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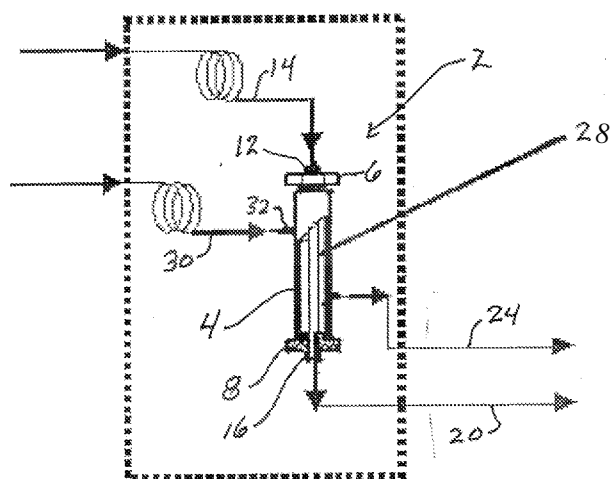


Figure 5

(57) **Abstract:** This invention presents a metal-doped zeolite membrane-based apparatus containing molecular sieving zeolite thin film on the seeded porous substrate. The metal-doped zeolite membrane exhibits high selectivity to olefin over paraffins. The membrane is synthesized by seed coating and secondary growth method, followed by metal doping and post treatment processes.

## COMPOSITE MEMBRANES FOR OLEFIN/PARAFFIN SEPARATION

STATEMENT REGARDING FEDERALLY SPONSORED  
RESEARCH OR DEVELOPMENT

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## FIELD OF THE INVENTION

[002] The present invention is directed to a metal-doped zeolite membrane, methods for making the zeolite membrane, and methods of separating olefins from paraffins using the zeolite membrane. The zeolite membrane comprises molecular sieving zeolite thin film with high selectivity to olefin over paraffins. The membrane is synthesized by seed coating and secondary growth method, and delivers high flux and selectivity with excellent durability.

## BACKGROUND OF THE INVENTION

[003] Olefins are the basic industrial synthetic building blocks for producing common plastics: synthetic fibers, glycols, and various surfactants. Ethylene and propylene are typically produced *via* steam cracking of naphtha, ethane, and other hydrocarbon feedstock, followed by distillation. In the conventional distillation process, ethylene/ethane, or propylene/propane mixtures are liquefied for cryo-distillation in large fractionating columns, which involves phase change and consumes a huge amount of energy. To reduce the energy consumption, alternative technologies have been actively sought after in both industry and academic research community. As a result, a number of processes have been proposed to solve the problem. Adsorption appears to be an attractive alternative because of the maturity of the basic technology. However, to obtain the olefin products with desirable purity, pressure-, vacuum-, and temperature-swing adsorption

(PSA, VSA, and TSA) processes have to be operated in at least a four-bed, five-step fashion that results in a high energy demand and a large capital investment.

[004] Membrane separation for olefin/paraffin mixtures offers an appealing energy-efficient alternative to the cryo-distillation process. Great effort has been dedicated in developing a high flux, high selectivity olefin separation membrane. The state-of-the-art membrane cannot meet the stringent requirements of real life olefin/paraffin separation, mainly due to problems such as trade-off between selectivity and flux; poor stability, especially in practical operating environments; and fouling or poisoning in the presence of contaminants (olefin, alkynes, dienes, olefin sulfide, and other sulfur species).

[005] Membrane candidates have been proposed ranging from polymers, ceramics, to the composites of polymers and ceramics. Although polymeric membranes have been used successfully in several gas separation applications, including nitrogen production from air and olefin removal from refinery streams, the selectivity and gas fluxes of such membranes are inadequate for separating olefins from saturated hydrocarbons. Under industrial operating conditions, those polymeric membranes suffer from plasticization. Even the best polymeric membranes can only offer olefin/paraffin selectivity of 4-5. To replace or supplement distillation for the separation of olefin/paraffin in steam crackers or propane de-olefination plants, membranes with selectivity of twenty or more are needed.

[006] Facilitated transport membranes have attracted research interest for a long time. Facilitated transport membranes incorporate a reactive carrier in the membrane, which reacts with and helps transport one of the components of the feed across the membrane. High loadings (more than 80 wt% or 40 vol%) of silver salt ( $\text{AgBF}_4$ ) as the carrier were normally used in the polymer membranes. Mixed-gas ethylene/ethane selectivity of more than 50 has been reported (U.S. Patents Nos. 6,414,202, 6,525,236, and 7,479,227). The main hurdles, however, include the lack of carrier stability due to washout of silver ions and the need for water vapor in the

feedstock. While complexing with olefins, the carriers also tend to react with other species causing undesirable carrier deactivation or poisoning over short time.

[007] Inorganic membranes, such as carbon membranes (A.F. Ismail, L.I.B. David, *J. Membrane Sci.*, 2001, 193, 1-18), and zeolite membranes have also been investigated for the separation of olefin/paraffin gas mixtures. Inorganic membranes have much greater thermal and chemical stability than polymer membranes. A few studies have indicated that zeolite membranes, specifically FAU (pore size 0.74 nm), and ETS-10 (pore size 0.56 nm) zeolite membrane, can separate olefins from paraffins. It has been reported that FAU-type zeolite membranes synthesized by secondary growth method can reach a separation factor for propylene/propane mixtures of  $13.7 \pm 1$  at 100°C, with the corresponding propylene permeance of  $0.75 \times 10^8 \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}$ , which surpassed the performance of polymer membranes as well as carbon membranes (I.G. Giannakopoulos, V. Nikolakis, *Ind. Eng. Chem. Res.*, 2005, 44, 226-230). Tiscornia et al. reported a method to prepare an ETS-10 zeolite membrane and its application in propylene/propane separation (I. Tiscornia, S. Frusta, C. Tellez, J. Coronas, J. Santamaria, *Journal of Membrane Science*, 2008, 311, 326-335). The membrane can only achieve propylene/propane selectivity of about 3-5. Hence, the separation factors of these pristine membranes are not high enough for practical olefin and paraffin separation in the industry.

[008] ETS-10 zeolite with mixed a coordination metallosilicate framework and general formula  $\text{Na}_2\text{TiSi}_3\text{O}_{13}$  was first discovered by Kuznicki et al. (U.S. Patent No. 4,853,202 and U.S. Patent No. 6,517,611). The modified ETS-10 zeolite powders were reported to be a good candidate to selectively adsorb ethylene over ethane (U.S. Patent No. 8,017,825). The powder cannot be used for continuous separation of olefin from paraffin.

## SUMMARY OF THE INVENTION

[009] It is known that olefins (e.g., ethylene and propylene) have unique affinity to silver and silver ion (I) species. Silver-salt-based polymer membranes have higher olefin selectivity mainly

through facilitated transport mechanism. It also known that zeolites possess excellent ion-exchange ability. By means of silver ion-exchange, Ag can be introduced inside pores of the zeolite membrane, which can not only fine tune the pore size but also provide great selectivity toward ethylene. A metal-containing modified agent can passivate the external surface and control the pore size of the zeolite. The pore structure of zeolites can thus be modified by introducing new species through various techniques, such as ion exchange, impregnation, chemical vapor deposition, or atomic layer deposition.

[0010] According to a method of the invention for preparing a composite zeolite membrane, a porous substrate is coated to form one or more seed layers on the porous substrate, and then the seeded substrate is put in contact with a precursor. The precursor and seeded substrate are heated under hydrothermal conditions to form a zeolite membrane having a framework, and then the zeolite membrane is subjected to metal doping.

[0011] The porous substrate can be selected from the group consisting of porous glass, porous carbon, porous ceramic, porous metal, and composites of two or more thereof. Also, the porous substrate can be in a typically useful shape, such as flat sheets, disks, tubes, or cylinders.

[0012] The porous substrate may be coated with a seed suspension.

[0013] With regard to metal doping, one or two metals are doped on specific sites of the zeolite membrane framework. The zeolite membrane framework has channels of zeolite pores and the doping sites are in the channels. The metal doped on the zeolite membrane framework is a transition metal or an alloy thereof, and preferably the transition metal is selected from the group consisting of transition metals of Groups IB, IIB, and VIII of the Periodic Table, more preferably the transition metal is selected from the group consisting of transition metals of Groups IB and VIII of the Periodic Table. Most preferably the transition metal is/are one or two of the group consisting of copper, silver, gold, cobalt, nickel, ruthenium, and palladium in the form of an alloy.

[0014] The metal doping is carried out by one or more of the processes selected from the group consisting of melting salt vapor deposition, plasma treatment, and ion exchange.

[0015] A dip-coating technique can be used for adhering nanoparticle seeds to the porous substrate to make the seeded substrate. Optionally spray coating or sputtering may be employed.

[0016] Preferably the nanoparticle seeds are dispersed in a suspension with a final pH value of from 6 - 8. The coating may comprise a further step of coating the porous substrate with a zeolite nanoparticle suspension one or more times to form one or more seeded layers on the seeded substrate.

[0017] A metal-doped zeolite membrane prepared by the method described above is particularly useful for separating olefins from paraffins.

[0018] In an aspect of the invention, a metal-doped zeolite membrane is useful for olefin/paraffin separation, wherein the membrane comprises a porous substrate and a zeolite layer with metal doping.

[0019] In another aspect of the invention, a metal-doped zeolite membrane comprises a zeolite layer with ETS-10 framework structure.

[0020] In another aspect of the invention, a metal doped zeolite membrane comprises heteroatoms incorporated into ETS-10 silica framework.

[0021] In another aspect of the invention, the zeolite membrane framework has channels of zeolite pores and there are sites in the channels.

[0022] In another aspect of the invention, a doping metal is a transition metal of Group IB, IIB, or VIII of the Periodic Table, an alloy thereof, or a combination thereof.

[002.3] In another aspect of the invention, a doping metal is a transition metal of Group IB or VIII of the Periodic Table, an alloy thereof, or a combination thereof.

[0024] In another aspect of the invention, a method for making a composite zeolite membrane comprises the steps of:

- providing a porous substrate;
- coating the porous substrate to form one or more seed layers;
- providing a precursor;
- placing the precursor in contact with the seeded substrate;
- heating the precursor and seeded substrate under hydrothermal conditions to form a zeolite membrane having a framework; and
- subjecting the zeolite membrane to metal doping.

[0025] In another aspect of a method of the invention, the porous substrate is selected from the group consisting of porous glass, porous carbon, porous ceramic, porous metal, and composites of two or more thereof.

[0026] In another aspect of a method of the invention, the porous substrate is in the shape of one of flat sheets, disks, tubes and cylinders.

[0027] In another aspect of a method of the invention, the porous substrate is coated with a seed suspension.

[0028] In another aspect of a method of the invention, a metal is doped on specific sites of the zeolite membrane framework.

[0029] In another aspect of a method of the invention, the zeolite membrane framework has channels of zeolite pores and the sites are in the channels.

[0030] In another aspect of a method of the invention, the metal doping is carried out by one or more of the processes selected from the group consisting of melting salt vapor deposition, plasma treatment, and ion exchange.

[0031] In another aspect of a method of the invention, the zeolite membrane framework comprises an ETS-10 structure.

[0032] In another aspect of a method of the invention, forming a seeded layer on a porous substrate, comprises the steps of:

- providing a porous substrate having a receptive outer surface;
- providing nanoparticle seeds comprising NaCl, KCl, KF, TiO<sub>2</sub>, Na<sub>2</sub>SiO<sub>3</sub>, and H<sub>2</sub>O;
- adhering the nanoparticle seeds to the outer surface of the porous substrate to form a seeded substrate; and
- subjecting the seeded substrate to temperature programming calcination.

[0033] In another aspect of a method of the invention, the porous substrate is selected from the group consisting of porous glass, porous carbon, porous ceramic, porous metal, and composites of two or more thereof.

[0034] In another aspect of a method of the invention, a dip-coating technique is used for adhering nanoparticle seeds to the porous substrate to make the seeded substrate.

[0035] In another aspect of a method of the invention, the method comprises the further step of coating the porous substrate with a zeolite nanoparticle suspension one or more times to form one or more seeded layers on the seeded substrate.

[0036] In another aspect of a method of the invention, the coating is carried out by one of dip coating, spray coating, and sputtering.

[0037] In another aspect of the invention, a metal-doped zeolite membrane is prepared by the method described above.

[0038] In another aspect of the invention, a molecular sieve comprises a metal-doped zeolite membrane prepared by the method described above.

[0039] In another aspect of the invention, an apparatus for olefin separation from an olefin/paraffin mixture comprises metal-doped zeolite membrane wherein the membrane comprises a porous substrate and a zeolite layer thereon having pores with metal clusters in the zeolite pores.

[0040] In another aspect of an apparatus of the invention, the zeolite membrane comprises transition metal clusters in the zeolite pores.

[0041] In another aspect of an apparatus of the invention, the zeolite membrane comprises one or two seed layers and one or two continuous zeolite layers on porous substrate.

[0042] In another aspect of an apparatus of the invention, a seed layer is prepared by coating a zeolite seed suspension onto the porous substrate by rubbing, spraying, dip-coating, or slip-coating.

[0043] In another aspect of an apparatus of the invention, the seed suspension is made from a homogenous precursor through hydrothermal synthesis.

[0044] In another aspect of an apparatus of the invention, the continuous zeolite layer comprises Y-type zeolite.

[0045] In another aspect of an apparatus of the invention, the continuous zeolite layer comprises ETS-10 type zeolite.

[0046] Another aspect of the invention comprises an improved method of separating olefins from paraffins using a molecular sieve described above as the catalyst.

[0047] In another aspect of a method of the invention, the improved method is carried out at high temperature ranging from 0° to 100°C.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0048] This invention may be more readily understood by reference to the following drawings wherein:

[0049] Figures 1(a) and 1(b) represent x-ray diffraction patterns of Y-type zeolite and ETS-10 zeolite, respectively;

[0050] Figure 2 represents a scanning electron microscopy (SEM) image of the ETS-10 zeolite membrane;

[0051] Figure 3 is a graphical representation of the separation performance of the ETS-10 membrane without metal doping;

[0052] Figure 4 is a graphical representation of the separation performance of the metal-doped ETS-10 membrane; and

[0053] Figure 5 is a schematic representation of a zeolite membrane-containing device for olefin/paraffin separation.

#### DETAILED DESCRIPTION OF THE INVENTION

[0054] In accordance with this invention, a composite zeolite membrane is prepared by the following procedure: (1) zeolite membrane is grown on a treated porous substrate (either

imcoated or nano-seal zeolite seed coated); (2) a template removal step (if necessary); and (3) metal doping of the membrane. It should be noted that each step mentioned above involves a unique technique specially employed to obtain a composite membrane in which specific molecules permeate through the membrane with high selectivity as well as high permeability.

[0055] With reference to the above-mentioned procedure, the porous substrates include a disk shaped, tubular, or hollow fiber porous ceramic, porous silica, metal mesh, or a sintered porous metallic support. Ceramic porous materials are preferred to be the substrates in this invention because of their good affinity to the zeolite materials. Optional seed materials include various zeolite nano-particles, zirconia, and titania. Transition metals or metal alloys with absorption/adsorption property and structure integrity can be selected as doping materials to be dispersed in the zeolitic pores by means of ion-exchange, melt salt vaporization, plasma irradiation, or photo-assisted irradiation.

[0056] The following examples are presented to better describe this invention. These examples are used to illustrate the process for zeolite membrane preparation, and not necessarily represent the best formula. It is noted that, this invention is not limited by the following examples. The chemicals used in this work included potassium chloride (99%, Aldrich), potassium fluoride (99%, Aldrich), sodium chloride (99.995%, Aldrich), sodium hydroxide (98%, Aldrich), sodium silicate solution ( $\text{Na}_2\text{SiO}_3$ : 27%  $\text{SiO}_2$ , 8%  $\text{Na}_2\text{O}$ , Aldrich), sodium aluminate (50-56%  $\text{Al}$  + 40-45%  $\text{Na}$  ( $\text{Fe} < 0.05\%$ ), **Riedel-de Haen**), titanium(III) chloride solution ( $\text{TiCl}_3/\text{HCl}$ , >12%, Aldrich), anatase (P-25, Aldrich), and titanium butoxide. The propylene (99.5%), propane (ACS grade) gases were obtained from Airgas.

## EXAMPLES

### Example 1. Preparation of Zeolite Nanoparticle Suspension

(a) *Y-type zeolite nano-particles.* The Y-type zeolite nanoparticle seeds were prepared by hydrothermal synthesis. Amounts of  $\text{NaAlO}_2$  (2.78 g) +  $\text{NaOH}$  (12.67 g) + distilled water

(149.91 g) were mixed and then stirred for 30 minutes. Water glass (41.83 g) was added, and the mixture was stirred for 12 hours. The resulting mixture was transferred into a TEFLON® bottle for hydrothermal synthesis at 90 °C for 12 hours. After the hydrothermal synthesis, the resulting seed suspension was washed to a pH of 8~9 for further use.

(b) *ETS-10 zeolite nanoparticles*. Sodium silicate solution was mixed with 15.4 g distilled water, 2.47 g sodium hydroxide, 2.33 g sodium chloride, and 3.63 g potassium chloride. This mixture was thoroughly stirred until a solution was obtained. Titanium dioxide (1.7 g) was then added with stirring, and a homogeneous gel formed. Static crystallization was carried out in TEFLON-lined autoclaves at 220°C for 24 hours. The products were then washed with distilled water to a pH between 9-10. The gel composition was  $4.7 \text{ Na}_2\text{O} : 1.5 \text{ K}_2\text{O} : \text{TiO}_2 : 5.5 \text{ SiO}_2 : 122 \text{ H}_2\text{O}$ .

The resultant zeolite nano-particle suspension was re-dispersed in distilled water to obtain a suspension with a dry solid concentration ranging from 0.1-10 wt%. 0.1 wt% hydroxyl propyl cellulose (HPC, Mw=1 00,000, Aldrich) solution was used as binder. The final stable colloidal suspension contained 0.1-10 wt%, preferably 0.5-2 wt%, of dry particles. The nanoparticle suspension was coated onto the polished side of a disc substrate by dip-coating. The contact time of the dip-coating process was 3-5 seconds or 3-5 minutes, dependent upon the affinity of seeds and substrates. After dip-coating, the disc was dried at room temperature and stored in an oven.

#### Example 2. Preparation of Membrane #Y-1, and Separation Performance.

This example is directed to the preparation of zeolite membrane #Y-1. The precursor solution for secondary growth was prepared in a TEFLON beaker by dissolving 1.235 g  $\text{NaAlO}_2$  and 6.965 g NaOH in 88.86 g de-ionized water, under rigorous stirring. After addition of 15.5 g water glass and stirring for another six hours at room temperature, the precursor was transferred into the TEFLON-lined synthesis vessels. The seeded alumina disc was placed vertically at the

bottom of the vessel and completely immersed in the synthesis solution about 1 cm below the liquid surface. The container was then moved into an oven to perform hydrothermal synthesis at 100 °C for 12 hours. The membrane was taken out, washed with distilled water, and dried at 70°C overnight. The membrane was then subjected to a second hydrothermal synthesis. This membrane was characterized by X-ray diffraction (XRD, Rigaku D/MAX-II), showing the pattern set forth in Figure 1(a).

For ion-exchange, the membrane prepared was placed into 0.04 M  $\text{AgNO}_3$  solution (10 ml) at room temperature for one hour. The membrane was then dried overnight at room temperature in a vacuum oven. After drying, the membrane was subjected to temperature program reduction under 5% (v)  $\text{H}_2$  (balanced with nitrogen) environment. This membrane showed a propylene selectivity of 1.29 over propane.

Example 3. Membrane #Y-2 Synthesis and Separation Performance.

Membrane #Y-2 preparation and ion-exchange process were the same as in Example 2, except that the membrane was subjected to calcination under a nitrogen environment. After calcination, the membrane was subjected to UV irradiation. This membrane showed a propylene selectivity of 1.31 over propane.

Example 4. #M-1 Zeolite Membrane Synthesis and Separation Performance.

This example shows the preparation procedure for ETS-10 zeolite membrane. ETS-10 zeolite membrane (#M-1) was synthesized by secondary growth method with the following procedure: 2.47 g NaOH was added into 20.0 g  $\text{Na}^+\text{SiO}_3$  solution with additional water of 15.4 g, stirring at room temperature for 30 minutes. Amounts of 3.63 g KCl, 2.33 g NaG, and 1.5 g KF were added into 15.4 g de-ionized water, and the resulting solution was stirred for five minutes. The two solutions were mixed, and the solution mixture was stirred for another 30 minutes. TiCb solution (10.7 g 15% TiCb solution) was added to the solution mixture, with

stirring at room temperature for 30 minutes. The precursor was transferred into an autoclave with seeded substrate, and sealed with TEFLON liner. The autoclave was placed in an oven for secondary growth synthesis at 200°C for 24 hours. After cooling down to room temperature, the membrane was taken out and rinsed with de-ionized water. The membranes were dried at 80°C in an oven overnight, and further dried at 300°C with both heating rate and cooling rate of 1°C/min for eight hours. This membrane showed a propylene selectivity of 4.5 over propane.

**Example 5.** #M-2 Zeolite Membrane Synthesis and Separation Performance.

This example shows the preparation procedure for metal-doped ETS-10 zeolite membrane and its separation performance. ETS-10 zeolite membrane (#M-2) was synthesized by secondary growth method with the following procedure: 1.3 g KG, 6.9 g NaCl, and 1.5 g KF were added into 20.0 de-ionized water with stirring for five minutes. An amount of 20.0 g Na<sub>2</sub>SiO<sub>3</sub> solution was then added to the above mixture with stirring at room temperature for 30 minutes. An amount of 1.3 g anatase was added with stirring at room temperature for 3-4 hours. The precursor was then transferred into an autoclave with seeded substrates, sealed with TEFLON liner. The autoclave was placed in an oven for hydrothermal synthesis at 220°C for 24 hours. After cooling down to room temperature, the membrane was taken out and rinsed with the de-ionized water. The membranes were dried overnight in an oven at 80°C before ion-exchange. The process of ion-exchange was conducted over the membranes by using silver nitrate solution (0.125 N) to ensure a certain amount of Ag ions doping in the zeolitic channels. The ion-exchanged membrane was subjected to post-treatment by UV irradiation.

The crystal growth was examined by x-ray diffraction, as shown in Figure 1(b). The membrane integrity was observed by using scanning electron microscope (SEM, Philips XL30), a pictograph of which is shown in Figure 2. Upon Ag ion modification and post treatment, this zeolite composite membrane gave separation performance with propylene selectivity of 106.5.

**Example 6.** #M-3 Zeolite Membrane Synthesis and Separation Performance.

This example shows the preparation procedure for metal-doped ETS-10 zeolite membrane. ETS-10 zeolite membrane (#M-3) was synthesized by secondary growth method with the following procedure: 2.47 g NaOH was added into 20.0 g  $\text{Na}_2\text{SiO}_3$  solution with additional water of 15.4 g, under stirring at room temperature for 30 minutes. Amounts of 3.63 g, KCl, 2.33 g NaCl, and 1.5 g KF were added into 15.4 g de-ionized water, under stirring for five minutes. The above two solutions were mixed, and the mixed solutions were stirred for another 30 minutes. TiCb solution (10.7 g 15% TiCb solution) was added to the solution mixture, under stirring at room temperature for 30 minutes. The precursor was transferred into an autoclave with seeded substrate, and sealed with TEFLON liner. The autoclave was placed in an oven for secondary growth synthesis at 200°C for 24 hours. After cooling down to room temperature, the membrane was taken out and rinsed with the de-ionized water. The membranes were dried overnight in an oven at 80°C before ion-exchange.

The process of ion-exchange was conducted over the membranes by using  $\text{Ag}(\text{NH}_3)_2\text{NO}_3$  solution. The ion-exchange process was similar to one with  $\text{AgNO}_3$  solution. The ETS-10 membrane was placed into above mentioned  $\text{Ag}(\text{NH}_3)_2\text{NO}_3$  solution (10 ml) at room temperature for 12 hours. The ion-exchanged membrane was subjected to post-treatment by UV irradiation.

Upon Ag ion modification and post treatment, this zeolite composite membrane gave separation performance with propylene selectivity as high as 98.6.

**Example 7.** #M-4 Zeolite Membrane Synthesis and Separation Performance.

This example shows the preparation procedure for metal-doped ETS-10 zeolite membrane and its separation performance. ETS-10 zeolite membrane (#M-4) was synthesized by secondary growth method with the following procedure: 1.3 g KCl, 6.9 g NaCl, and 1.5 g KF were added into 20.0 de-ionized water with stirring for five minutes. An amount of 20.0 g

$\text{Na}_2\text{SiO}_3$  solution was then added in the above mixture with stirring at room temperature for 30 minutes. An amount of 5.6 g titanium butoxide was added with stirring at room temperature for 3-4 hours. The precursor was then transferred into an autoclave with seeded substrates, sealed with TEFLON liner. The autoclave was placed in an oven for hydrothermal synthesis at  $220^\circ\text{C}$  for 24 hours. After cooling down to room temperature, the membrane was taken out and rinsed with the de-ionized water. The membranes were dried overnight in an oven at  $80^\circ\text{C}$  before ion-exchange.

A process of ion-exchange was conducted over the membranes by using  $\text{Ag}(\text{NH}_3)_2\text{NO}_3$  solution. The ion-exchanged membrane was subjected to temperature programmed calcination at  $450^\circ\text{C}$  in air for eight hours with a heating and cooling rate of  $1^\circ\text{C}/\text{min}$ . before UV irradiation.

Upon Ag ion modification and UV irradiation, this zeolite composite membrane gave separation performance with propylene selectivity as high as 9.8.

#### Example 8. #M-5 Zeolite Membrane Synthesis and Separation Performance.

This example shows the preparation procedure for metal-doped ETS-10 zeolite membrane. ETS-10 zeolite membrane (#M-5) was synthesized by secondary growth method with the following procedure: 2.47 g NaOH was added into 20.0 g  $\text{Na}_2\text{SiO}_3$  solution with additional water of 15.4 g, stirring at room temperature for 30 minutes. Amounts of 3.63 g KCl, 2.33 g NaCl, and 1.5 g KF were added into 15.4 g de-ionized water, under stirring for five minutes. The two solutions were mixed and then stirred for another 30 minutes.  $\text{TiCl}_4$  solution (10.7 g 15%  $\text{TiCl}_4$  solution) was added into the mixture, and the mixture was stirred at room temperature for 30 minutes. The precursor was transferred into an autoclave with seeded substrate, and sealed with TEFLON liner. The autoclave was placed in an oven for secondary growth synthesis at  $20^\circ\text{C}$  for 24 hours. After cooling down to room temperature, the membrane was taken out and rinsed with the de-ionized water. The membranes were dried overnight in an oven at  $80^\circ\text{C}$  before ion-exchange.

The process of ion-exchange was conducted over the membranes by using  $\text{Ag}(\text{NH}_3)_2\text{NO}_3$  solution. The ion-exchanged membrane was then thermally treated in nitrogen at  $300^\circ\text{C}$  with a heating rate and cooling rate of  $1^\circ\text{C}/\text{min}$ . for eight hours. The thermally treated membrane was subjected to UV irradiation.

Upon Ag ion modification, thermal treatment and UV-irradiation, this zeolite composite membrane gave separation performance with propylene selectivity as high as 123.7.

Separation performance of the ETS-10 membrane is set forth in Figures 3 and 4. In Figure 3, which represents the separation performance of the ETS-10 membrane without metal doping, the propylene/propane selectivity is about 4.5 (triangle dot), and propylene permeance is about  $0.34 \times 10^{-8} \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}$  (square dot).

In Figure 4, which represents the separation performance of the metal-doped ETS-10 membrane, the propylene/propane selectivity is about 120 (triangle dot) and propylene permeance is about  $0.85 \times 10^{-8} \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}$  (square dot).

Figure 5 is a schematic representation of a zeolite membrane-based device or apparatus useful for olefin/paraffin separation according to the invention. A device such as a cartridge 2 has a cylindrical body 4 closed with closed ends 6 and 8. Closed end 6 has an inlet 12 for receipt of olefin/paraffin feed mixture 14, and closed end 8 has an outlet 16 for retentate 20, that is, olefin depleted mixture. Cylindrical body 4 has at least one outlet 22 for permeate 24, that is, olefin enriched mixture. Cylindrical body 4 comprises zeolite membrane material, preferably arranged in cylindrical porous structures 28 of alumina covered with a metal doped zeolite layer. The cylinders 28 are arranged adjacent and parallel to each other within cylindrical body 4. Optionally a sweep gas 30 may enter cylindrical body 4 at inlet 32 to assist in collecting the permeate 24.

[0057] Although the invention has been described in detail for the purpose of illustration based on what is currently considered to be the most practical and preferred embodiments, it is to be understood that such detail is solely for that purpose and that the invention is not limited to the disclosed embodiments, but, on the contrary, is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims. For example, it is to be understood that the present invention contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

## WE CLAIM :

- 1) An apparatus for olefin separation from an olefin/paraffin mixture, comprising metal-doped zeolite membrane wherein the membrane comprises a porous substrate and a zeolite layer thereon having pores with metal clusters in the zeolite pores.
- 2) The apparatus of claim 1, wherein the zeolite membrane comprises transition metal clusters in the zeolite pores.
- 3) The apparatus of claim 2, wherein the zeolite membrane comprises one or two seed layers and one or two continuous zeolite layers on the porous substrate.
- 4) The apparatus of claim 3, wherein a seed layer is prepared by coating a zeolite seed suspension onto the porous substrate by rubbing, spraying, dip-coating, or slip-coating.
- 5) The apparatus of claim 4, wherein the seed suspension is made from a homogenous precursor through hydrothermal synthesis.
- 6) The apparatus of claim 3, wherein the continuous zeolite layer comprises Y-type zeolite.
- 7) The apparatus of claim 3, wherein the continuous zeolite layer comprises ETS-10 type zeolite.
- 8) The apparatus of claim 3, wherein the continuous zeolite layer is synthesized by a process comprising the steps of:
  - a) placing seed substrate vertically in a TEFLON container;
  - b) adding a homogeneous precursor containing sodium chloride, sodium hydroxide, potassium chloride, potassium fluoride, sodium silicate solution, and a source of titanium to the container;

- c) putting the TEFLON container into an autoclave with good sealing; and
  - d) heating the autoclave in an oven for hydrothermal synthesis at a temperature in the range of from 180° to 240°C for from 24 to 72 hours to form a continuous zeolite layer on the seeded substrate.
- 9) The apparatus of claim 8, wherein the source of titanium is titanium dioxide, titanium chloride, or titanium butoxide
- 10) The apparatus of claim 3, wherein the porous substrate is made from organic or inorganic material
- 11) The apparatus of claim 1, wherein the metal clusters comprise a metal or metal alloy of a transition metal from Group IB, IIB, or VIII of the Periodic Table.
- 12) The apparatus of claim 11, wherein the metal clusters comprise a metal or metal alloy of a transition metal from Group IB or VIII of the Periodic Table.
- 13) The apparatus of claim 11, wherein the transition metal is one or two of the group consisting of copper, silver, gold, cobalt, nickel, ruthenium, and palladium.
- 14) The apparatus of claim 1, wherein metal doping is achieved by vapor deposition, plasma treatment, or ion-exchange or a combination of two or more thereof.
- 15) The apparatus of claim 14, wherein the zeolite membrane is subjected to additional treatment selected from the group consisting of temperature programmed reduction, temperature programmed calcination, and UV-irradiation.
- 16) The apparatus of claim 1, wherein the zeolite membrane is fabricated in the shape of a flat-sheet, a tubular member, or a hollow fiber.

- 17) The apparatus of claim 1 which comprises a canister or cylindrical structure coupled to receive a gas or liquid stream containing olefin, paraffin, and other components.
- 18) The apparatus of claim 17, wherein the canister or cylindrical structure is coupled to receive a gas stream containing an olefin.
- 19) The apparatus of claim 18, wherein the olefin-containing gas is mixed in a feedstock containing paraffin and other components.
- 20) The apparatus of claim 17, which comprises a canister or cylindrical structure coupled to receive a gas or liquid stream containing ethylene and ethane, propylene and propane, or butylene and butane, and other components.
- 21) The apparatus of claim 18, which is used to enrich or recycle the olefins in the gas stream from a refinery gas, steam cracking plant, a gas stream from an oil field, or a venting gas from a propylene polymerization plant.
- 22) The apparatus of claim 21, wherein the olefins are light hydrocarbons obtained from fluidized catalytic cracking.

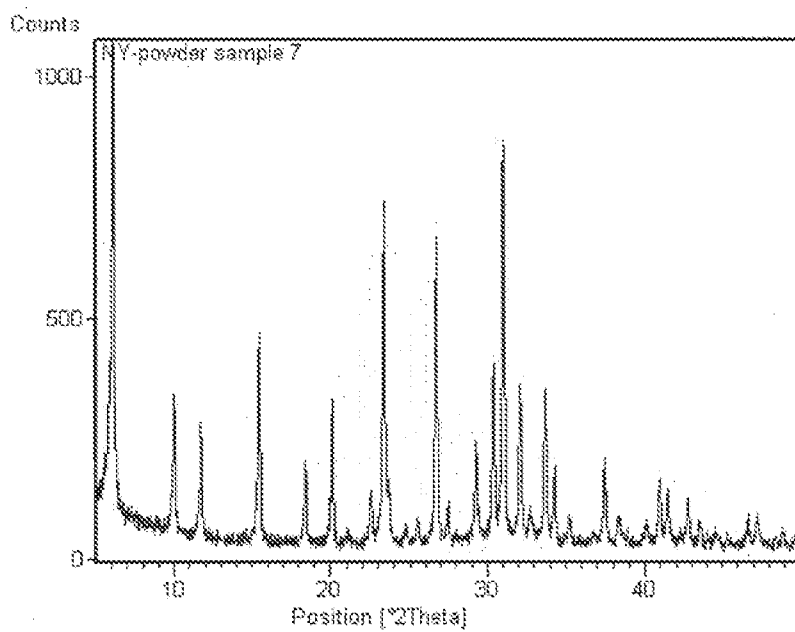


Figure 1(a)

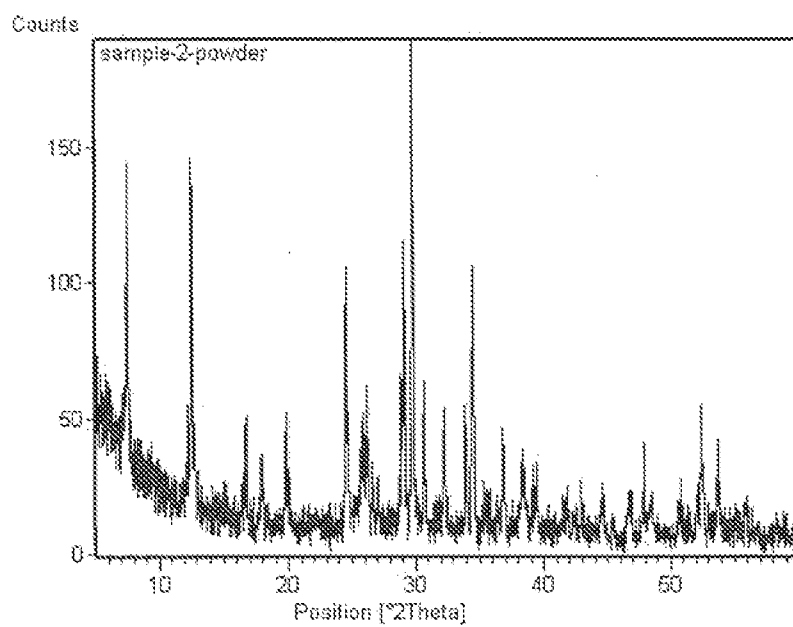


Figure 1(b)

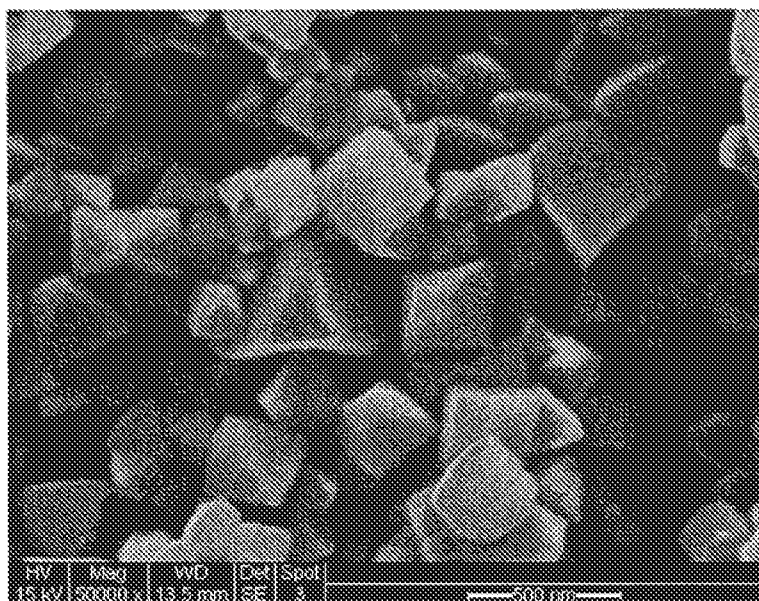


Figure 2

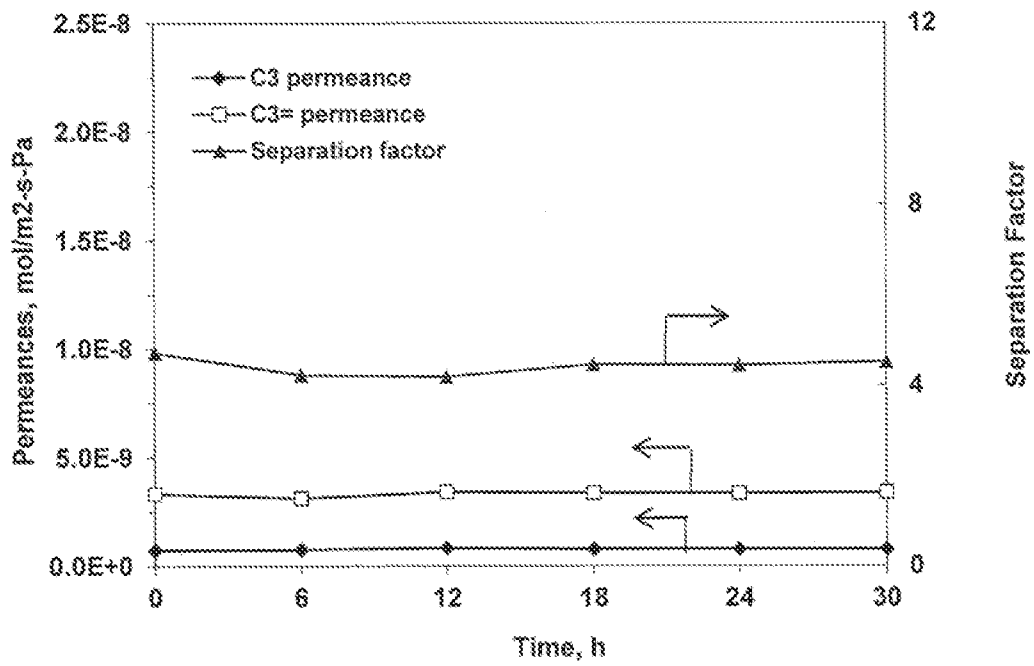


Figure 3

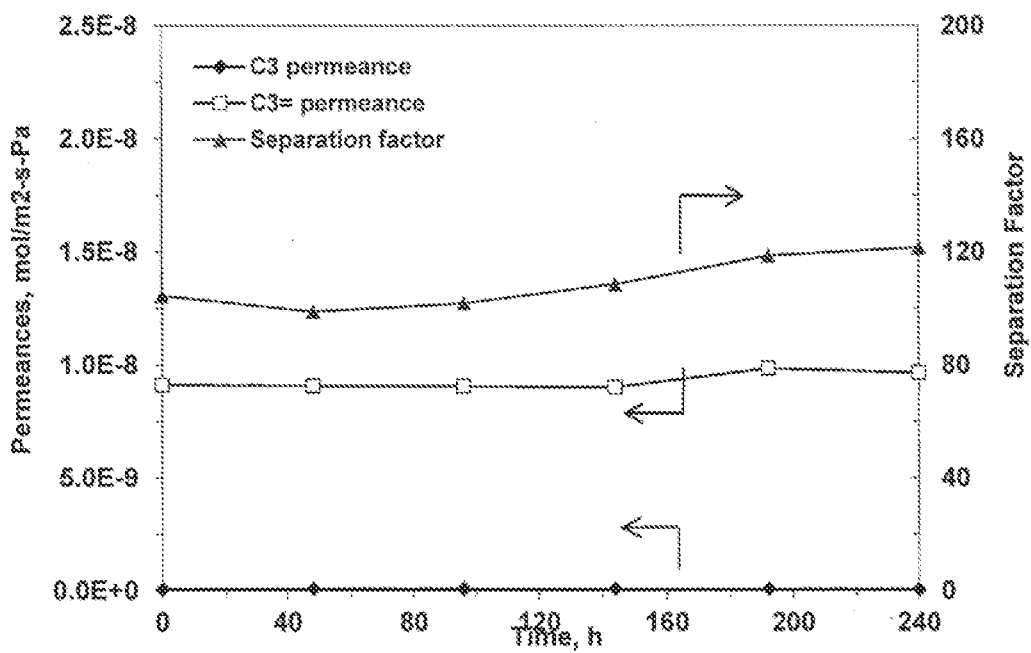


Figure 4

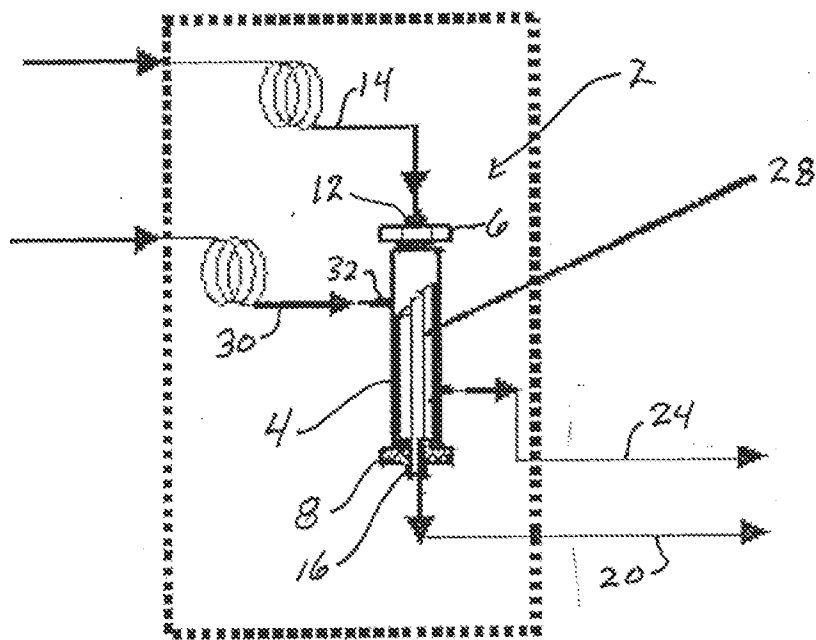


Figure 5

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/29801

## A. CLASSIFICATION OF SUBJECT MATTER

**IPC(8)** - C07C 7/144 (2015.01)**CPC** - C07C 7/144; B01D 61/362; C10G 31/11

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

CPC - C07C 7/144; B01D 61/362; C10G 31/11

IPC(8) - C07C 7/144 (2015.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
Patents and non-patent literature (classification, keyword; search terms below)Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
PatBase, Google Scholar (NPL), Google Patents; search terms: olefin separation, paraffin mixture, metal-doped zeolite membrane, porous substrate, continuous zeolite layer, metal clusters, transition metal, copper, cobalt, nickel, seed layer, zeolite seed suspension

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,763,347 A (LAI) 09 June 1998 (09.06.1998) col 2, ln 33-35; col 6, ln 24-26; col 7, ln 1-4, 24-37; col 9, ln 30-31, 39-42, 58-61; abstract	1-22
A	US 2006/0201884 A1 (KULPRATHIPANJA et al.) 14 September 2006 (14.09.2006) para [0029]-[0033], [0068], [0070], [0113], [0222]	1-22
A	US 5,744,687 A (RAMACHANDRAN et al.) 28 April 1998 (28.04.1998) col 1, ln 11-13; col 2, ln 44-55; col 3, ln 39-46, 58-67; col 4, ln 6-9, 17-25	1-22
A,P	US 2015/0044130 A1 (TANG et al.) 12 February 2015 (12.02.2015) entire document	1-22
A,P	US 2015/0065767 A1 (HENA O et al.) 05 March 2015 (05.03.2015) para [0009], [0011], [0033], [0122]-[0123]; abstract	1-22



Further documents are listed in the continuation of Box C.



## \* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

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Date of mailing of the international search report

12 AUG 2015

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