hollow fibres.

5 Examples

Preparative Example 1

A stoichiometric amount of 2,2'-bis(3,4-carboxylphenyl) hexafluoropropane dianhydride (6FDA) was added to an N-methylpyrrolidinone (NMP) solution of 2,3,5,6-tetramethyl-1,4-phenylene diamine (durene diamine) and 1,3-phenylene diamine (mPDA) (the molar ratio of durene diamine to mPDA was 50:50) with stirring under argon at ambient temperature. 24 h later, a mixture of acetic anhydride and triethylamine (the molar ratio of acetic anhydride/triethylamine to 6FDA was 4:1) was slowly added to the solution to complete imidization for 24 h. The polymer was slowly precipitated in methanol. After being filtered and washed with fresh methanol, the resultant polymer was dried under 150 °C in vacuum for 24 h. Its inherent viscosity was measured to be 1.00 dL/g in NMP.

Preparative Example 2

The spinning of dual-layer hollow fibers was carried out as follows. 26wt% 6FDA-durene/mPDA (50:50) in a solvent mixture of NMP/THF (5:3 by weight) was chosen as the dope to yield the outer dense selective layer, whereas 28wt % polyethersulfone (PES) in a solvent mixture of NMP/H₂O (10:1 by weight) was selected as the dope to form the inner porous substrate layer. The two dopes were delivered to the spinneret by two metering pumps at a rate of 0.2 ml/min for the outer layer and 0.6 ml/min for the inner layer, respectively. The spinneret temperature was controlled at 60°C. A 95:5 mixture solvent of NMP: H₂O in weight was selected as the bore fluid and delivered by an

- 15 -

ISCO 500D syringe pump at a rate of 0.2 ml/min. After passing through an air gap of 0.3 cm, the nascent hollow fibers were drawn into a tap water coagulation bath at ambient temperature and collected at a take-up velocity of 40 cm/min. After having been stored in water for 3 days at room temperature, the dual-layer hollow fibers were immersed in methanol three times and then in hexane three times for solvent exchange. Fresh solvents were used in each solvent exchange with a duration of 30 min. Subsequently, thermal treatments of the hollow fibers were carried out progressively under vacuum at 35°C, 45°C, 55°C, 65°C for 30 min, respectively, and finally at 75° C for 1 hour.

SEM photomicrographs of the dual-layer asymmetric hollow fibres are shown in Figure-1. For SEM experiments the dual-layer hollow fibres were fractured after being immersed in liquid nitrogen, and then sputtered with gold using a JEOL JFC-1100E ion sputtering device. A Philips XL30-SEM was used to investigate the fibre morphology. The dual-layer hollow fibres have a good concentricity with a center bore diameter of 170 µm. Figure 1 exhibits the asymmetric morphology of the outer layer which consists of a thin dense selective layer near the outer surface. The thickness of the outer polyimide layer and inner PES porous layer are 10 and 100 µm, respectively. No delamination between the outer layer and inner layer is observed. The inner layer is comprised of macrovoids with interconnected porosities which may significantly minimize the substructure resistance for gas transport. As a result, the outer polyimide layer determines gas separation performance properties of the dual layer hollow fibres.

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Five modules were prepared by sealing one of the ends of a bundle of 10 dual-layer fibres with a length of

- 16 -

20 cm with a 5 min rapid solidified epoxy resin (Araldite®, Switzerland) and gluing the other end onto an aluminum holder with an epoxy resin H-711 (Tianjin Jindong Chemical Plant, Tianjin, P. R. China) cured by using a hardener 105 (Changsha Institute of Chemical Engineering, Changsha, P. R. China).

The O₂ and CH₄ permeation rates were conducted at 200 psi, while N₂ and CO₂ were at a pressure range from 50 to 500 psi. All measurements took place at 24°C. The gas permeance and separation factor were determined using a bubble-flow meter and calculated based on the equation described in a previous paper [J. J. Shieh, T. S. Chung, Cellulose nitrate-based multilayer composite membranes for gas separation, J. Membr. Sci., 66 (2000) 259]. Table 1 summarizes the gas permeation properties of these modules just after their fabrication.

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Table 1

Gas separation properties of the as-spun polyimide-polyethersulfone dual-layer hollow fibre modules.^a

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Module No.	Permeance (GPU) ^b		Separation Factor		
	CO ₂	O ₂	O ₂ /N ₂	CO ₂ /N ₂	CO ₂ /CH ₄
1	240	27.0	4.1	37	56
2	227	31.0	4.5	33	47
3	206	29.7	4.3	30	40
4	219	32.1	4.1	28	38
5	218	23.7	4.4	41	60

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^a measured at 24°C, for CO₂ and other gases the feed pressure was 100 and 200 psi respectively.

^b 1 GPU = 1 × 10⁻⁶ cm³(STP)/cm².sec.cmHg.

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Comparative Example 1 and Examples 2-5

In order to remove the plasticization effects of CO₂ during and subsequently after the permeance measurements, chemical cross-linking modification of the modules was carried out 5 days after the CO₂ permeance tests. Module 1 is used as the reference and modules 2, 3, 4 and 5 were immersed in a 5% (wt/v) p-xylenediamine methanol solution for 0.5, 1, 3 and 5 min respectively.

ATR-FTIR measurements were carried out utilizing a Perkin Elmer FTIR spectrometer and carefully flattened hollow fibres. Figure 2 shows a comparison of FTIR spectra of the outer layers of polyimide dual-layer hollow fibers before and after the cross-linking modification. The characteristic peaks of amide group at 1660 cm⁻¹ (asymmetric stretch of C=O in the amide group) and 1539 cm⁻¹ (symmetric stretch of C=O in the amide group) appear after the modification as shown in Figures 2b to 2e. With the progress of chemical modification, the intensities of the characteristic peaks of imide group at 1786 cm⁻¹ (asymmetric stretch of C=O in the imide group), 1713 cm⁻¹ (symmetric stretch of C=O in the imide group) and 1350 cm⁻¹ (stretch of C-N in the imide group) decrease with an increase in the immersion time. These phenomena show that the reactions between p-xylenediamine and imide groups produce amide groups and form the chemical cross-linking.

Figure 3 shows a comparison of the polyethersulfone inner-layer's FTIR spectra of the unmodified and modified dual-layer hollow fibers after carefully removing the polyimide outer layer. No apparent changes in the chemical structure of the PES inner layer can be detected in Figure 3b as compared with

3a. It clearly indicates the inert property of the PES inner layer to the proposed chemical cross-linking modification. The modified sample is obtained by immersing the hollow fibers in a 5% wt/v p-xylenediamine methanol solution for 16 h. However, the chemical modification induces significant changes in the chemical structure of the polyimide outer layer illuminated by the comparison of Figures 2a to 2e. The inert property of the PES inner-layers gives assurance that there is no significant adversary effect of the chemical cross-linking modification on the substrate layer. For example, in the case of mechanical properties, the cross-linked dual-layer hollow fibers obtained by an immersion in a 5% wt/v p-xylenediamine methanol solution for 16 h remain flexible, while a 1h immersion makes single layer 6FDA-durene/MPDA (50:50) hollow fibers fragile.

Table 2 tabulates the gas separation properties of the reference module and cross-linking modified modules, which are referred to as module 1a, 2c, 3c, 4c and 5c correspondingly. Since the dual layer membranes were fabricated using the phase inversion technique, the precipitation process is a non-equilibrium stage. Similar to single layer asymmetric hollow fiber membranes [W. J. Koros, G. K. Fleming, Membrane-based gas separation, J. Membr. Sci., 83 (1993) 1; S. A. Stern, Polymers for the gas separation: the next decade, J. Membr. Sci., 94 (1994) 1; T. S. Chung, S. K. Teoh, The ageing phenomenon of polyethersulfone hollow fiber membranes for gas separation and their characteristics, J. Membr. Sci., 152 (1999) 175], the permeance of the as-spun dual layer membranes drops steeply during the 40 days following fabrication and levels off thereafter. This ageing phenomenon is a typical nature of glass polymers, which have the tendency to relax and densify toward an equilibrium

state. The densification reduces the free volume and interstitial space among polymeric chains available for gas transport. Thus, a comparison of Tables 1 and 2 indicate a significant permeance drop for the unmodified module after seven days of ageing (5 days to remove the CO₂ effects after permeance measurements and two days for cross-linking modification).

Table 2

Gas separation properties of the reference and cross-linked polyimide-polyethersulfone dual-layer hollow-fibre modules.^a

Module No.	Immersion time (min)	Permeance (GPU) ^b		Separation Factor		
		CO ₂	O ₂	O ₂ /N ₂	CO ₂ /N ₂	CO ₂ /CH ₄
1a	0	70.4	12.9	3.6	25	40
2c	0.5	59.2	8.86	3.5	30	55
3c	1	57.8	7.60	3.0	24	46
4c	3	32.7	3.73	3.4	40	84
5c	5	28.3	3.01	3.8	41	101

^a measured at 23°C, the feed pressure of O₂ and N₂ was 200 psi and of CO₂ was 100 psi.

^b 1 GPU = 1 x 10⁻⁶ cm³(STP)/cm².sec.cmHg.

A comparison of the cross-linked modules 2c, 3c, 4c and 5c with the reference module 1a listed in Table 2 clearly shows that cross-linking modification of dual-layer hollow fibers leads to a decrease in gas permeation rate and an increase in gas separation factor, especially for CO₂/CH₄. In addition, a longer immersion results in a lower gas permeation rate.

Figures 4 and 5 display the gas permeation rates of relatively un-condensable gas, N₂, and relatively

condensable gas, CO_2 , measured over a pressure range from 50 to 500 psi at 23 °C.

Since polyimide/PES dual-layer hollow fibres cannot be
5 plasticized by the absorption of N_2 , the experimental
results shown in Figure 4 indicate that the N_2
permeance of the dual-layer hollow fibres decreases
with an increase in the feed pressure. This
relationship is consistent with the partially
10 immobilized dual-sorption model because the Langmuir
sites are rapidly saturated and also have a much less
contribution to the overall diffusivity. In contrast,
Figure 5 illustrates that the CO_2 permeance of the
dual-layer hollow fibers shows an upward relationship
15 with increasing feed pressure in the whole pressure
range from 50 to 500 psi. This phenomenon arises from
the fact that plasticization induced by the absorption
of condensable CO_2 results in increased free volume
and polymer chain mobility. The upward inflection in
20 gas permeability when the feed pressure is higher than
the plasticization pressure has been extensively
investigated on thick polymeric dense films. However,
the degree of CO_2 plasticization on thick dense films
and dual layer fibers are different. Figure 5 depicts
25 that the CO_2 permeance of the unmodified dual-layer
hollow fibers, module 1a, increases with increasing
pressure in the whole measurement range starting from
50 psi, and by about 4.1 times when the feed pressure
reaches 500 psi. Under the similar situation, the
30 increase is by about 2 times for a 20 mm polyimide
dense film of similar structure [M. J. Thundiyil, Y. H.
Jois, W. J. Koros, Effect of permeate pressure on the
mixed gas permeation of carbon dioxide and methane in
a glassy polyimides, J. Membr. Sci., 152 (1999) 29].
35 The higher permeance increase is due to the fact that
the plasticization initiates at a lower feed pressure
for the dual-layer hollow fibers, indicating the thin

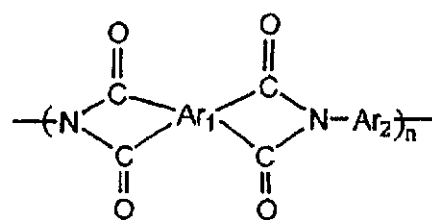
asymmetric polyimide outer layer is more subject to plasticization than a thick dense film. A similar phenomenon has been observed by Prof. Koros' research group [S. M. Jordan, M. A. Henson, W. J. Koros, The effect of carbon dioxide conditioning on the permeation behavior of hollow fiber asymmetric membranes, J. Membr. Sci., 54 (1990) 103] where they reported the plasticisation of single-layer asymmetric hollow fibers is heavier than that of thick and flat dense films. The easier plasticization for asymmetric hollow fibers probably resulted from the fact that the thin dense selective layer of hollow fibers consists of loose packed nodules. Thus, they can be swelled easily with the CO₂ absorption.

Figure 5 shows that the proposed chemical cross-linking modification is efficient to suppress the plasticisation of the dual-layer hollow fibers induced by CO₂. The cross-linked dual-layer hollow fibers, modules 2c, 3c, 4c, and 5c, obviously have lower permeance increases with an increase in the feed pressure when compared with unmodified module 1a. In addition, a higher degree of cross-linking resulting from a longer time immersion leads to a lower plasticization tendency. The improvements in anti-plasticisation properties is mainly attributed to the fact that the proposed cross-linking modification tightens and strengthens the polyimide nodules, thus reduces the CO₂ sorption and hinders the nodules from swelling. As a result, the integrity of the outer thin dense selective layer and its effective thickness are less susceptible to CO₂ sorption after the chemical modification.

Claims

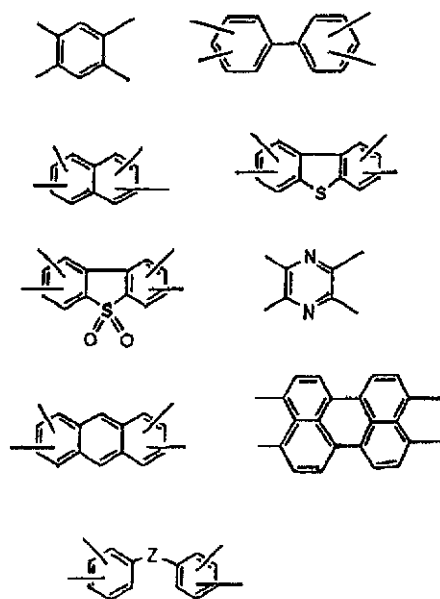
1. A process for chemically modifying a dual-layer hollow fibre, wherein said fibre comprises a
5 first layer consisting essentially of a polyimide and a second layer consisting essentially of a polymer which is substantially unaffected by the chemical modification process, which process comprises contacting said polyimide layer with a
10 polyamine.
2. A process as claimed in claim 1 wherein the polyimide forms the outer-layer of the dual-layer hollow fibre and the polymer which is
15 substantially unaffected by the chemical modification process forms the inner-layer of the dual-layer hollow fibre.
3. A process as claimed in any preceding claim
20 wherein the polyamine contacts only one side of the polyimide layer.
4. A process as claimed in any preceding claim wherein the polyimide layer is contacted with the
25 polyamine at a temperature in the range of from 5°C to 50°C.
5. A process as claimed in any preceding claim wherein the polyimide layer is contacted with the
30 polyamine at a temperature in the range of from 15°C to 30°C.
6. A process as claimed in any preceding claim wherein the polyamine is in the form of a
35 solution in a suitable solvent when it is contacted with the polyimide layer.

7. A process as claimed in claim 6 wherein the polyimide layer is washed with the solvent after contact with the polyamine solution.
- 5 8. A process as claimed in any preceding claim wherein, at the end of the process, the dual-layer hollow fibre is dried at a temperature in the range of from 5°C to 80°C.
- 10 9. A process as claimed in any preceding claim wherein, at the end of the process, the dual-layer hollow fibre is dried at a temperature in the range of from 15°C to 40°C.
- 15 10. A process as claimed in any preceding claim wherein the polyimide layer is an aromatic polyimide membrane.
- 20 11. A process as claimed in any preceding claim wherein the polyimide layer consists essentially of the following structural units:

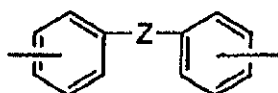
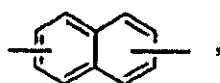
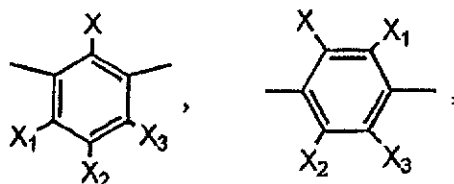


- 25 where each of the n Ar₁ groups is a quadrivalent aromatic moiety independently selected from the group consisting of:

- 24 -



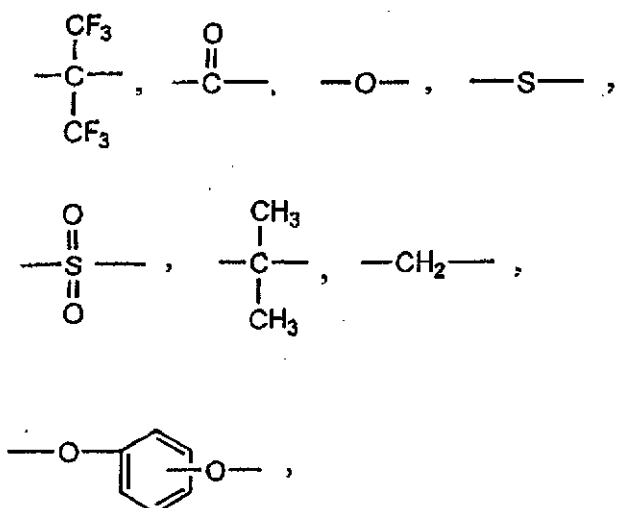
and where each of the n Ar_2 groups is a bivalent aromatic moiety independently selected from the group consisting of:



5

where Z is selected from the group consisting of:

- 25 -



and where X, X₁, X₂ and X₃ are each independently selected from hydrogen, C₁₋₅alkyl, C₁₋₅alkoxy, phenyl or phenoxy.

5

12. A process as claimed in claim 11 where n is a number sufficient that said polymer has an inherent viscosity of at least 0.3 dL/g as measured at 25°C on a 0.5% by weight solution in N-methylpyrrolidinone.

10

13. A process as claimed in any preceding claim wherein the polyamine is an aliphatic-aromatic polyamine.

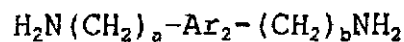
15

14. A process as claimed in any preceding claim wherein the polyamine is an aliphatic-aromatic diamine.

20

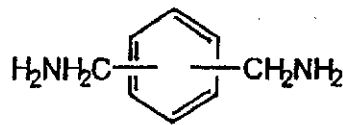
15. A process as claimed in any preceding claim wherein the polyamine is an aliphatic-aromatic diamine having the general structure:

- 26 -



where Ar_2 is as defined in claim 10 above and a and b are each independently selected from the range 1 to 6.

16. A process as claimed in any preceding claim wherein the polyamine is an aliphatic-aromatic diamine having the general structure:



17. A process as claimed in any preceding claim wherein the polyamine is selected from m-xylylenediamine or p-xylylenediamine.
18. A process as claimed in any preceding claim wherein the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 2wt% to 50wt% based on the total weight of the solution.
19. A process as claimed in any preceding claim wherein the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 2wt% to 20wt% based on the total weight of the solution.
20. A process as claimed in any preceding claim wherein the polyamine is contacted with the polyimide layer in the form of a solution having a concentration of polyamine of from 5wt% to 10wt% based on the total weight of the solution.

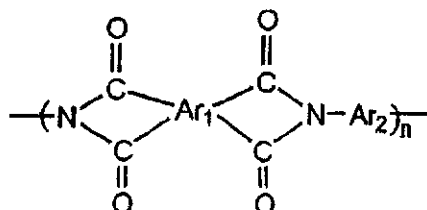
- 27 -

21. A chemically modified dual-layer hollow fibre obtained by a process as claimed in any one of claims 1 to 20.
- 5 22. A process for separating at least one gas from a mixture of two or more gases, which process comprises bringing a pressurised mixture of said gases into contact with a dual-layer hollow fibre as claimed in claim 21.
- 10 23. A process as claimed in claim 22 wherein the gas mixtures for separation are selected from mixtures of He and N₂, H₂ and N₂, O₂ and N₂, CO₂ and CH₄, CO₂ and H₂S and CH₄, and CO₂ and H₂S and CH₄ and C₂-C₄ hydrocarbons.
- 15 24. A process as claimed in claim 22 wherein the gas mixtures for separation are selected from mixtures of CO₂ and CH₄, and CO₂ and H₂S and CH₄.
- 20 25. A process for chemically modifying a polyimide membrane, which process comprises contacting said membrane with an alcoholic solution of an aliphatic-aromatic polyamine.
- 25 26. A process as claimed in claim 25 wherein the alcoholic solution of an aliphatic-aromatic polyamine is a methanolic solution of an aliphatic-aromatic polyamine.
- 30 27. A process as claimed in claim 25 or claim 26 wherein the membrane is contacted with the solution at a temperature in the range of from 5°C to 50°C.
- 35 28. A process as claimed in any one of claims 25 to 27 wherein the membrane is contacted with the

- 28 -

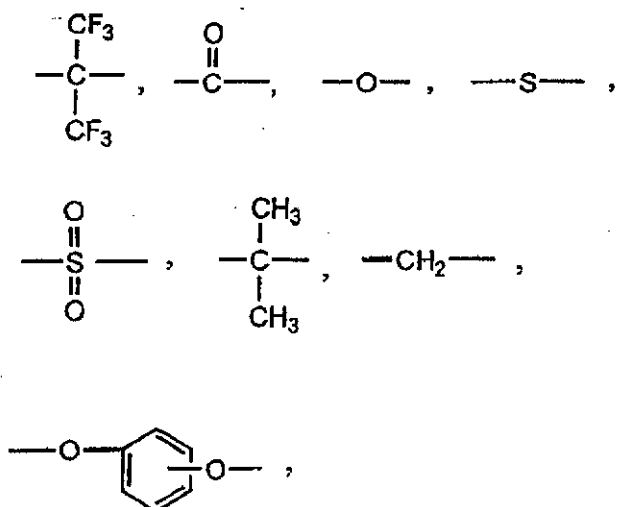
solution at a temperature in the range of from 15°C to 30°C.

29. A process as claimed in any one of claims 25 to 28 wherein the membrane is washed with the alcoholic solvent after contact with the solution.
30. A process as claimed in any one of claims 25 to 29 wherein, after contact with the solution or after being washed with the alcoholic solvent, the membrane is dried at a temperature in the range of from 5°C to 80°C.
31. A process as claimed in claim 30 wherein the membrane is dried at a temperature in the range of from 15°C to 40°C.
32. A process as claimed in any one of claims 25 to 31 wherein the polyimide membrane is an aromatic polyimide membrane.
33. A process as claimed in any one of claims 25 to 32 wherein the polyimide membrane consists essentially of the following structural units:



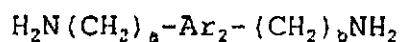
where each of the n Ar_1 groups is a quadrivalent aromatic moiety independently selected from the group consisting of:

- 30 -



and where X, X₁, X₂ and X₃ are each independently
 selected from hydrogen, C₁₋₅alkyl, C₁₋₅alkoxy,
 phenyl or phenoxy.

34. A process as claimed in claim 33 where n is a
 number sufficient that said polymer has an
 inherent viscosity of at least 0.3 dL/g as
 measured at 25°C on a 0.5% by weight solution in
 N-methylpyrrolidinone
35. A process as claimed in any one of claims 25 to
 34 wherein the aliphatic-aromatic polyamine is an
 aliphatic-aromatic diamine.
36. A process as claimed in any one of claims 25 to
 35 wherein the aliphatic-aromatic polyamine is an
 aliphatic-aromatic diamine having the general
 structure:



where Ar_2 is as defined above and a and b are each independently selected from the range 1 to 6.

- 5 37. A process as claimed in any one of claims 25 to 36 wherein the aliphatic-aromatic polyamine is an aliphatic-aromatic diamine having the general structure:



10

38. A process as claimed in any one of claims 25 to 37 wherein the aliphatic-aromatic polyamine is selected from m-xylylenediamine or p-xylylenediamine.

15

39. A process as claimed in any one of claims 25 to 38 wherein the aliphatic-aromatic polyamine is present in the solution in a concentration of from 2wt% to 50wt% based on the total weight of the solution.

20

40. A process as claimed in any one of claims 25 to 39 wherein the aliphatic-aromatic polyamine is present in the solution in a concentration of from 2wt% to 20wt% based on the total weight of the solution.

25

41. A process as claimed in any one of claims 25 to 40 wherein the aliphatic-aromatic polyamine is present in the solution in a concentration of from 5wt% to 10wt% based on the total weight of the solution.

30

42. A process as claimed in any one of claims 25 to 41 where the polyimide membrane is in the form of a hollow fibre.
- 5 43. A process as claimed in any one of claims 25 to 41 where the polyimide membrane is the outer-layer of a dual-layer hollow fibre, the inner-layer of said dual-layer hollow fibre comprising a polymer which is substantially unaffected by
10 the chemical modification process.
44. A process as claimed in any one of claims 25 to 41 where the polyimide membrane is the inner-layer of a dual-layer hollow fibre, the outer-layer of said dual-layer hollow fibre comprising
15 a polymer which is substantially unaffected by the chemical modification process.
- 20