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(54) **Title**: MEMBRANE FOR REMOVING MOISTURE IN THE AIR

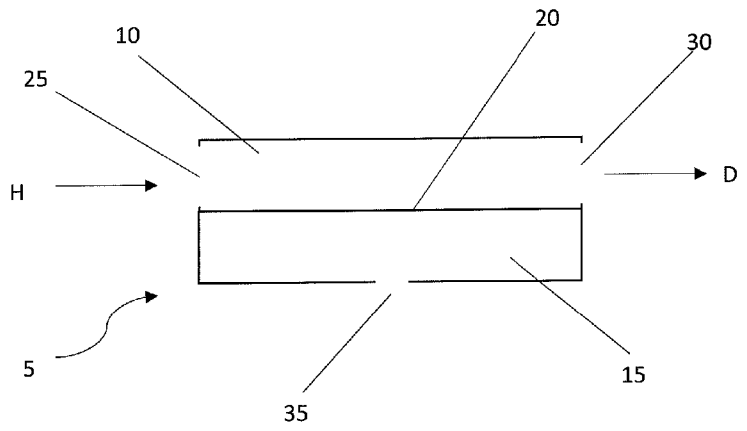

Figure 2

(57) **Abstract**: The present invention relates to a membrane. In particular, the present invention relates to a membrane for removing moisture in the air and, more particularly, in an air stream. The membrane comprising (a) a metal scaffold structure; (b) a ceramic material formed within the scaffold structure; and (c) a hydrophilic polymer outer coating. The membrane may be used in any suitable device. In addition, the present invention also relates to a method for removing water vapour in an air stream using said membrane.

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MEMBRANE FOR REMOVING MOISTURE IN THE AIR

The present invention relates to a membrane. In particular, the present invention relates to a membrane for removing moisture in the air and, more particularly, in an air stream. The membrane may be used in any suitable device. In addition, the present invention also relates to a method for removing water vapour in an air stream using said membrane.

Conventional air conditioning involves the use of chillers for removing latent heat by condensing out the moisture from the supply air. The process is illustrated as A-C-D-B pathway on psychrometric chart in Figure 1, in which A is the starting point (average weather conditions in Singapore) and B is the desired thermal comfort level. The air is passed over cooling coils at a temperature below its dew point to condense the moisture (from point A to points C and D). The dehumidified air is then passed over heating coils to raise its temperature to reach the human thermal comfort level (from point D to point B). The excessive energy consumption in cooling and heating steps makes this process inefficient.

Another conventional way to get thermal comfort air condition (temperature and humidity) is through the use of desiccants. The process is illustrated as A-E-B pathway on psychrometric chart in Figure 1. The air is passed through a desiccant where water vapor is removed from the air stream and absorbed by the desiccant. However, due to exothermic interactions between water vapor and the desiccant material, the temperature of air increases significantly (from point A to point E). The air is then cooled down to reach the desired temperature (from point E to point B). Overall efficiency of this process is low because the system requires excessive energy for cooling the air and for regenerating the desiccant at high temperature. Additionally, the air can be contaminated with a certain amount of undesired desiccant molecules.

In warm and humid climates, the efficiency of air conditioning is lowered by the need to remove the moisture from the air.

Recently, Liu and coworkers have developed a thin porous Ni-supported NaA zeolite membrane suitable for dehumidification [1].

In order to ensure that the separation system works efficiently, the working membrane must be:

a) highly permeable, because partial pressure of water vapor in air is small;
b) highly selective, because permeation or leakage of air will raise power consumption of vacuum pump;
c) robust, to resist deformation caused by strong vacuum force and other physical/chemical/biological corrosion; and
d) easily scalable and cost-effective to be suitable for industrial production.

Liu's results showed that the membrane has a water vapor permeance as high as 6.8×10^{-6} mol/(m^2 Pa s). They estimated that when their membrane is used a 50% or higher energy efficiency gain over a conventional vapor compression system can be obtained. However, the selectivity of this membrane in term of ratio of water vapor permeance to air permeance is low, maximum of 36:1. If this membrane is used in humid climate region with the molecular ratio of air to water vapor of around 100:3 at average temperature of 27°C and average relative humidity of 85%, the ratio of air flux to water vapor flux permeating through the membrane is minimum 100:108 — 1:1. It means that the work load for vacuum pump is at least two times the requirement to remove only water vapor. In addition, Liu used a multi-step preparation method involving high-grade and expensive chemicals, high pressure, high temperature and complicated apparatuses to prepare their membrane [2]. This means the membrane will be unsuitable for large-scale production and the final product will be quite costly.

As such, there is a need for an efficient way to remove moisture from the air.

The listing or discussion of an apparently prior-published document in this specification should not necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

Any document referred to herein is hereby incorporated by reference in its entirety.

In a first aspect of the present invention, there is provided a membrane for removing moisture in the air, the membrane comprising (a) a metal scaffold structure; (b) a ceramic material formed within the scaffold structure; and (c) a hydrophilic polymer outer coating.

Essentially, the present invention is a novel hybrid membrane comprising three key components, a stainless steel wire mesh scaffold structure, a ceramic material applied to the scaffold structure via a casting and/or dipping method and a hydrophilic polymer made of polyvinyl alcohol and lithium chloride. The membrane incorporates the unique characteristic of each component, namely, strength and durability of stainless steel, high diffusivity of ceramic membrane and high permeability and selectivity of hydrophilic polymer. It has high water vapour selectivity and permeability. It possesses sufficient strength which allows it to be used under pressurized condition. Testing results have shown that the membrane dehumidifies air efficiently. It easily turns humid input air with 90% relative humidity into a drier and comfortable output air with 50% relative humidity. The present membrane demonstrates outstanding results in comparison to existing dehumidification technologies, as will be shown below.

By "scaffold structure", it is meant to include any framework that acts as a support structure or backbone to give the membrane its desired mechanical characteristics and strength. As such, the ceramic material is formed within and on, or encasing, the scaffold structure. The ceramic material fills the spaces in the mesh and also forms a surface that is suitable for coating the hydrophilic polymer on the outer surface of the membrane. In an embodiment, the metal scaffold structure is a stainless steel wire mesh. By "mesh", it is meant to include any network of connected strands of stainless steel metal (similar to a web or a net) to form the scaffold structure. The stainless steel wire mesh may be prepared by any suitable method known to the skilled person or may be obtained commercially.

Preferably, any suitable ceramic material may be used. In an embodiment, the ceramic materials may be fine porous metal and/or non-metal oxides such as titanium dioxide, silica, zeolites, bentonite powder. TiO_2 powder is used because it is abundant, inexpensive,

environmental friendly, chemically and physically stable and is highly compatible with the polymer and the mesh.

Preferably, the hydrophilic polymer is any one selected from the group comprising: polyvinyl alcohol, nafion polymer, polyamide, polyacrylic acid and cellulose acetate. More preferably, the hydrophilic polymer further comprises a hygroscopic additive. The hygroscopic additive is any one selected from the group comprising: lithium chloride, triethylene glycol, calcium chloride and lithium bromide. In a preferred embodiment, the hydrophilic polymer includes polyvinyl alcohol and lithium chloride and/or triethylene glycol. The ratio of polyvinyl alcohol and lithium chloride present in the hydrophilic polymer is from 3:1 to 1:1 . Alternatively, the ratio of polyvinyl alcohol and triethylene glycol present in the hydrophilic polymer may be from 1:6 to 1:10.

In embodiment, wherein the membrane is tubular. By "tubular", it is meant to include any structure that is tube-like, for example long, round and hollow. Such tubular membranes increase the surface area exposed to the ambient air stream for removing moisture, increasing the efficiency of such membranes and devices employing said membranes.

In a second aspect of the present invention, there is provided a device for removing moisture in the air, the device comprising (a) a housing having a first chamber and a second chamber; (b) a membrane according to the first aspect of the present invention, the membrane separating the first and second chambers; (c) the first chamber having an inlet for receiving ambient air and an outlet for releasing dryer air; (d) the second chamber having an opening for providing fluid communication with a vacuum or suction pump for applying a pressure gradient across the membrane, the opening further discharges moisture removed from the ambient air.

In an embodiment, the membranes are flat such that the housing may comprise a plurality of first and second chambers (with a membrane sandwiched between them) stacked on each other.

In an alternative embodiment, the membrane is tubular, the hollow interior of the tubular membrane forms the first chamber, and the cavity enclosed by the exterior of the tubular membrane and the housing forms the second chamber. In such an embodiment, preferably, the housing further comprises a plurality of tubular membranes spaced apart in the housing. These tubular membranes may be fixed in their places in the housing by placing them in slots placed that both ends of the housing (i.e. the inlet and outlet). Ambient air will enter the tubular membrane at one end (the inlet) and exit the tubular membrane (the outlet) at the other opposite end.

In a third aspect of the present invention, there is provided a method for removing water vapour, the method comprising (a) providing a membrane according to the first aspect of the present invention, the membrane having a first surface and a second surface; (b) exposing ambient air to the first surface of the membrane; (c) applying a pressure gradient across the membrane; and (d) removing the water vapour from the second surface of the membrane.

Preferably, the pressure gradient is applied by subjecting the second surface of the membrane with a vacuum pressure. In an embodiment, the transmembrane pressure applied on the membrane is from 900 to 1000mbar.

Preferably, the first surface of the membrane is constantly exposed to ambient air, and the flow of the ambient air stream is parallel to the plane of the membrane.

Preferably, the flow rate of the ambient air stream is about 28 cm/s.

Preferably, wherein the temperature of the ambient air is about 24°C.

Preferably, the ambient air has a relative humidity of about 90% and humidity ratio of 17g of water vapour to 1 kg of air.

Preferably, the relative humidity of the air leaving the membrane is about 34%.

Advantageously, the inventors of the present invention have arrived at preparing a high-performance composite membrane that is suitable for removing moisture in the air, i.e. for dehumidification application. Such a membrane can withstand the required mechanical strength due to the stainless steel wire mesh scaffold structure, high diffusivity due to the porous titanium dioxide and high water vapor permeability and selectivity due to the highly hydrophilic polyvinyl alcohol. The membrane is cheap, physically and chemically durable, easy to manufacture and suitable in industrial production scale. When a pressure difference is applied across the membrane, moisture in the air (in the form of water vapor) can selectively diffuse from high pressure side to low pressure side with high flux density. The feasibility of the membrane in real dehumidification application has been tested and will be described below.

The operation of the separation system relies much on a working membrane that has high water vapor permeability and selectivity. The driving force for water vapor/air separation is a difference in partial water vapor pressure between two sides of the membrane. This membrane is an efficient and green means to dehumidify air. No heat source is needed, no regeneration is involved and no environmental emission is generated.

In order that the present invention may be fully understood and readily put into practical effect, there shall now be described by way of non-limitative examples only preferred embodiments of the present invention, the description being with reference to the accompanying illustrative figures.

In the Figures:

Figure 1 is a psychometric chart illustration showing the relationship between water vapour content in the air and cooling said air.

Figure 2 is a schematic drawing showing a device according to an embodiment of the present invention.

Figure 3 is an illustration showing the preparation process of the membrane according to an embodiment of the present invention.

Figure 4. SEM images of (A) wire mesh, (B) TiO_2 layer on the mesh and (C) top polymer layer; (D) a thin and flexible synthesized composite membrane.

Figure 5 shows results comparing the water vapour permeance and selectivity characteristics between a membrane according to the present invention with that reported in [1].

Figure 6 shows moisture removal performance of the membrane according to an embodiment of the present invention.

Figure 7. (A) water vapor permeance and (B) selectivity of the membranes. The membranes were made with PVA:LiCl = 3:2 and the measurements were tested at 24°C.

Figure 8. Dehumidification performance of membranes with different TEG (tetra ethylene glycol) and LiCl content at 24°C, 80%RH at 1lpm.

Figure 9 is a schematic drawing showing a device according to an embodiment of the present invention.

Figure 10 is a schematic drawing showing a device according to another embodiment of the present invention.

Figure 11 is a schematic drawing showing a device according to yet another embodiment of the present invention.

The present invention proposes a much more efficient way to remove latent heat by using membrane separation system. The process is illustrated as A-F-B pathway on psychometric chart in Figure 1. Firstly, humid air is passed over a membrane to selectively sieve out moisture without any temperature change (from point A to point F). Then, the dried air is

cooled down to thermal comfort level with minimal energy consumption (from point F to point B). As can be seen from the figure, the sensible cooling, and thus energy, required in this process is much lower than the sensible cooling and heating required in the two conventional processes to achieve the same threshold comfort level. As such, the membrane of the present invention may be used in air-conditioning systems to improve the efficiency of such systems.

Preparing the membrane

The membrane is synthesized using cheap and commercially available materials processed through a green preparation method, which is appropriate for large scale production. In an embodiment of the present invention, the membrane is flat or tubular. This composite membrane comprises stainless steel scaffold, fine and porous TiO_2 (Degussa P25) and hydrophilic polymer made of polyvinyl alcohol and lithium chloride with certain ratio. The wet P25 TiO_2 is applied on the stainless steel wire mesh by ~~a~~ casting and/or dipping method. The obtained mesh with intermediate layer of TiO_2 is dried at 80°C in 10 minutes, and then coated with an aqueous solution containing polyvinyl alcohol and lithium chloride by using casting and/or dipping method. By using optimal values of the concentration of polyvinyl alcohol, coating speeds as well as number of coatings, a smooth and bubble-free polymer top layer is formed. The final composite membrane is obtained after drying at 80°C for 10 minutes. The preparation steps are shown in Figure 3. A flat, thin, smooth and flexible final composite membrane with a width of 4 cm, length of 12 cm and thickness of 0.15 mm is shown in Figure 4D.

Figure 4 shows the surface morphology of the stainless steel wire mesh, the TiO_2 intermediate layer and the outer (or top) polymer layer. The twilled dutch weave stainless steel mesh is used as a scaffold providing mechanical strength for the membrane. Due to the large gaps between wires of the mesh (Figure 4A), it is difficult to coat a thin layer of the hydrophilic polymer directly on it. Therefore, fine TiO_2 powder (Degussa P25) was coated to fill in the gap forming an intermediate support layer for the top polymeric layers (Figure 4B). The TiO_2 powder is selected because it is inexpensive, environmental friendly, chemically and physically stable and is highly compatible with the polymer and the mesh. In addition, it

can fill the gaps to form a thin intermediate supporting layer, and it does not affect the permeability of water vapor. A thin permselective layer of hydrophilic polymer was successfully coated on top of the TiO_2 intermediate layer (Figure 4C). Figure 4D shows a thin and flexible synthesized composite membrane.

Comparing the water vapor permeance and selectivity characteristics between the present membrane with the NaA zeolite membrane reported in [1] are shown in Figure 5. The results in Figure 5 a. show that the stainless steel wire mesh with TiO2 intermediate layer has water vapor permeance in the same order as that of the reported NaA zeolite membrane. This is reasonable because both membranes have similar physical content consisting of a porous metallic support (porous Ni sheet or stainless steel wire mesh) and a dense ceramic layer (NaA zeolite or porous P25 TiO2). However, ceramic P25 TiO2 layer itself is not a good membrane because it has very low selectivity in term of ratio of water vapor permeance to air permeance, as shown in Figure 5.b. When the ceramic TiO2 layer is coated with hydrophilic polyvinyl alcohol, the water permeance depreciated slightly as shown in Figure 5 a. However, the selectivity of the resulted composite membrane is raised tremendously, up to 780:1, more than 20 times higher than that of the reported NaA zeolite membrane, as shown in Figure 5 b.

In addition to the above, Figure 7 shows the water vapour permeability and selectivity characteristics of the membranes. The selectivity of the membrane mostly is attributed to the top polymer layer. When the number of polymer dips increases from 3 to 6, the water vapor permeance (graph A) decreases gradually while the membrane's selectivity in term of water/air permeance ratio (graph B) increases rapidly. It means that while increasing the number of polymer dips makes the membrane slightly thicker, it drastically reduces non-selective pathways by covering any macro surface defects of the membrane.

The membrane can withstand strong mechanical forces under varying operating conditions, for example being subject to a pressure gradient. Such a pressure gradient increases the efficiency of the membrane. When low vacuum pressure of 0.1 mbar was applied on one side of the membrane, no physical damage was detected. The membrane dehumidification

performance can be sustained for three to four months without any major degradation – physically or performance outcome.

In alternative embodiments, alternative hygroscopic additives may be used For example, lithium chloride, TEG, calcium chloride, or lithium bromide may be used. Here, two chemical combinations, polyvinyl alcohol + lithium chloride and polyvinyl alcohol + TEG, have been tested. The tested content of LiCl in PVA was from 0 to 50%, and the tested content of TEG was from 30 to 91%. The overall effect of the TEG and LiCl contents on the maximum moisture removal performance can be seen in Figure 8. There is a linear increase in moisture removal performance with increasing TEG or LiCl content. The LiCl content tested was capped at 50% due to limitations in the drying membranes with LiCl contents.

Preparing the device

In order to test the present membrane in a real dehumidification system, a membrane with a physical dimension of 10cm (length) x 2cm (width) is mounted in an experimental setup as shown in Figure 2.

Figure 2 shows a typical single membrane dehumidifier setup. The setup, or device 5, has a first chamber 10 and a second chamber 15. Here, the first 10 and second 15 chambers may be known as the air chamber and vacuum chambers respectively. Separating the two chambers is the robust, highly permeable and highly selective composite membrane 20 of the present invention. The first chamber 10 has an inlet 25 for receiving humid ambient air H under normal (atmospheric) pressure and an outlet 30 for releasing dryer air D. As shown in the Figure, the membrane 20 is parallel to the flow of the air stream. In addition, the second chamber 15 is connected to a vacuum pump via an opening 35 to produce a transmembrane pressure gradient. Water vapor will be continuously and selectively removed from the humid air stream H with high flux, and the air becomes dried D at outlet 30.

The feed air H was passed over the membrane 20 at room temperature, around 24°C, with relative humidity of 90% and humidity ratio of around 17 g water vapor/1 kg air. The system is tested by adjusting the feed flow rate, pressure gradient between two sides of membranes, and composition of hydrophilic polyvinyl alcohol. The performance of the membrane is determined by the percentage of water vapor removed from the feed air stream. The results are shown in Figure 6.

Figure 6 a shows the dependence of moisture removal on pressure difference between two sides of a composite membrane with ratio PVA:LiCl= 3:1 and a feed velocity of 28 cm/s. During this experiment, it is apparent that our composite membrane can withstand a very low vacuum and there was no crack, distortion or deformation even under 0.1 mbar. The performance of our membrane in term of percentage of moisture removed increases slowly when the pressure difference increases from 0 to 900 mbar. However, the performance peaks sharply when pressure difference increases from 900 mbar to 1000 mbar. Based on our experimental result and numerical calculation, the pressure difference should be approximately 1000 mbar as possible in order to achieve the highest membrane performance for air-moisture separation.

Figure 6 b shows the dependence of moisture removal on the feed velocity and the content of lithium chloride added to polyvinyl alcohol. The test was carried out with pressure difference of 1000 mbar. As shown in this diagram, with every feed velocity tested, similar increasing proportional relationship between percentage of moisture removal and content of LiCl was observed. This result is consistent with the transport model for air dehumidification that water molecules are adsorbed on one side of the membrane where the water vapor partial pressure is high, diffuse through the bulk of membrane, and desorb on the other side of the membrane where water vapor partial pressure is low. The increase in the content of LiCl increases the hydrophilicity of the membrane [3], therefore, increases permeating rate of water molecules through the membrane, and increases the performance of the whole system. However, the content of LiCl higher than 50% is not recommended because the membrane turns deliquescent and may contaminate the air stream. Experimental results from the lab have demonstrated that a 43% moisture removal with the membrane containing PVA:LiCl= 1:1 (pressure difference = 1000 mbar, feed velocity = 28

cm/s) is good enough to reduce relative humidity of inlet air from 90% to a comfortable level of 52% at outlet air, at a constant temperature.

Figure 6 b also shows that with the same content of LiCl, the percentage of moisture removal always increases when the feed velocity decreases. For example, with the LiCl content of 50%, the performance of the membrane system increases linearly from 43 to 67% when the feed velocity of humid air decreases from 28 to 2.8 cm/s. At the highest performance, the relative humidity of outlet air is reduced to 34% from the value of 90% of inlet air.

Figure 9 shows another view of the device 5 shown in Figure 2. Here, the second chamber 15 is enclosed within the housing 40 and the membrane 20. Ambient humid air H enters the inlet 25 at one end of the housing 40 and leaves the housing 40 at the outlet 30 at the end opposite the inlet 25. Air flows through the device 5 and within the housing 40 in a planar fashion that is parallel to the plane of the membrane 20. An opening 35 in the second chamber 15 is connected to a vacuum pump to provide the transmembrane pressure gradient required to work the device 5 and also to discharge the moisture that is removed from the humid ambient air H.

In an alternative embodiment, the dehumidifier system and device 5 using the composite membrane 20 as shown in Figure 2 can be physically re-configured to maximize contacting between air and membrane in order to increase the performance by narrowing and elongating the membrane. In addition, it also can be employed to operate in a multi-membrane setup in order to meet the required feed velocity of air stream. An example is shown in Figure 10. Figure 10 essentially shows a plurality of the device 5 (shown in Figure 9) stacked on each other.

In yet another alternative embodiment of the present invention, the membrane may be tubular in structure, i.e. have a hollow core or center. As shown in Figure 11, a plurality of tubular membranes 20 are disposed spaced apart in the housing 40. Any pre-determined suitable number of tubular membranes 20 may be used. Naturally, just one membrane will work the invention. However, having a plurality of tubular membranes 20 increase the

surface area of the membranes that are exposed to the humid ambient air H. The tubular membrane may be prepared from the flat membrane by any suitable techniques known to the skilled person, including rolling the flat membrane to form the tubular structure.

Similar to the workings of the device 5 shown in Figure 9, humid ambient air H enters the device 5 at the inlets 25. These inlets form from the hollow interior of the tubular membrane 20. It is taken that the hollow interior also forms the first chamber 10 of the device 5. The second chamber 15 of the device 5 is the cavity that is enclosed by the exterior of the tubular membrane 20 and the housing 40. End caps 45 disposed at the two opposite ends of the device 5 provide cut-out or stamped-out openings for placement of the tubular membranes 20 such that the openings not only provides support for the tubular membranes 20 but also forms the inlet 25 for receiving humid ambient air H. These openings are circular to match the diameter of the tubular membranes 20. The remaining portions of the end caps 45 provide the enclosure for enclosing the second chamber 15, which includes an opening 35 for connection to a vacuum pump and removal of water vapour.

The above key results have demonstrated the capability of the composite membrane to effectively sieve out moisture from humid air and, thereby, confirm the potential and capability of our synthesized composite membranes in dehumidification applications.

Discussion

For the first time, a novel composite membrane comprising three key components: stainless steel wire mesh, porous titania and hydrophilic polymer made of polyvinyl alcohol and lithium chloride was synthesized. All the components are low-cost and commercially available materials. The preparation method is green and suitable for large scale production. The membrane inherits unique and valuable properties of each component such as strength and durability of stainless steel, high diffusivity of ceramic material and high permeability and selectivity of hydrophilic polymer. It has high selectivity and permeability for water vapor over air. In terms of selectivity, it is more than 20 times better

than the reported NaA zeolite membrane. It is also strong enough to be used in a high vacuum or pressure system. Additionally, it is corrosion resistance.

The membrane's dehumidification capacity has been tested in a single sheet setup shown in Figure 2. The membrane is mounted with one side facing the air stream while the other side is subjected to vacuum pressure. The result shows that the membrane dehumidifies the air effectively. It easily dries the humid input air with 90% relative humidity to a dry and comfortable output air with 50% relative humidity. Compared with existing dehumidification technologies, our invention has demonstrated marked improvement in air dehumidification.

Conventional air-conditioning using chillers dehumidifies the air inefficiently since the cooled and dehumidified air needs to be reheated before it is useable. Additionally, as the moisture in the air around the coil condenses the dew-point temperature of the air drops. This means an increasingly lower coil temperature is needed to continue dehumidification. Therefore, it is inefficient to achieve very low humidity levels using this method as it is impossible to achieve dew points below freezing. The proposed invention can achieve significant energy savings by removing the moisture without changing temperature. The dehumidified air can then be directly cooled to the desired temperature.

As described earlier, the present membrane separation setup achieves significantly better dehumidification compared to commercial silica gel. Commercial solid desiccant wheels are employed in existing HVAC systems to remove latent load and they require high temperature thermal heat to ensure sustainable operation. Their dehumidification performance markedly degrades as they approach saturation during high humidity condition. The energy cost to regenerate is high due to the need for high quality heat of above 100°C. Silica-gel, the most effective desiccant for air/gas dehumidification, requires temperature often greater than 120°C. Additionally, large pressure drops across the desiccant wheels translates to higher operating cost due to larger fan power. The proposed membrane separation setup using the synthesized composite membrane has higher efficiency and requires no thermal regeneration and it does not cause potential air stream

blockage. In addition, this membrane setup is more compact and does not require complicated operation and maintenance.

Employing the present novel composite membrane for air dehumidification can provide a healthy indoor environment in an energy efficient manner. The incorporation of this system to any HVAC system can achieve significant savings in the chillers' energy used to provide thermal comfort conditions. Industrial processes requiring low humidity such as medical industry, wafer fabrication etc. can also apply this technology to obtain relative humidity as low as 30%.

The current invention still has some energy consumption associated with the vacuum pump. However, this energy consumption value is considered low in relative to the energy due to chilled water condensation. Thanks to the high selectivity of the present composite membrane, only water is sieved out and goes through the membrane. Because the amount of water vapor in air is small, the flux of water vapor through the membrane is small and the only a little periodical running time of the vacuum pump is required to maintain low pressure.

Whilst there has been described in the foregoing description preferred embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations or modifications in details of design or construction may be made without departing from the present invention.

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Claims

1. A membrane for removing moisture in the air, the membrane comprising:
   (a) a metal scaffold structure;
   (b) a ceramic material formed within the scaffold structure; and
   (c) a hydrophilic polymer outer coating.

2. The membrane according to claim 1, wherein the metal scaffold structure is a stainless steel wire mesh.

3. The membrane according to any one of the preceding claims, where the ceramic material is titanium dioxide.

4. The membrane according to any one of the preceding claims, wherein the hydrophilic polymer is any one selected from the group comprising: polyvinyl alcohol, nafion polymer, polyamide, polyacrylic acid and cellulose acetate.

5. The membrane according to any one of the preceding claims, wherein the hydrophilic polymer further comprises a hygroscopic additive.

6. The membrane according to claim 5, wherein the hygroscopic additive is any one selected from the group comprising: lithium chloride, triethylene glycol, calcium cholride and lithium bromide.

7. The membrane according to claim 6, wherein the ratio of polyvinyl alcohol and lithium chloride present in the hydrophilic polymer is from 3:1 to 1:1. Alternatively, the ratio of polyvinyl alcohol and triethylene glycol is from 1:6 to 1:10.

8. The membrane according to claim 6, wherein the ratio of polyvinyl alcohol and triethylene glycol is from 1:6 to 1:10.

9. The membrane according to any one of the preceding claims, wherein the membrane is tubular.

10. A device for removing moisture in the air, the device comprising:

(a) a housing having a first chamber and a second chamber;

(b) a membrane according to any one of claims 1 to 9, the membrane separating the first and second chambers;

(c) the first chamber having an inlet for receiving ambient air and an outlet for releasing dryer air;

(d) the second chamber having an opening for providing fluid communication with a vacuum pump for applying a pressure gradient across the membrane, the opening further discharges moisture removed from the ambient air.

11. The device according to claim 10, wherein the housing comprising a plurality of first and second chambers stacked on each other.

12. The device according to claim 10, wherein the membrane is tubular, the hollow interior of the tubular membrane forms the first chamber, and the cavity enclosed by the exterior of the tubular membrane and the housing forms the second chamber.

13. The device according to claim 12, further comprising a plurality of tubular membranes spaced apart in the housing.

14. A method for removing water vapour, the method comprising:

(a) providing a membrane according to any one of claims 1 to 9, the membrane having a first surface and a second surface;

(b) exposing ambient air to the first surface of the membrane;

(c) applying a pressure gradient across the membrane; and

(d) removing the water vapour from the second surface of the membrane.

15. The method according to claim 14, wherein the pressure gradient is applied by subjecting the second surface of the membrane with a vacuum pressure.

16. The method according to any one of claims 14 or 15, wherein the transmembrane pressure applied on the membrane is from 900 to 1000mbar.

17. The method according to any one of claims 14 to 16, wherein the first surface of the membrane is constantly exposed to ambient air, and the flow of the ambient air stream is parallel to the plane of the membrane.

18. The method according to claim 17, wherein the flow rate of the ambient air stream is about 28 cm/s.

19. The method according to any one of claims 14 to 18, wherein the temperature of the ambient air is about 24°C.

20. The method according to any one of claims 14 to 19, wherein the ambient air has a relative humidity of about 90% and humidity ratio of 17g of water vapour to 1 kg of air.

21. The method according to claim 20, wherein the relative humidity of the air leaving the membrane is about 34%.

22. A membrane for removing moisture in the air as substantially described herein with reference to and as illustrated by the accompanying drawings.

23. A device for removing moisture in the air as substantially described herein with reference to and as illustrated by the accompanying drawings.

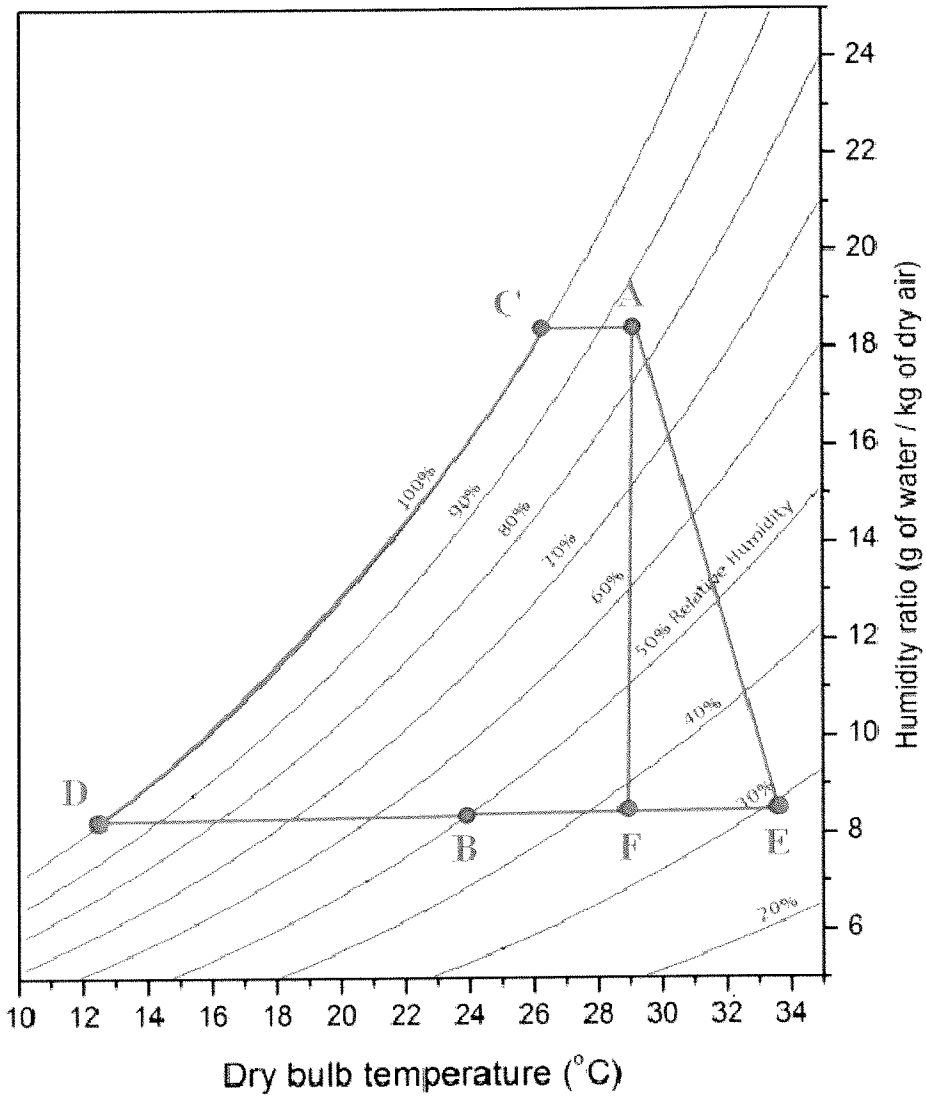

C
A
D
B
F
E
100%
90%
80%
70%
60%
50% Relative Humidity
40%
30%
20%
10 12 14 16 18 20 22 24 26 28 30 32 34
Dry bulb temperature (°C)
6 8 10 12 14 16 18 20 22 24
Humidity ratio (g of water / kg of dry air)

Figure 1

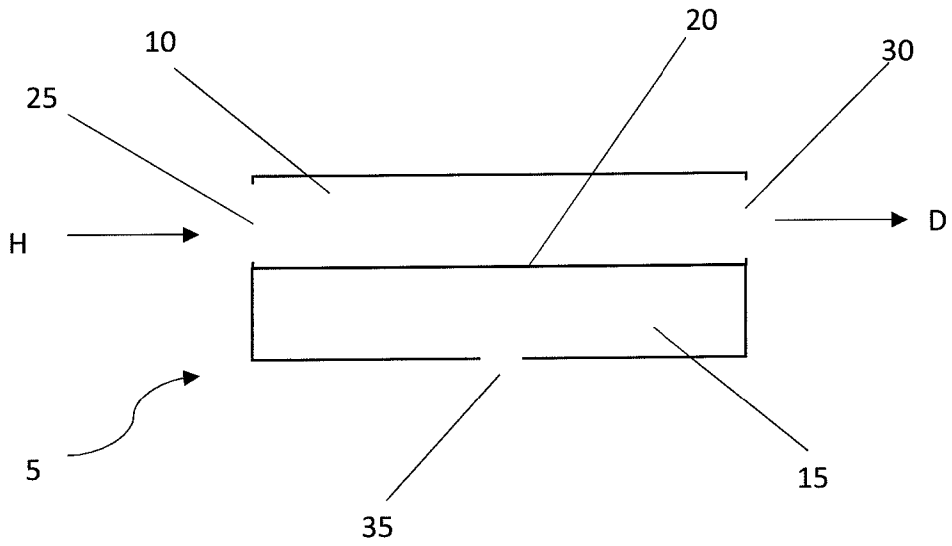


Figure 2

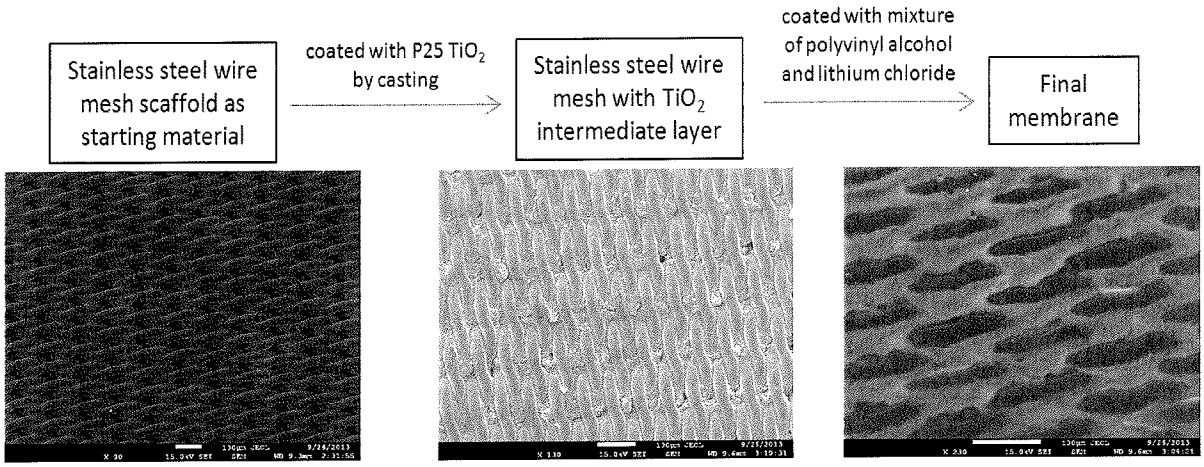

Stainless steel wire mesh scaffold as starting material
coated with P25 TiO_2 by casting
Stainless steel wire mesh with TiO_2 intermediate layer
coated with mixture of polyvinyl alcohol and lithium chloride
Final membrane

Figure 3

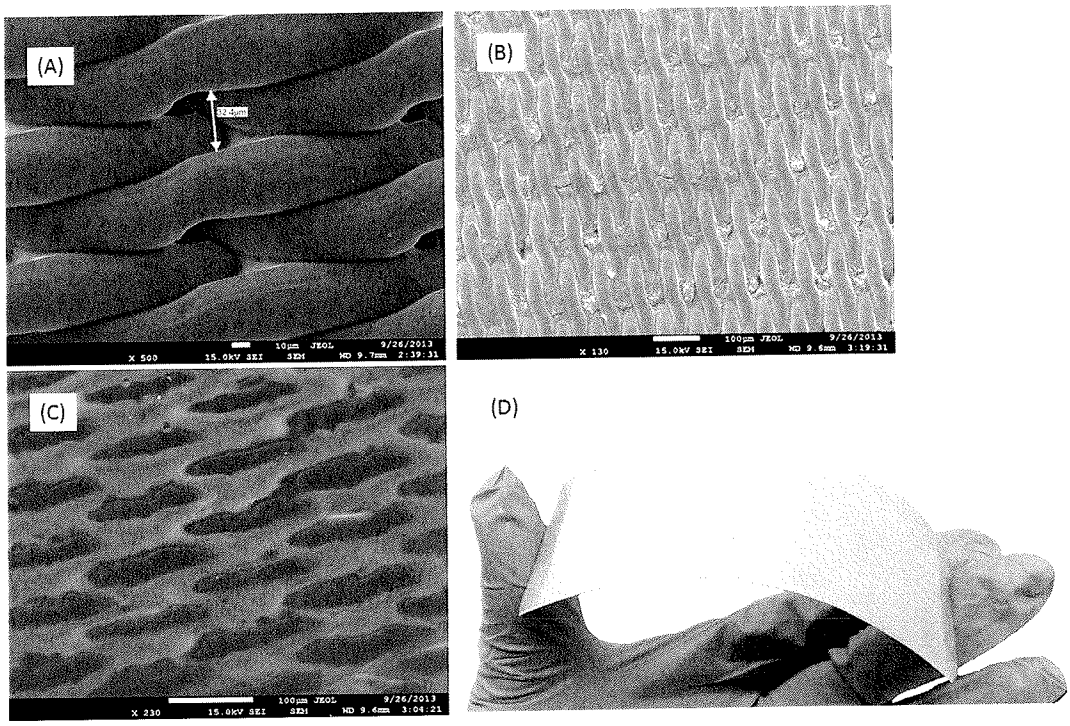

(A)
32.4μm
X 500 10μm JEOL 9/26/2013
15.0kV SEI SEM WD 9.7mm 2:39:31
(B)
X 130 100μm JEOL 9/26/2013
15.0kV SEI SEM WD 9.6mm 3:19:31
(C)
X 230 100μm JEOL 9/26/2013
15.0kV SEI SEM WD 9.6mm 3:04:21
(D)

Figure 4

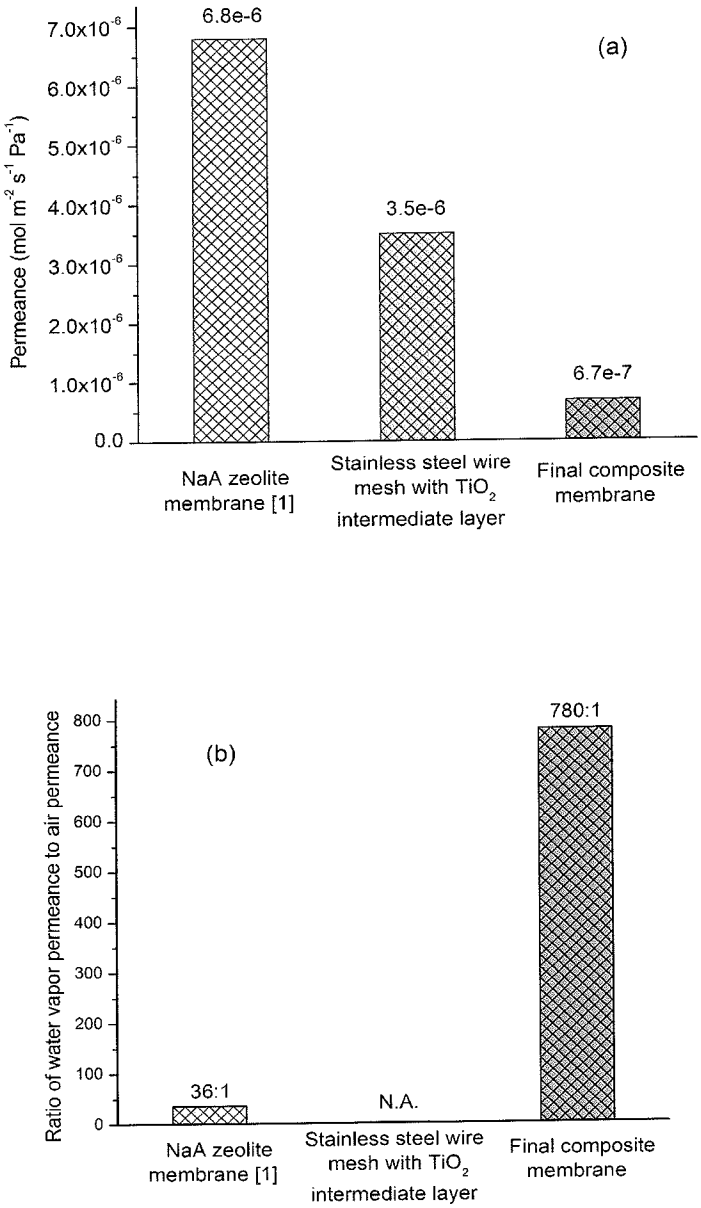
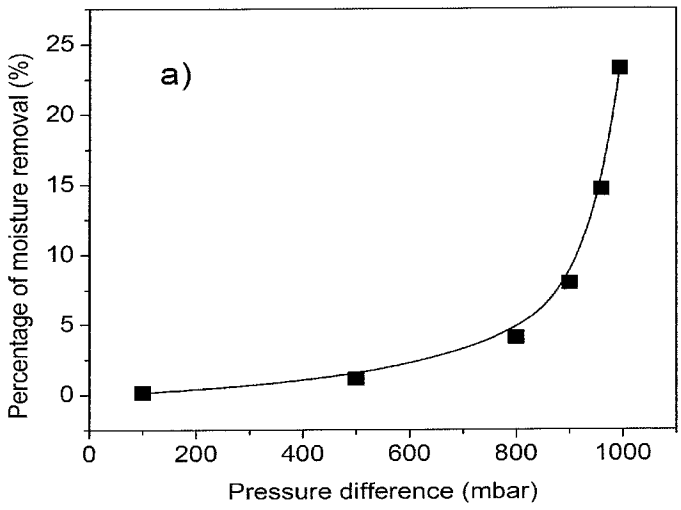

(a)
Permeance (mol m-2 s-1 Pa-1)
7.0x10-6
6.0x10-6
5.0x10-6
4.0x10-6
3.0x10-6
2.0x10-6
1.0x10-6
0.0
6.8e-6
3.5e-6
6.7e-7
NaA zeolite membrane [1]
Stainless steel wire mesh with TiO2 intermediate layer
Final composite membrane
(b)
Ratio of water vapor permeance to air permeance
800
700
600
500
400
300
200
100
0
36:1
N.A.
780:1
NaA zeolite membrane [1]
Stainless steel wire mesh with TiO2 intermediate layer
Final composite membrane

Figure 5


a)
Percentage of moisture removal (%)
0
5
10
15
20
25
0
200
400
600
800
1000
Pressure difference (mbar)

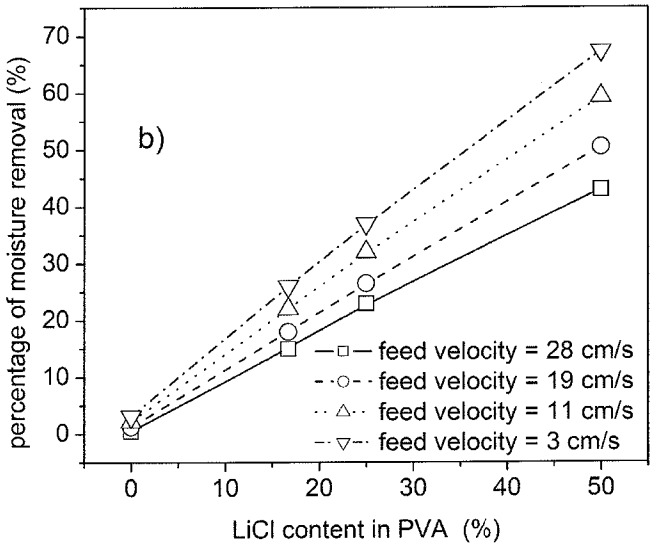

b)
percentage of moisture removal (%)
0
10
20
30
40
50
60
70
0
10
20
30
40
50
LiCl content in PVA (%)
feed velocity = 28 cm/s
feed velocity = 19 cm/s
feed velocity = 11 cm/s
feed velocity = 3 cm/s

Figure 6

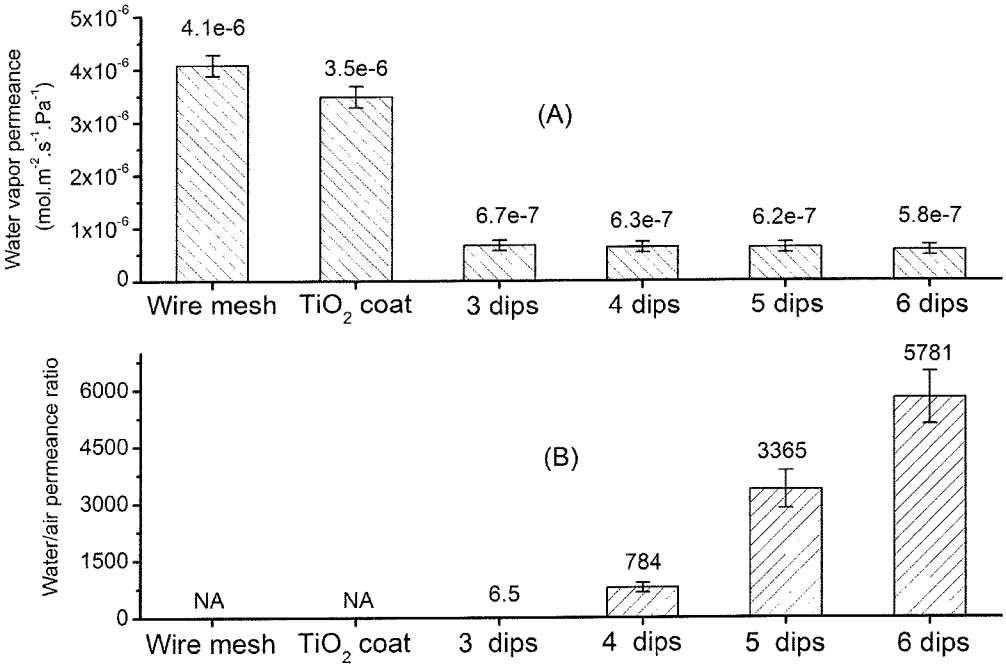

Water vapor permeance (mol.m-2.s-1.Pa-1)
5x10-6
4x10-6
3x10-6
2x10-6
1x10-6
0
4.1e-6
3.5e-6
6.7e-7
6.3e-7
6.2e-7
5.8e-7
(A)
Wire mesh
TiO2 coat
3 dips
4 dips
5 dips
6 dips
Water/air permeance ratio
6000
4500
3000
1500
0
NA
NA
6.5
784
3365
5781
(B)
Wire mesh
TiO2 coat
3 dips
4 dips
5 dips
6 dips

Figure 7

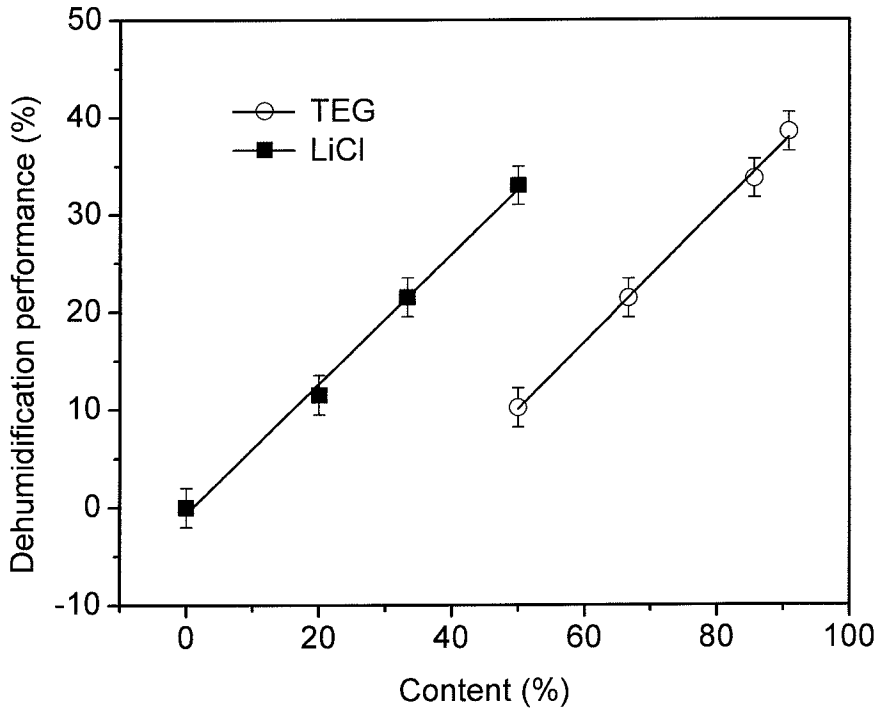

Dehumidification performance (%)
Content (%)
TEG
LiCl
50
40
30
20
10
0
-10
0
20
40
60
80
100

Figure 8

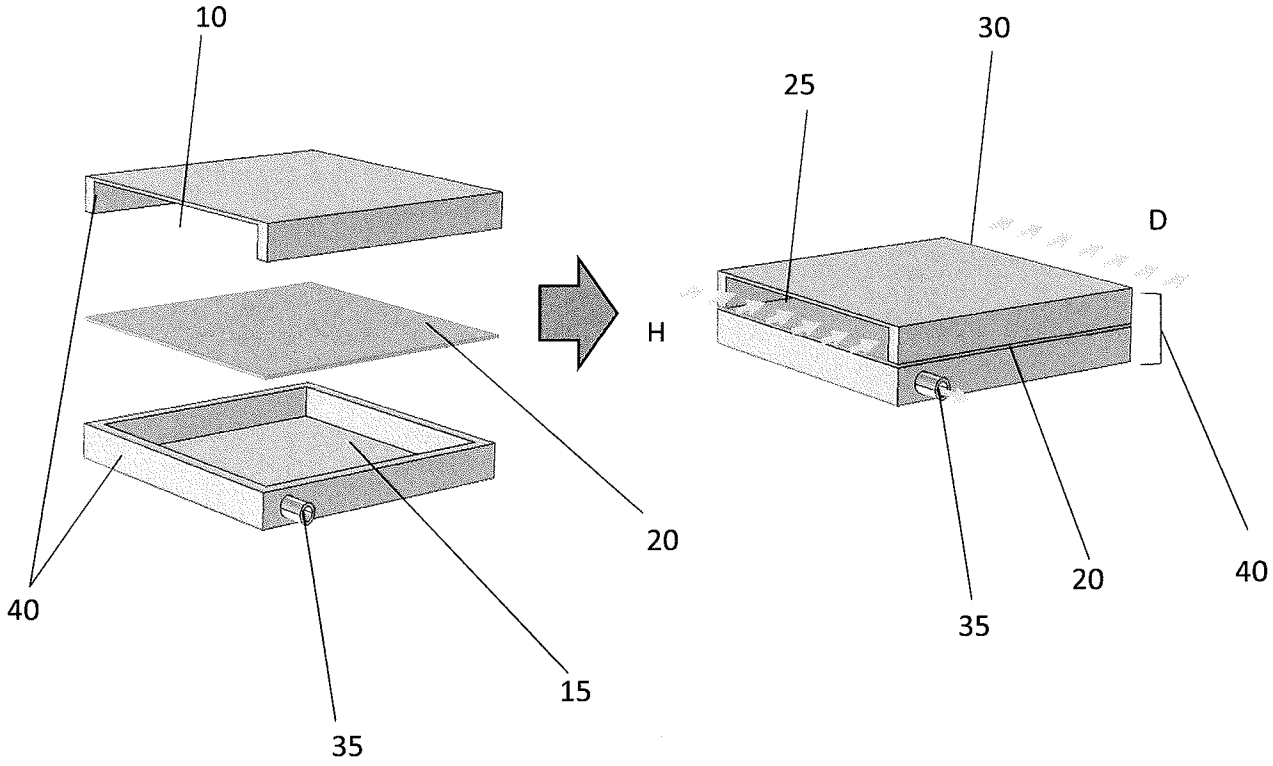


Figure 9

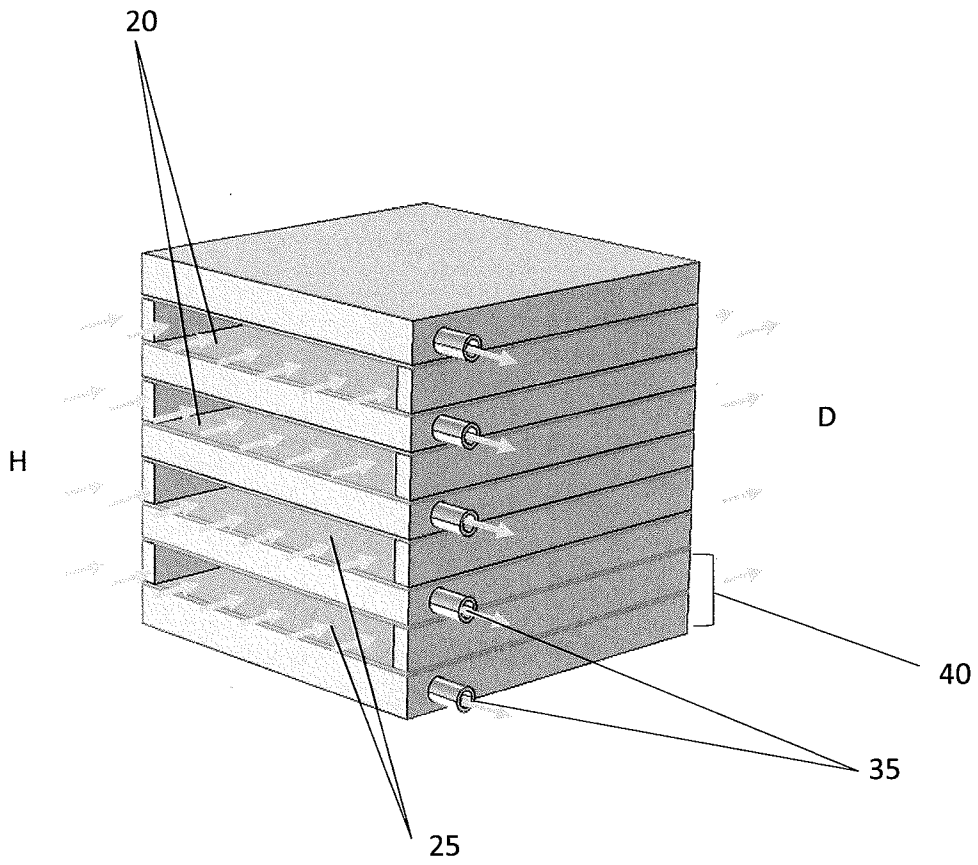


Figure 10

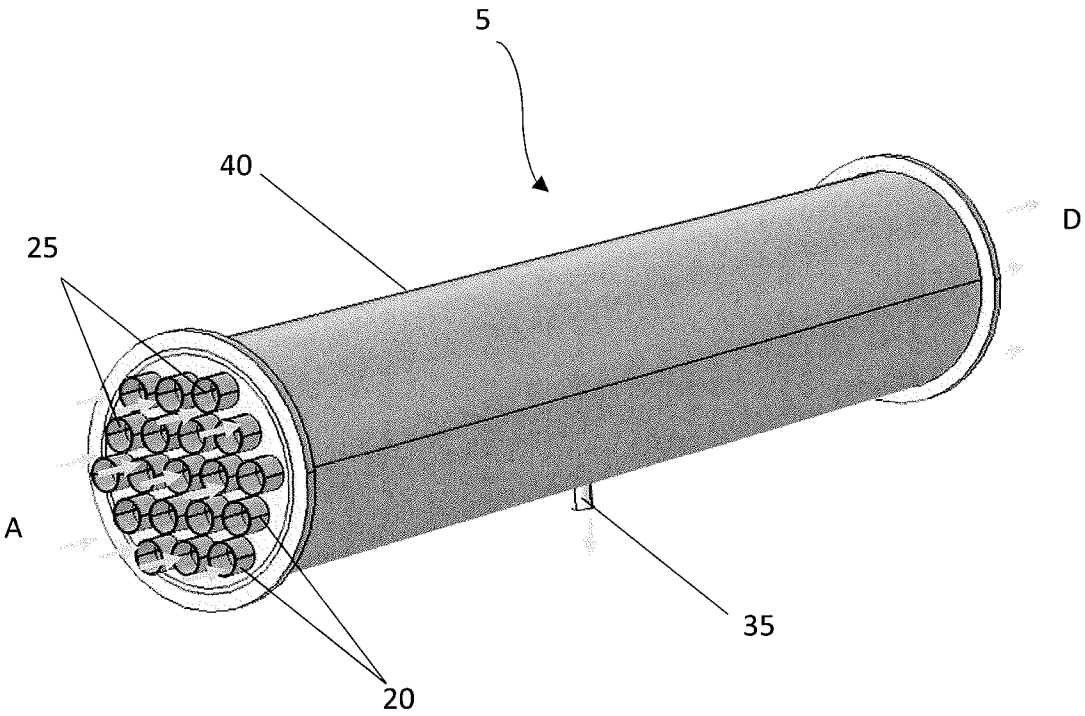


Figure 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2015/050219

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. B01D53/26(2006.01)i, B01D69/10(2006.01)i, B01D69/12(2006.01)i, B01D71/02(2006.01)i

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)

Int.Cl. B01D53/26, B01D69/10, B01D69/12, B01D71/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2015
Registered utility model specifications of Japan 1996-2015
Published registered utility model applications of Japan 1994-2015

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2006-305463 A (MITSUBISHI HEAVY INDUSTRIES, LTD.) 2006.11.09, claim 1, 4-7, paragraphs[0001], [0010], [0012], [0018], [0020]-[0026], [0042], Figs. 1- 2 (Family: none)	1-23
Y	JP 49-045882 A (Mitsubishi Electric Corporation) 1974.05.01, claim, p.2, upper right column, lower left column, lower right column (Family: none)	1-10, 12-23
Y	WO 2010/132983 A1 (DPOINT TECHNOLOGIES INC.) 2010.11.25, claim 24, paragraphs [0005], [0040]-[0041], [0047], [0052]-[0053], [0056], [0067], [0071], [0074], Fig. 2, Fig. 4a & JP 2012-527336 A & US 2012/0061045 A1 & EP 2435171 A1 & KR 10-2012-0012990 A & CN 102458625 A	1-10, 12-23

☑ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"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
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13.10.2015	20.10.2015

Name and mailing address of the ISA/JP	Authorized officer
Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Mie Okada Telephone No. +81-3-3581-1101 Ext. 3421

4D 3768

INTERNATIONAL SEARCH REPORT

International application No.
PCT/SG2015/050219

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 2012-020232 A (UNITIKA LTD.) 2012.02.02, claim 1, 5, paragraphs [0001], [0018] (Family: none)	4, 16, 18-23
Y	US 2007/0287036 A1 (ASAHI KASEI CHEMICALS CORPORATION) 2007.12.13, Fig. 7-8, Fig. 10, paragraphs [0081]-[0083], [0095], [0097]-[0098],[0133]-[0137], [0151]-[0158], [0181], [0207]-[0208] & US 2007/0287036 A1 & WO 2005/110581 A1 & DE 112005001084 T & CN 1953799 A	4, 11, 16, 18-23
Y	JP 06-106021 A (NITTO DENKO CORPORATION) 1994.04.19, paragraphs [0001]-[0002], [0007], [0009]-[0010] (Family: none)	5-8, 16, 18-23
Y	JP 2007-075699 A (Asahi Kasei Chemicals Corporation) 2007.03.29, paragraphs [0018], [0024]-[0025], [0042], Fig. 7-8 (Family: none)	11, 16, 18-23
A	JP 2011-041921 A (Mitsubishi Chemical Corporation) 2011.03.03, claim 1-2, 4, 10, paragraphs [0001], [0019]-[0020], [0027]-[0028], [0031], [0033] (Family: none)	1-23
A	WO 2009/121124 A1 (COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION) 2009.10.08, page 5, lines 19-page 6, lines8, page 7, lines16-page 8, lines 14, page 9, lines 19-21, page 11, lines 3-12, page 13, lines 15-23, Fig. 1-2 & US 2011/0107911 A1 & EP 2274079 A & AU 2009230868 A	1-23
A	US 2007/0193946 A1 (GKSS -Forschungszentrum Geesthacht GmbH) 2007.08.23, paragraphs [0008]-[0011], [0019]-[0023], claim 1, 9-10 & WO 2006/048068 A1 & EP 1807175 A1 & DE 102004053402 B & CN 101035605 A & IL 182846 A	1-23