

(12) **United States Patent**  
**Claridge et al.**

(10) **Patent No.:** **US 8,685,144 B2**  
(45) **Date of Patent:** **Apr. 1, 2014**

(54) **SYSTEM AND METHOD FOR EFFICIENT AIR DEHUMIDIFICATION AND LIQUID RECOVERY**

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(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 257 days.

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(21) Appl. No.: **12/945,714**

(22) Filed: **Nov. 12, 2010**

(65) **Prior Publication Data**

US 2012/0118145 A1 May 17, 2012

(51) **Int. Cl.**  
**B01D 53/22** (2006.01)

(52) **U.S. Cl.**  
USPC ..... **95/52**; 95/45; 95/43; 96/4; 96/7; 96/10

(58) **Field of Classification Search**  
USPC ..... 95/43, 45, 52; 96/4, 7, 10  
See application file for complete search history.

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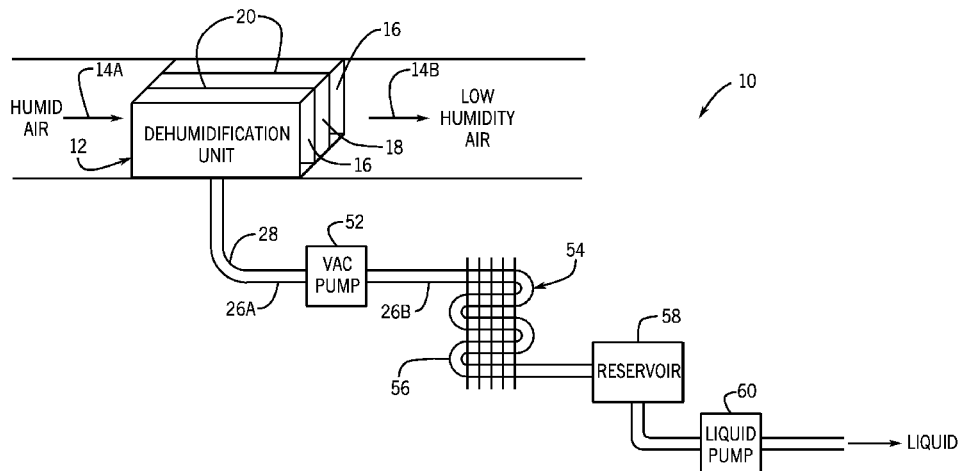
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(57) **ABSTRACT**

The present invention relates to systems and methods for dehumidifying air by establishing a humidity gradient across a water selective permeable membrane in a dehumidification unit. Water vapor from relatively humid atmospheric air entering the dehumidification unit is extracted by the dehumidification unit without substantial condensation into a low pressure water vapor chamber operating at a partial pressure of water vapor lower than the partial pressure of water vapor in the relatively humid atmospheric air. For example, water vapor is extracted through a water permeable membrane of the dehumidification unit into the low pressure water vapor chamber. As such, the air exiting the dehumidification unit is less humid than the air entering the dehumidification unit. The low pressure water vapor extracted from the air is subsequently condensed and removed from the system at ambient conditions.

**13 Claims, 6 Drawing Sheets**



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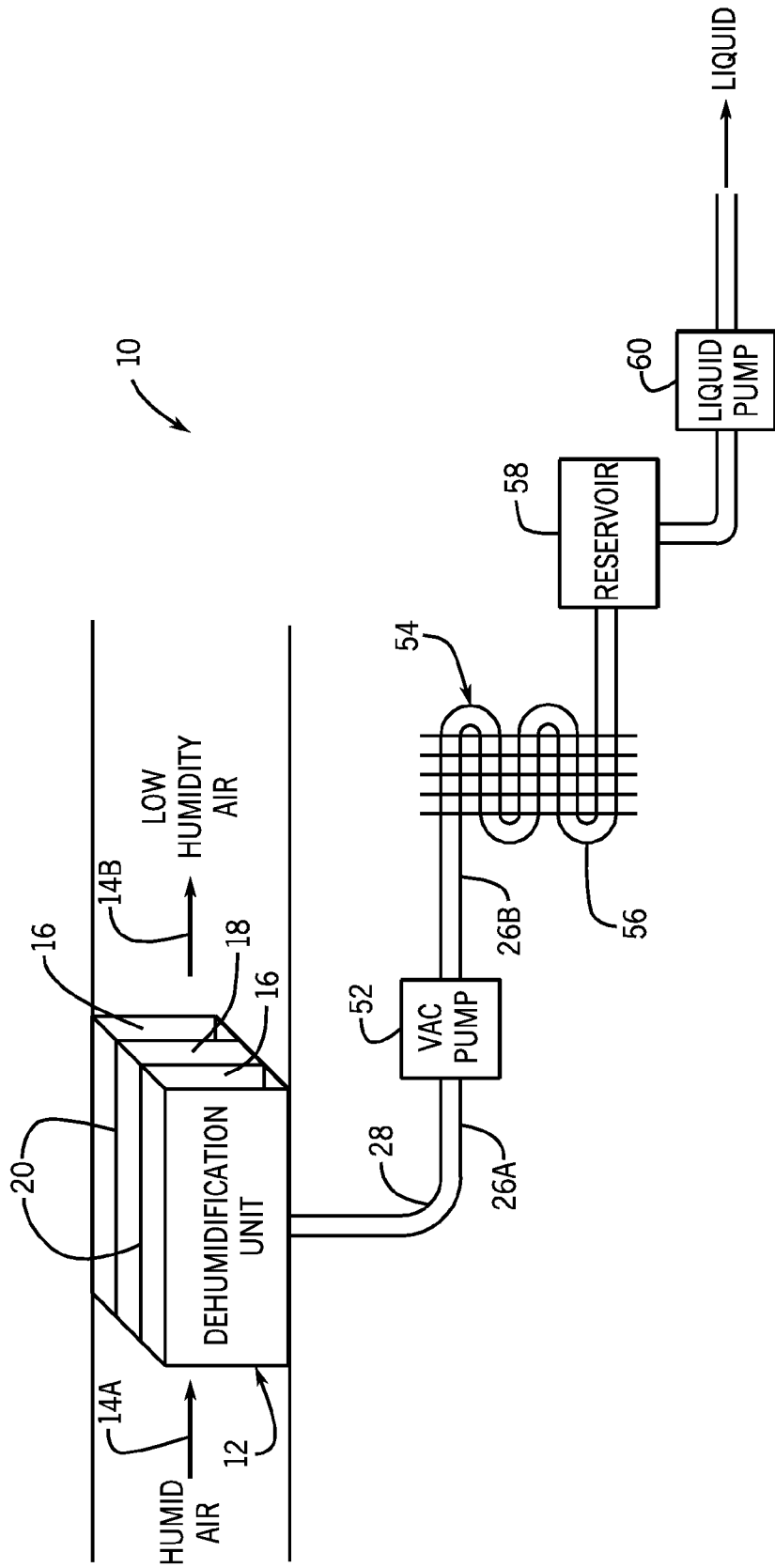


FIG. 1

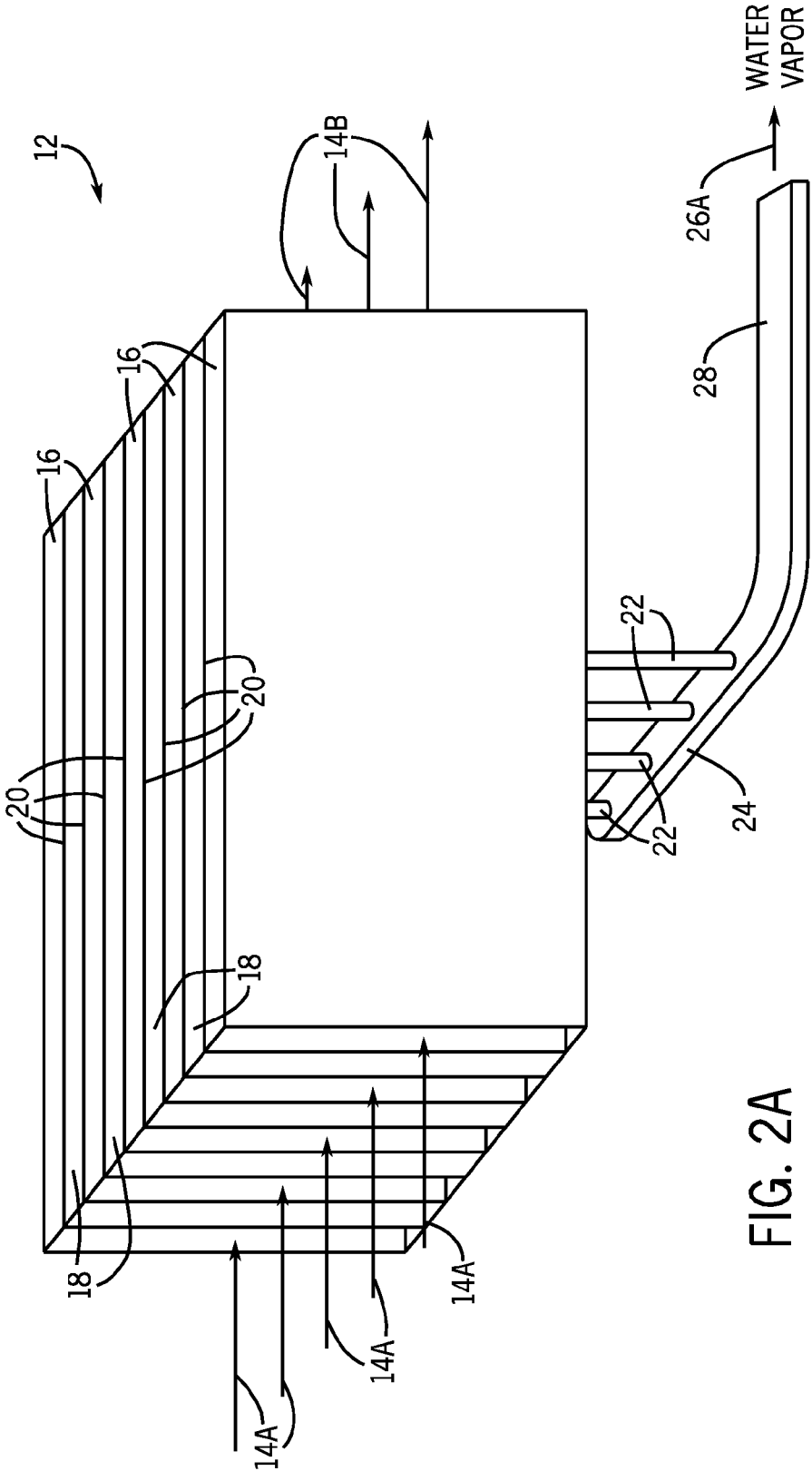


FIG. 2A

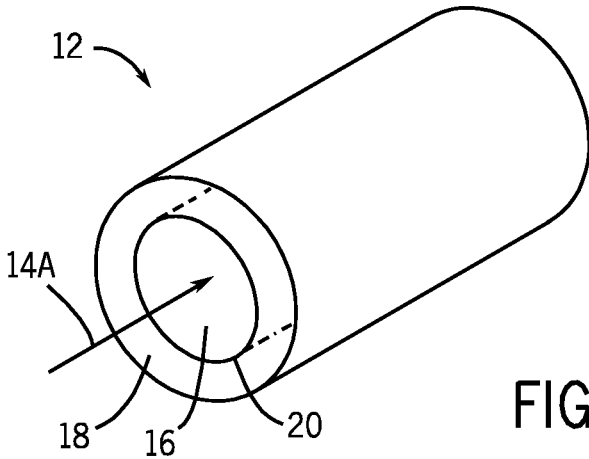


FIG. 2B

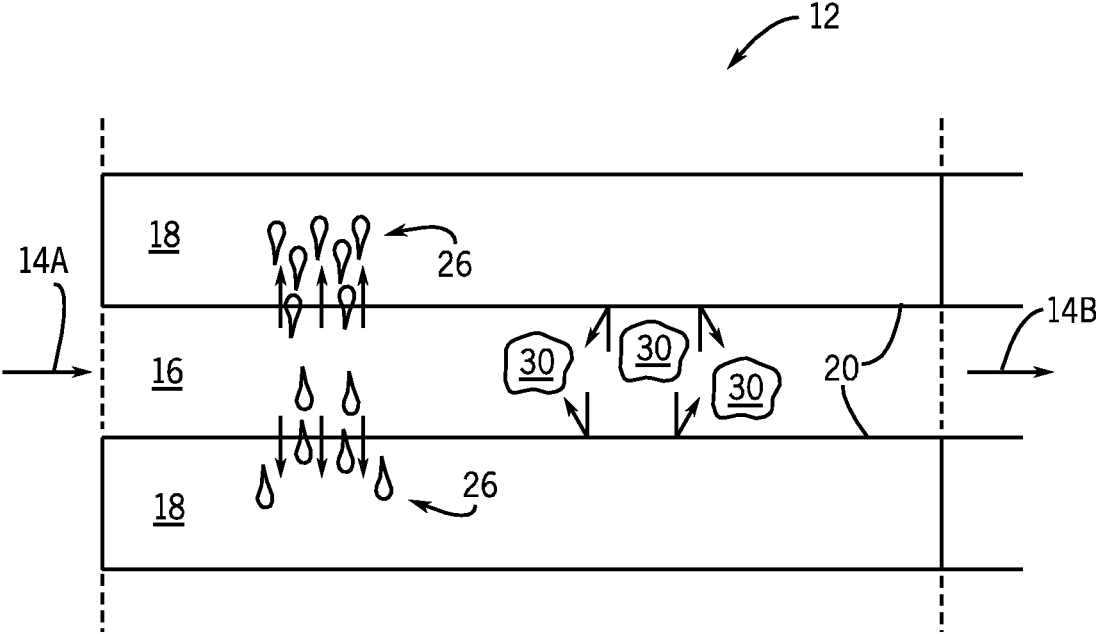


FIG. 3

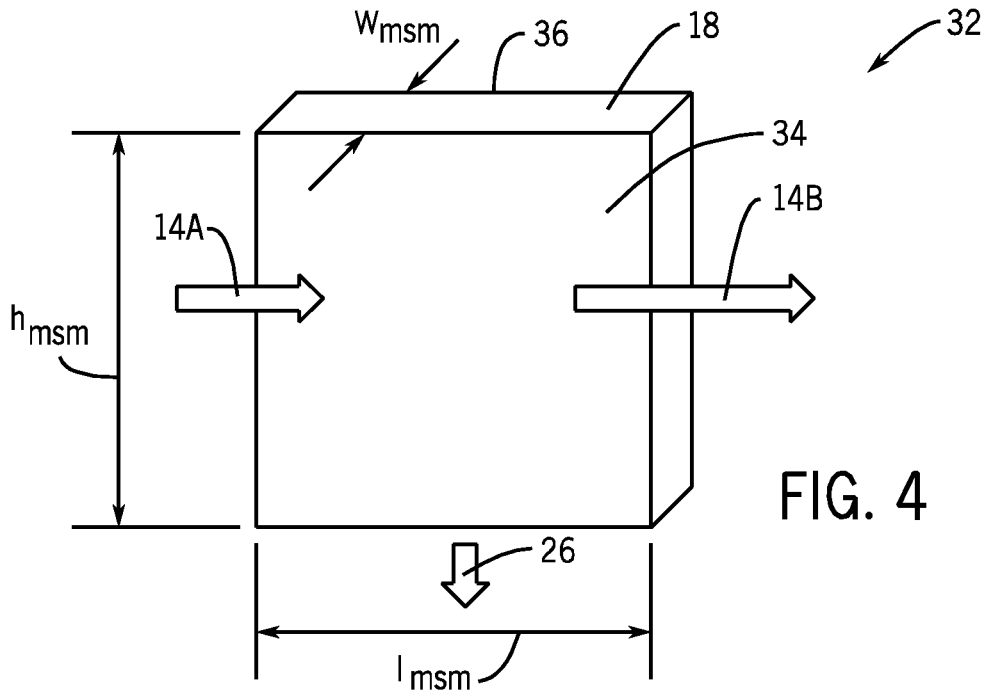


FIG. 4

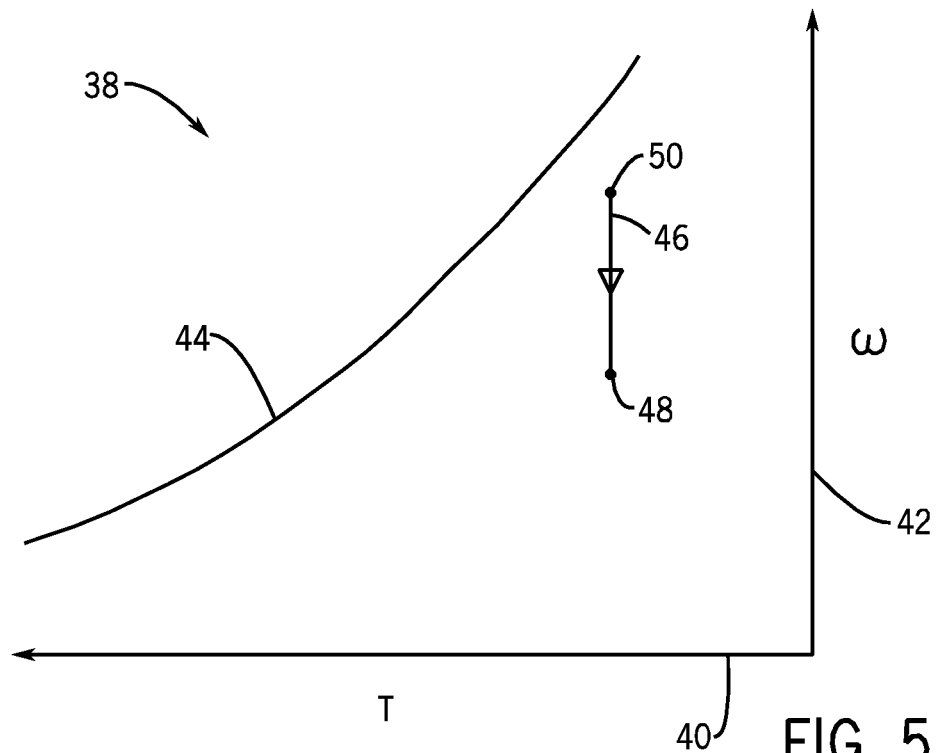


FIG. 5

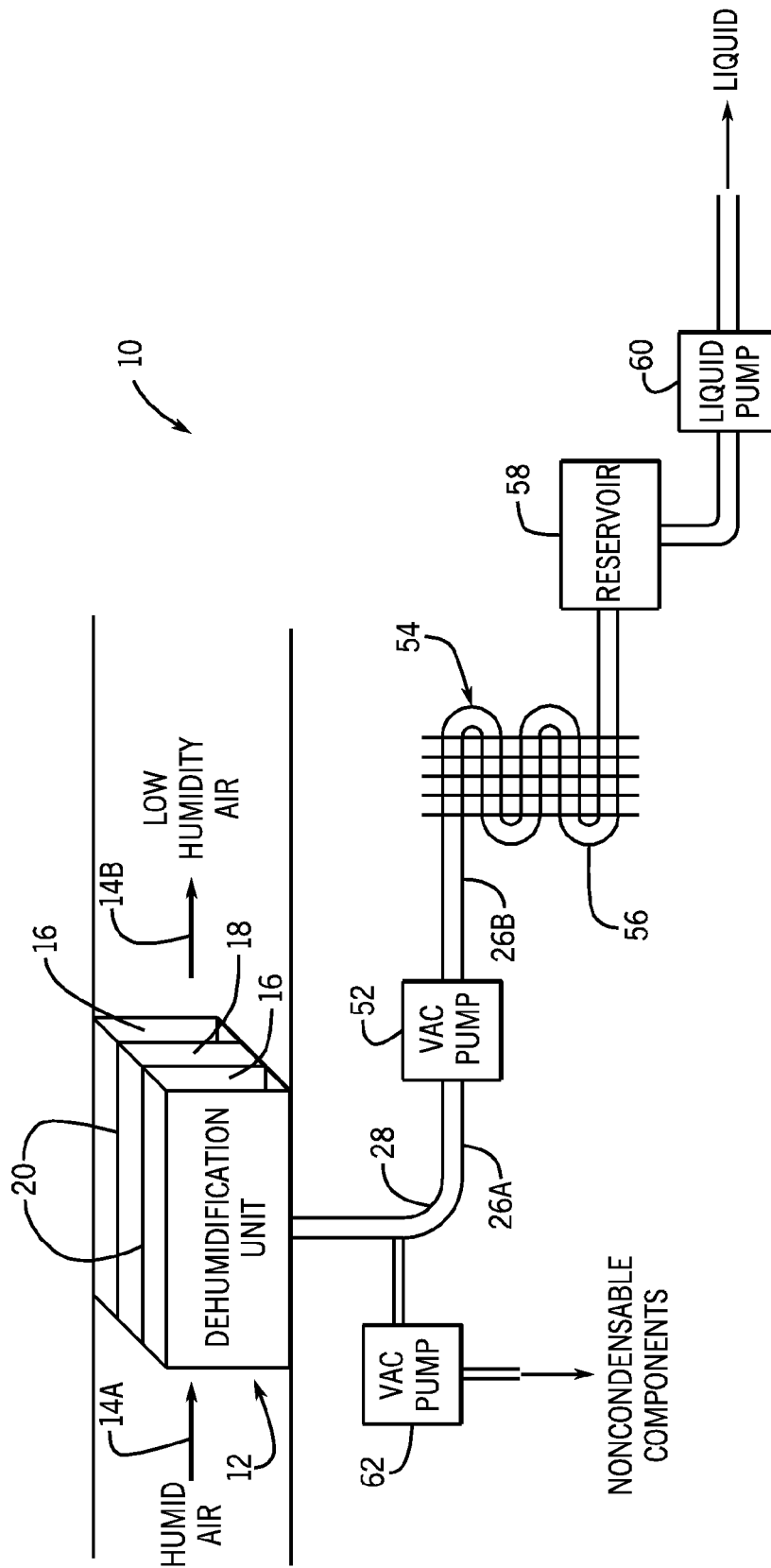


FIG. 6

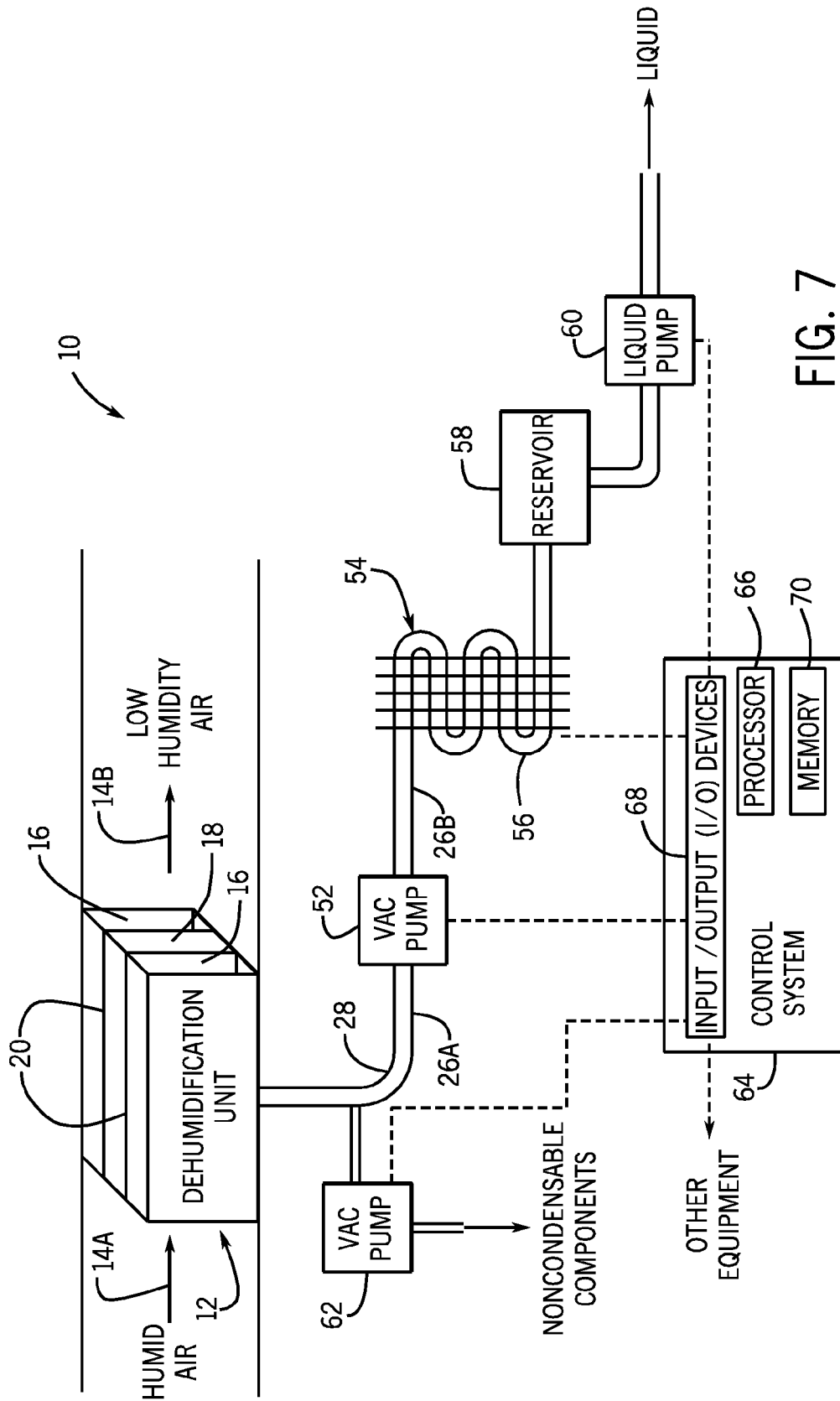


FIG. 7



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## SYSTEM AND METHOD FOR EFFICIENT AIR DEHUMIDIFICATION AND LIQUID RECOVERY

### BACKGROUND

Heating, ventilating, and air conditioning (HVAC) systems often have dehumidification systems integrated into the cooling apparatus for dehumidifying the air being conditioned by such systems. When cooling is required in warm to hot environments, the air being cooled and dehumidified will usually have a humidity ratio above approximately 0.009 (pounds of H<sub>2</sub>O per pounds of dry air). In these environments, the HVAC systems traditionally use refrigerant compressors for sensible cooling of the air and removal of latent energy (i.e., humidity). The air is typically cooled to about 55° F., which condenses H<sub>2</sub>O out of the air until the air is about 100% saturated (i.e., relative humidity at about 100%). The 55° F. temperature lowers the humidity ratio to about 0.009 pounds of H<sub>2</sub>O per pounds of dry air, which is the water vapor saturation point at 55° F., resulting in a relative humidity of almost 100%. When this air warms to about 75° F., the humidity ratio remains approximately the same, and the relative humidity drops to approximately 50%. This traditional method of dehumidification requires the air to be cooled to about 55° F., and can usually achieve a coefficient of performance (COP) of approximately 3-5.

### BRIEF DESCRIPTION

Certain embodiments commensurate in scope with the present disclosure are summarized in the following. These embodiments are not intended to limit the scope of the claimed invention, but rather these embodiments are intended only to provide a brief summary of possible forms of the invention. Indeed, the invention may encompass a variety of forms that may be similar to or different from the embodiments set forth in the following.

In a first embodiment, a dehumidification system for removing water vapor from an airstream is provided. The dehumidification system includes a first and second channel separated by a membrane. The membrane is configured to facilitate removal of water vapor from an airstream flowing through the first channel by facilitating passage of H<sub>2</sub>O from the water vapor to the second channel through permeable volumes of the membrane while substantially blocking all other components of the airstream from passing through the membrane. The dehumidification system also includes a pressure increasing device configured to create a lower partial pressure of water vapor within the second channel than in the first channel, such that the H<sub>2</sub>O moves through the membrane to the second channel. The pressure increasing device is also configured to increase the pressure of water vapor at an outlet of the pressure increasing device to a partial pressure of water vapor in a range suitable for subsequent condensing into liquid water. The dehumidification system further includes a condensation device configured to receive the water vapor from the pressure increasing device and condense the water vapor into liquid water. In addition, the dehumidification system includes a water transport device configured to transport the liquid water from the condensation device.

In a second embodiment, a system includes a dehumidification system for removing H<sub>2</sub>O vapor from an airstream. The dehumidification system includes an air channel configured to receive an inlet airstream and discharge an outlet airstream. The dehumidification system also includes an H<sub>2</sub>O permeable material adjacent to the air channel. The H<sub>2</sub>O

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permeable material is configured to selectively enable H<sub>2</sub>O from H<sub>2</sub>O vapor in the inlet airstream to pass through the H<sub>2</sub>O permeable material to a suction side of the H<sub>2</sub>O permeable material and substantially block other components in the inlet airstream from passing through the H<sub>2</sub>O permeable material to the suction side of the H<sub>2</sub>O permeable material. The dehumidification system further includes a pressure increasing device configured to create a lower partial pressure of H<sub>2</sub>O vapor on the suction side of the H<sub>2</sub>O permeable material than the partial pressure of the H<sub>2</sub>O vapor in the inlet airstream to drive passage of the H<sub>2</sub>O from the H<sub>2</sub>O permeable material, and to increase the pressure at an outlet of the pressure increasing device to a partial pressure of H<sub>2</sub>O vapor suitable for condensing H<sub>2</sub>O vapor into liquid H<sub>2</sub>O. In addition, the dehumidification system includes a condensation device configured to receive the H<sub>2</sub>O vapor from the outlet of the pressure increasing device, and to condense the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O.

In a third embodiment, a method includes using a pressure differential across an H<sub>2</sub>O permeable material to provide a force to move H<sub>2</sub>O through the H<sub>2</sub>O permeable material into an H<sub>2</sub>O vapor channel. The method also includes receiving H<sub>2</sub>O vapor from the H<sub>2</sub>O permeable material into the H<sub>2</sub>O vapor channel. The method further includes receiving the H<sub>2</sub>O vapor from the H<sub>2</sub>O vapor channel into a pressure increasing device and expelling the H<sub>2</sub>O vapor from the pressure increasing device at a slightly increased partial pressure of H<sub>2</sub>O vapor. In addition, the method includes receiving the H<sub>2</sub>O vapor from the pressure increasing device into a condensation device and condensing the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O. The method also includes transporting the liquid H<sub>2</sub>O from the condensation device to ambient conditions.

### BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of embodiments of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. 1 is a schematic diagram of an HVAC system having a dehumidification unit in accordance with an embodiment of the present disclosure;

FIG. 2A is a perspective view of the dehumidification unit of FIG. 1 having multiple parallel air channels and water vapor channels in accordance with an embodiment of the present disclosure;

FIG. 2B is a perspective view of the dehumidification unit of FIG. 1 having a single air channel located inside a single water vapor channel in accordance with an embodiment of the present disclosure;

FIG. 3 is a plan view of an air channel and adjacent water vapor channels of the dehumidification unit of FIGS. 1, 2A, and 2B in accordance with an embodiment of the present disclosure;

FIG. 4 is a perspective view of a separation module formed using a membrane that may be used as a water vapor channel of the dehumidification unit of FIGS. 1-3 in accordance with an embodiment of the present disclosure;

FIG. 5 is a psychrometric chart of the temperature and the humidity ratio of the moist air flowing through the dehumidification unit of FIGS. 1-3 in accordance with an embodiment of the present disclosure;

FIG. 6 is a schematic diagram of the HVAC system and the dehumidification unit of FIG. 1 having a vacuum pump for

removing noncondensable components from the water vapor in the water vapor extraction chamber of the dehumidification unit in accordance with an embodiment of the present disclosure; and

FIG. 7 is a schematic diagram of the HVAC system and the dehumidification unit of FIG. 6 having a control system for controlling various operating conditions of the HVAC system and the dehumidification unit in accordance with an embodiment of the present disclosure.

#### DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Specific embodiments of the present disclosure will be described herein. In an effort to provide a concise description of these embodiments, all features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions must be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

When introducing elements of various embodiments of the present invention, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

The subject matter disclosed herein relates to dehumidification systems and, more specifically, to systems and methods capable of dehumidifying air without initial condensation by establishing a humidity gradient in a dehumidification unit. In one embodiment, a water vapor permeable material (i.e., a water vapor permeable membrane) is used along at least one boundary separating an air channel from a secondary channel or chamber to facilitate the removal of water vapor from the air passing through the air channel. The secondary channel or chamber separated from the air channel by the water vapor permeable material may receive water vapor extracted from the air channel via the water vapor permeable material.

In operation, the water vapor permeable material allows the flow of H<sub>2</sub>O (which may refer to H<sub>2</sub>O as water molecules, gaseous water vapor, liquid water, adsorbed/desorbed water molecules, absorbed/desorbed water molecules, or combinations thereof) through the water vapor permeable material from the air channel to the secondary channel or chamber, while substantially blocking the flow of other components of the air flowing through the air channel from passing through the water vapor permeable material. As such, the water vapor permeable material reduces the humidity of the air flowing through the air channel by removing primarily only water vapor from the air. Correspondingly, the secondary channel or chamber is filled with primarily water vapor. It should be noted that the passage of H<sub>2</sub>O through the water vapor permeable material may be facilitated by a pressure differential. Indeed, a lower partial pressure of water vapor (i.e., a partial pressure less than the partial pressure of water vapor in the air channel) may be created in the secondary channel or chamber to further facilitate passage of the H<sub>2</sub>O through the water vapor permeable material. Accordingly, the side of the water

vapor permeable material opposite the air channel may be referred to as the suction side of the water vapor permeable material.

Once the H<sub>2</sub>O has been passed through the water vapor permeable material, a vacuum pump is used to increase the partial pressure of the water vapor on the suction side of the water vapor permeable material to a minimal saturation pressure required to enable condensation of the water vapor by a condenser. That is, the vacuum pump compresses the water vapor to a pressure in a range suitable for condensing the water vapor into liquid water (e.g., a range of approximately 0.25-1.1 pounds per square inch absolute (psia), with the higher value applying to embodiments using multiple dehumidification units in series), depending on desired conditions for condensation. The condenser then condenses the water vapor into a liquid state, and the resulting liquid water is then pressurized to approximately atmospheric pressure, such that the liquid water may be rejected at ambient atmospheric conditions. By condensing the water vapor to a liquid state prior to expelling it, certain efficiencies are provided. For example, pressurizing liquid water to atmospheric pressure requires less energy than pressurizing water vapor to atmospheric pressure. It should also be noted that the dehumidification unit described herein in general uses significantly less energy than conventional systems.

While the embodiments described herein are primarily presented as enabling the removal of water vapor from air, other embodiments may enable the removal of other H<sub>2</sub>O components from air. For example, in certain embodiments, instead of a water vapor permeable material, an H<sub>2</sub>O permeable material may be used. As such, the H<sub>2</sub>O permeable material may allow the flow of one, all, or any combination of H<sub>2</sub>O components (i.e., water molecules, gaseous water vapor, liquid water, adsorbed/desorbed water molecules, absorbed/desorbed water molecules, and so forth) through the H<sub>2</sub>O permeable material from the air channel to the secondary channel or chamber, while substantially blocking the flow of other components of the air flowing through the air channel from passing through the H<sub>2</sub>O permeable material. In other words, the disclosed embodiments are not limited to the removal of water vapor from air, but rather to the removal of H<sub>2</sub>O (i.e., in any of its states) from air. However, for conciseness, the embodiments described herein are primarily focused on the removal of water vapor from air.

FIG. 1 is a schematic diagram of an HVAC system 10 having a dehumidification unit 12 in accordance with an embodiment of the present disclosure. As illustrated, the dehumidification unit 12 may receive inlet air 14A having a relatively high humidity and expel outlet air 14B having a relatively low humidity. In particular, the dehumidification unit 12 may include one or more air channels 16 through which the air 14 (i.e., the inlet air 14A and the outlet air 14B) flows. In addition, the dehumidification unit 12 may include one or more water vapor channels 18 adjacent to the one or more air channels 16. As illustrated in FIG. 1, the air 14 does not flow through the water vapor channels 18. Rather, the embodiments described herein enable the passage of water vapor from the air 14 in the air channels 16 to the water vapor channels 18, thus dehumidifying the air 14 and accumulating water vapor in the water vapor channels 18. In particular, water vapor from the air 14 in the air channels 16 may be allowed to flow through an interface 20 (i.e., a bather or membrane) between adjacent air channels 16 and water vapor channels 18, while the other components (e.g., nitrogen, oxygen, carbon dioxide, and so forth) of the air 14 are blocked from flowing through the interface 20. In general, the water vapor channels 18 are sealed to create the low pressure that

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pulls the water vapor from the air **14** in the air channels **16** through the interfaces **20** as H<sub>2</sub>O (i.e., as water molecules, gaseous water vapor, liquid water, adsorbed/desorbed water molecules, absorbed/desorbed water molecules, and so forth, through the interfaces **20**).

As such, a humidity gradient is established between the air channels **16** and adjacent water vapor channels **18**. The humidity gradient is generated by a pressure gradient between the air channels **16** and adjacent water vapor channels **18**. In particular, the partial pressure of water vapor in the water vapor channels **18** is maintained at a level lower than the partial pressure of water vapor in the air channels **16**, such that the water vapor in the air **14** flowing through the air channels **16** tends toward the suction side (i.e., the water vapor channels **18** having a lower partial pressure of water vapor) of the interfaces **20**.

Components of air other than H<sub>2</sub>O may be substantially blocked from passing through the interfaces **20** in accordance with present embodiments. In other words, in certain embodiments, approximately 95% or more, approximately 96% or more, approximately 97% or more, approximately 98% or more, or approximately 99% or more of components of the air **14** other than H<sub>2</sub>O (e.g., nitrogen, oxygen, carbon dioxide, and so forth) may be blocked from passing through the interfaces **20**. When compared to an ideal interface **20** that blocks 100% of components other than H<sub>2</sub>O, an interface **20** that blocks 99.5% of components other than H<sub>2</sub>O will experience a reduction in efficiency of approximately 2-4%. As such, the components other than H<sub>2</sub>O may be periodically purged to minimize these adverse effects on efficiency.

FIG. 2A is a perspective view of the dehumidification unit **12** of FIG. 1 having multiple parallel air channels **16** and water vapor channels **18** in accordance with an embodiment of the present disclosure. In the embodiment illustrated in FIG. 2A, the air channels **16** and the water vapor channels **18** are generally rectilinear channels, which provide a substantial amount of surface area of the interfaces **20** between adjacent air channels **16** and water vapor channels **18**. Further, the generally rectilinear channels **16**, **18** enable the water vapor **26A** to be removed along the path of the air channels **16** before the air **14** exits the air channels **16**. In other words, the relatively humid inlet air **14A** (e.g., air with a dew point of 55° F. or higher such that the air is appropriate for air conditioning) passes straight through the air channels **16** and exits as relatively dry outlet air **14B** because moisture has been removed as the air **14** traverses along the atmospheric pressure side of the interfaces **20** (i.e., the side of the interfaces **20** in the air channels **16**). In an embodiment where a single unit is dehumidifying to a 60° F. saturation pressure or below, the suction side of the interfaces **20** (i.e., the side of the interfaces **20** in the water vapor channels **18**) will generally be maintained at a partial pressure of water vapor that is lower than the partial pressure of water vapor on the atmospheric pressure side of the interfaces **20**.

As illustrated in FIG. 2A, each of the water vapor channels **18** is connected with a water vapor channel outlet **22** through which the water vapor in the water vapor channels **18** is removed. As illustrated in FIG. 2A, in certain embodiments, the water vapor channel outlets **22** may be connected via a water vapor outlet manifold **24**, wherein the water vapor **26A** from all of the water vapor channels **18** is combined in a single water vapor vacuum volume **28**, such as a tube or a chamber. Other configurations of the air channels **16** and the water vapor channels **18** may also be implemented. As another example, FIG. 2B is a perspective view of the dehumidification unit **12** of FIG. 1 having a single air channel **16** located inside a single water vapor channel **18** in accordance with an

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embodiment of the present disclosure. As illustrated, the air channel **16** may be a cylindrical air channel located within a larger concentric cylindrical water vapor channel **18**. The embodiments illustrated in FIGS. 2A and 2B are merely exemplary and are not intended to be limiting.

FIG. 3 is a plan view of an air channel **16** and adjacent water vapor channels **18** of the dehumidification unit **12** of FIGS. 1, 2A, and 2B in accordance with an embodiment of the present disclosure. In FIG. 3, a depiction of the water vapor **26** is exaggerated for illustration purposes. In particular, the water vapor **26** from the air **14** is shown flowing through the interfaces **20** between the air channel **16** and the adjacent water vapor channels **18** as H<sub>2</sub>O (i.e., as water molecules, gaseous water vapor, liquid water, adsorbed/desorbed water molecules, adsorbed/desorbed water molecules, and so forth, through the interfaces **20**). Conversely, other components **30** (e.g., nitrogen, oxygen, carbon dioxide, and so forth) of the air **14** are illustrated as being blocked from flowing through the interfaces **20** between the air channel **16** and the adjacent water vapor channels **18**.

In certain embodiments, the interfaces **20** may include membranes that are water vapor permeable and allow the flow of H<sub>2</sub>O through permeable volumes of the membranes while blocking the flow of the other components **30**. Again, it should be noted that when the H<sub>2</sub>O passes through the interfaces **20**, it may actually pass as one, all, or any combination of states of water (e.g., as water vapor, liquid water, adsorbed/desorbed water molecules, adsorbed/desorbed water molecules, and so forth) through the interfaces **20**. For example, in one embodiment, the interfaces **20** may adsorb/desorb water molecules. In another example, the interfaces **20** may adsorb/desorb water molecules and enable passage of water vapor. In other embodiments, the interfaces **20** may facilitate the passage of water in other combinations of states. The interfaces **20** extend along the flow path of the air **14**. As such, the water vapor **26** is continuously removed from one side of the interface **20** as the relatively humid inlet air **14A** flows through the air channel **16**. Therefore, dehumidification of the air **14** flowing through the air channel **16** is accomplished by separating the water vapor **26** from the other components **30** of the air **14** incrementally as it progresses along the flow path of the air channel **16** and continuously contacts the interfaces **20** adjacent to the air channel **16** from the inlet air **14A** location to the outlet air **14B** location.

In certain embodiments, the water vapor channels **18** are evacuated before use of the dehumidification unit **12**, such that a lower partial pressure of the water vapor **26** (i.e., a partial pressure less than the partial pressure of water vapor in the air channels **16**) is created in the water vapor channels **18**. For example, the partial pressure of the water vapor **26** in the water vapor channels **18** may be in the range of approximately 0.10-0.25 psia during normal operation, which corresponds to dehumidifying to a 60° F. saturation pressure or below. In this example, an initial condition in the 0.01 psia range may be used to remove noncondensables, whereas the partial pressure of water vapor in the air channels **16** may be in the range of approximately 0.2-1.0 psia. However, at certain times, the pressure differential between the partial pressure of the water vapor in the water vapor channels **18** and the air channels **16** may be as low as (or lower than) 0.01 psia. The lower partial pressure of water vapor in the water vapor channels **18** further facilitates the flow of water vapor **26** from the air channels **16** to the water vapor channels **18** because the air **14** flowing through the air channels **16** is at local atmospheric pressure (i.e., approximately 14.7 psia at sea level). Since the partial pressure of water vapor in the air **14** in the air channels **16** is greater than the partial pressure of the water vapor **26** in the

water vapor channels 18, a pressure gradient is created from the air channels 16 to the water vapor channels 18. As described previously, the interfaces 20 between adjacent air channels 16 and water vapor channels 18 provide a barrier, and allow substantially only water vapor 26 to flow from the air 14 in the air channels 16 into the water vapor channels 18. As such, the air 14 flowing through the air channels 16 will generally decrease in humidity from the inlet air 14A to the outlet air 14B.

The use of water vapor permeable membranes as the interfaces 20 between the air channels 16 and the water vapor channels 18 has many advantages. In particular, in some embodiments, no additional energy is required to generate the humidity gradient from the air channels 16 to the water vapor channels 18. In addition, in some embodiments, no regeneration is involved and no environmental emissions (e.g., solids, liquids, or gases) are generated. Indeed, in accordance with one embodiment, separation of the water vapor 26 from the other components 30 of the air 14 via water permeable membranes (i.e., the interfaces 20) can be accomplished at energy efficiencies much greater than compressor technology used to condense water directly from the airstream.

Because water vapor permeable membranes are highly permeable to water vapor, the costs of operating the dehumidification unit 12 may be minimized because the air 14 flowing through the air channels 16 does not have to be significantly pressurized to facilitate the passage of H<sub>2</sub>O through the interfaces 20. Water vapor permeable membranes are also highly selective to the permeation of the water vapor from the air 14. In other words, water vapor permeable membranes are very efficient at preventing components 30 of the air 14 other than water vapor from entering the water vapor channels 18. This is advantageous because the H<sub>2</sub>O passes through the interfaces 20 due to a pressure gradient (i.e., due to the lower partial pressures of water vapor in the water vapor channels 18) and any permeation or leakage of air 14 into the water vapor channels 18 will increase the power consumption of the vacuum pump used to evacuate the water vapor channels 18. In addition, water vapor permeable membranes are rugged enough to be resistant to air contamination, biological degradation, and mechanical erosion of the air channels 16 and the water vapor channels 18. Water vapor permeable membranes may also be resistant to bacteria attachment and growth in hot, humid air environments in accordance with one embodiment.

One example of a material used for the water vapor permeable membranes (i.e., the interfaces 20) is zeolite supported on thin, porous metal sheets. In particular, in certain embodiments, an ultrathin (e.g., less than approximately 2 μm), dense zeolite membrane film may be deposited on an approximately 50 μm thick porous metal sheet. The resulting membrane sheets may be packaged into a membrane separation module to be used in the dehumidification unit 12. FIG. 4 is a perspective view of a separation module 32 formed using a membrane that may be used as a water vapor channel 18 of the dehumidification unit 12 of FIGS. 1-3 in accordance with an embodiment of the present disclosure. Two membrane sheets 34, 36 may be folded and attached together into a generally rectangular shape with a channel for the water vapor having a width  $w_{msm}$  of approximately 5 mm. The separation module 32 may be positioned within the dehumidification unit 12 such that the membrane coating surface is exposed to the air 14. The thinness of the metal support sheet reduces the weight and cost of the raw metal material and also minimizes resistance to the H<sub>2</sub>O diffusing through the water vapor permeable membrane film deposited on the membrane sheets 34, 36. The metallic nature of the sheets 34, 36 provides mechanical

strength and flexibility for packaging such that the separation module 32 can withstand a pressure gradient of greater than approximately 60 psi (i.e., approximately 4 times atmospheric pressure).

Separation of water vapor from the other components 30 of the air 14 may create a water vapor permeation flux of approximately 1.0 kg/m<sup>2</sup>/h (e.g., in a range of approximately 0.5-2.0 kg/m<sup>2</sup>/h), and a water vapor-to-air selectivity range of approximately 5-200+. As such, the efficiency of the dehumidification unit 12 is relatively high compared to other conventional dehumidification techniques with a relatively low cost of production. As an example, approximately 7-10 m<sup>2</sup> of membrane area of the interfaces 20 may be needed to dehumidify 1 ton of air cooling load under ambient conditions. In order to handle such an air cooling load, in certain embodiments, 17-20 separation modules 32 having a height  $h_{msm}$  of approximately 450 mm, a length  $l_{msm}$  of approximately 450 mm, and a width  $w_{msm}$  of approximately 5 mm may be used. These separation modules 32 may be assembled side-by-side in the dehumidification unit 12, leaving approximately 2 mm gaps between the separation modules 32. These gaps define the air channels 16 through which the air 14 flows. The measurements described in this example are merely exemplary and not intended to be limiting.

FIG. 5 is a psychrometric chart 38 of the temperature and the humidity ratio of the moist air 14 flowing through the dehumidification unit 12 of FIGS. 1-3 in accordance with an embodiment of the present disclosure. In particular, the x-axis 40 of the psychrometric chart 38 corresponds to the temperature of the air 14 flowing through the air channels 16 of FIG. 1, the y-axis 42 of the psychrometric chart 38 corresponds to the humidity ratio of the air 14 flowing through the air channels 16, and the curve 44 represents the water vapor saturation curve of the air 14 flowing through the air channels 16. As illustrated by line 46, because water vapor is removed from the air 14 flowing through the air channels 16, the humidity ratio of the outlet air 14B (i.e., point 48) from the dehumidification unit 12 of FIGS. 1-3 is lower than the humidity ratio of the inlet air 14A (i.e., point 50) into the dehumidification unit 12 of FIGS. 1-3, while the temperature of the outlet air 14B and the inlet air 14A are substantially the same.

Returning now to FIG. 1, as described previously, a lower partial pressure of the water vapor 26 (i.e., a partial pressure less than the partial pressure of water vapor in the air channels 16) is created in the water vapor channels 18 of the dehumidification unit 12 to further facilitate the passage of H<sub>2</sub>O through the interfaces 20 from the air channels 16 to the water vapor channels 18. In certain embodiments, the water vapor channels 18 may initially be evacuated using a vacuum pump 52. In particular, the vacuum pump 52 may evacuate the water vapor channels 18 and the water vapor vacuum volume 28, as well as the water vapor outlets 22 and the water vapor manifold 24 of FIG. 2A. However, in other embodiments, a pump separate from the vacuum pump 52 may be used to evacuate the water vapor channels 18, water vapor vacuum volume 28, water vapor outlets 22, and water vapor manifold 24. As illustrated in FIG. 1, the water vapor 26 removed from the air 14 in the dehumidification unit 12 may be distinguished between the water vapor 26A in the water vapor vacuum volume 28 (i.e., the suction side of the vacuum pump 52) and the water vapor 26B expelled from an exhaust side (i.e., an outlet) of the vacuum pump 52 (i.e., the water vapor 26B delivered to a condensation unit). In general, the water vapor 26B expelled from the vacuum pump 52 will have a slightly higher pressure and a higher temperature than the water vapor 26A in the water vapor vacuum volume 28. The vacuum pump 52 may be a compressor or any other suitable pressure

increasing device capable of maintaining a lower pressure on the suction side of the vacuum pump 52 than the partial pressure of water vapor in the humid air 14.

For example, the lower partial pressure of water vapor 26A maintained in the water vapor vacuum volume 28 may be in the range of approximately 0.15-0.25 psia, which corresponds to saturation temperatures of approximately 45° F. to 60° F., with the water vapor 26A typically be in the range of approximately 65-75° F. However, in other embodiments, the water vapor 26A in the water vapor vacuum volume 28 may be maintained at a partial pressure of water vapor in the range of approximately 0.01-0.25 psia and a temperature in the range of approximately 55° F. up to the highest ambient air temperature. A specific embodiment may be designed to lower the partial pressure in the water vapor vacuum volume 28 to the range of 0.01 psia to increase the capacity for removing water vapor from the air 14 to enable an evaporative cooler to process the entire air conditioning load when atmospheric conditions permit this mode of operation.

In certain embodiments, the vacuum pump 52 is a low-pressure pump configured to decrease the pressure of the water vapor 26A in the water vapor vacuum volume 28 to a lower partial pressure than the partial pressure of water vapor on the atmospheric side of the interfaces 20 (i.e., the partial pressure of the air 14 in the air channels 16). On the exhaust side of the vacuum pump 52, the partial pressure of the water vapor 26B has been increased just high enough to facilitate condensation of the water vapor (i.e., in a condensation unit 54). Indeed, the vacuum pump 52 is configured to increase the pressure such that the water vapor 26B in the condensation unit 54 is at a pressure proximate to a minimal saturation pressure in the condensation unit 54.

As an example, when in operation, the air 14 may enter the system at a partial pressure of water vapor of 0.32 psia, which corresponds to a humidity ratio of 0.014 pounds of H<sub>2</sub>O per pounds of dry air. The system may be set to remove 0.005 pounds of H<sub>2</sub>O per pounds of dry air from the air 14. Pressure differentials across the interfaces 20 may be used to create a flow of H<sub>2</sub>O through the interfaces 20. For example, the partial pressure of water vapor in the water vapor vacuum volume 28 may be set to approximately 0.1 psia. The pressure of the water vapor 26B is increased by the vacuum pump 52 in a primarily adiabatic process, and as the pressure of the water vapor 26B increases, the temperature increases as well (in contrast to the relatively negligible temperature differential across the interfaces 20). As such, if for example the pressure of the water vapor 26B is increased in the vacuum pump 52 by 0.3 psi (i.e., to approximately 0.4 psia), the condensation unit 54 is then capable of condensing the water vapor 26B at a temperature of approximately 72-73° F., and the temperature of the water vapor 26B will increase to a temperature substantially higher than the condenser temperature. The system may continually monitor the pressure and temperature conditions of both the upstream water vapor 26A and the downstream water vapor 26B to ensure that the water vapor 26B expelled from the vacuum pump 52 has a partial pressure of water vapor just high enough to facilitate condensation in the condensation unit 54. It should be noted that the pressure and temperature values presented in this scenario are merely exemplary and are not intended to be limiting.

Note that as the pressure difference from the water vapor 26A entering the vacuum pump 52 to the water vapor 26B exiting the vacuum pump 52 increases, the efficiency of the dehumidification unit 12 decreases. For example, in a preferred embodiment, the vacuum pump 52 will be set to adjust the pressure of the water vapor 26B in the condensation unit 54 slightly above the saturation pressure at the lowest ambient

temperature of the cooling media (i.e., air or water) used by the condensation unit 54 to condense the water vapor 26B. In another embodiment, the temperature of the water vapor 26B may be used to control the pressure in the condensation unit 54. The temperature of the water vapor 26B expelled from the vacuum pump 52 may be substantially warmer than the humid air 14A (e.g., this temperature could reach 200° F. or above depending on a variety of factors). Because the vacuum pump 52 only increases the pressure of the water vapor 26B to a point where condensation of the water vapor 26B is facilitated (i.e., approximately the saturation pressure), the power requirements of the vacuum pump 52 are relatively small, thereby obtaining a high efficiency from the dehumidification unit 12.

Once the water vapor 26B has been slightly pressurized (i.e., compressed) by the vacuum pump 52, the water vapor 26B is directed into the condensation unit 54, wherein the water vapor 26B is condensed into a liquid state. In certain embodiments, the condensation unit 54 may include a condensation coil 56, a pipe/tube condenser, a flat plate condenser, or any other suitable system for causing a temperature below the condensation point of the water vapor 26B. The condensation unit 54 may either be air cooled or water cooled. For example, in certain embodiments, the condensation unit 54 may be cooled by ambient air or water from a cooling tower. As such, the costs of operating the condensation unit 54 may be relatively low, inasmuch as both ambient air and cooling tower water are in relatively limitless supply.

Once the water vapor 26B has been condensed into a liquid state, in certain embodiments, the liquid water from the condensation unit 54 may be directed into a reservoir 58 for temporary storage of saturated vapor and liquid water. However, in other embodiments, no reservoir 58 may be used. In either case, the liquid water from the condensation unit 54 may be directed into a liquid pump 60 (i.e., a water transport device), within which the pressure of the liquid water from the condensation unit 54 is increased to approximately atmospheric pressure (i.e., approximately 14.7 psia) so that the liquid water may be rejected at ambient conditions. As such, the liquid pump 60 may be sized just large enough to increase the pressure of the liquid water from the condensation unit 54 to approximately atmospheric pressure. Therefore, the costs of operating the liquid pump 60 may be relatively low. In addition, the liquid water from the liquid pump 60 may be at a slightly elevated temperature due to the increase in the pressure of the liquid water. As such, in certain embodiments, the heated liquid water may be transported for use as domestic hot water, further increasing the efficiency of the system by recapturing the heat transferred into the liquid water.

Although the interfaces 20 between the air channels 16 and the water vapor channels 18 as described previously generally allow only H<sub>2</sub>O to pass from the air channels 16 to the water vapor channels 18, in certain embodiments, very minimal amounts (e.g., less than 1% of the oxygen (O<sub>2</sub>), nitrogen (N<sub>2</sub>), or other noncondensable components) of the other components 30 of the air 14 may be allowed to pass through the interfaces 20 from the air channels 16 to the water vapor channels 18. Over time, the amount of the other components 30 may build up in the water vapor channels 18 (as well as in the water vapor vacuum volume 28, the water vapor outlets 22, and the water vapor manifold 24 of FIG. 2A). In general, these other components 30 are noncondensable at the condenser temperature ranges used in the condensation unit 54. As such, the components 30 may adversely affect the performance of the vacuum pump 52 and all other equipment downstream of the vacuum pump 52 (in particular, the condensation unit 54).

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Accordingly, in certain embodiments, a second vacuum pump may be used to periodically purge the other components **30** from the water vapor vacuum volume **28**. FIG. **6** is a schematic diagram of the HVAC system **10** and the dehumidification unit **12** of FIG. **1** having a vacuum pump **62** for removing noncondensable components **30** from the water vapor **26A** in the water vapor vacuum volume **28** of the dehumidification unit **12** in accordance with an embodiment of the present disclosure. The vacuum pump **62** may, in certain embodiments, be the same pump used to evacuate the water vapor vacuum volume **28** (as well as the water vapor channels **18**, the water vapor outlets **22**, and the water vapor manifold **24**) to create the lower partial pressure of water vapor described previously that facilitates the passage of the H<sub>2</sub>O through the interfaces **20** from the air channels **16** to the water vapor channels **18**. However, in other embodiments, the vacuum pump **62** may be different from the pump used to evacuate the water vapor vacuum volume **28** to create the lower partial pressure of water vapor.

The dehumidification unit **12** described herein may also be controlled between various operating states, and modulated based on operating conditions of the dehumidification unit **12**. For example, FIG. **7** is a schematic diagram of the HVAC system **10** and the dehumidification unit **12** of FIG. **6** having a control system **64** for controlling various operating conditions of the HVAC system **10** and the dehumidification unit **12** in accordance with an embodiment of the present disclosure. The control system **64** may include one or more processors **66**, for example, one or more “general-purpose” microprocessors, one or more special-purpose microprocessors and/or ASICs (application-specific integrated circuits), or some combination of such processing components. The processors **66** may use input/output (I/O) devices **68** to, for example, receive signals from and issue control signals to the components of the dehumidification unit **12** (i.e., the vacuum pumps **52**, **62**, the condensation unit **54**, the reservoir **58**, the liquid pump **60**, other equipment such as a fan blowing the inlet air **14A** through the dehumidification unit **12**, sensors configured to generate signals related to characteristics of the inlet and outlet air **14A**, **14B**, and so forth). The processors **66** may take these signals as inputs and calculate how to control the functionality of these components of the dehumidification unit **12** to most efficiently remove the water vapor **26** from the air **14** flowing through the dehumidification unit **12**. The control system **64** may also include a nontransitory computer-readable medium (i.e., a memory **70**) which, for example, may store instructions or data to be processed by the one or more processors **66** of the control system **64**.

For example, the control system **64** may be configured to control the rate of removal of the noncondensable components **30** of the water vapor **26A** from the water vapor vacuum volume **28** of the dehumidification unit **12** by turning the vacuum pump **62** on or off, or by modulating the rate at which the vacuum pump **62** removes the noncondensable components **30** of the water vapor **26A**. More specifically, in certain embodiments, the control system **64** may receive signals from a sensor in the water vapor vacuum volume **28** that detects when too many noncondensable components **30** are present in the water vapor **26A** contained in the water vapor vacuum volume **28**. This process of noncondensable component removal will operate in a cyclical manner. In “normal” operation of removing the water vapor **26** from the air **14**, the vacuum pump **62** will not be in operation. As the noncondensable components **30** build up in the water vapor vacuum volume **28**, the internal pressure in the water vapor vacuum volume **28** will eventually reach a setpoint. At this point in time, the vacuum pump **62** will turn on and remove all com-

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ponents (i.e., both the noncondensable components **30** as well as H<sub>2</sub>O, including the water vapor) until the internal pressure in the water vapor vacuum volume **28** reaches another setpoint (e.g., lower than the starting vacuum pressure). Then, the vacuum pump **62** shuts off and the dehumidification unit **12** returns to the normal operational mode. Setpoints may either be preset or dynamically determined. A preferred method will be to have the vacuum pump **62** only operating in the purge mode intermittently.

Another example of the type of control that may be accomplished by the control system **64** is modulating the lower partial pressure of the water vapor **26A** in the water vapor vacuum volume **28** (as well as the water vapor channels **18**, the water vapor outlets **22**, and the water vapor manifold **24**) to modify the water vapor removal capacity and efficiency ratio of the dehumidification unit **12**. For example, the control system **64** may receive signals from pressure sensors in the water vapor vacuum volume **28**, the water vapor channels **18**, the water vapor outlets **22**, and/or the water vapor manifold **24**, as well as signals generated by sensors relating to characteristics (e.g., temperature, pressure, flow rate, relative humidity, and so forth) of the inlet and outlet air **14A**, **14B**, among other things. The control system **64** may use this information to determine how to modulate the lower partial pressure of the water vapor **26A** (e.g., with respect to the partial pressure of water vapor in the air **14** flowing through the air channels **16**) to increase or decrease the rate of removal of water vapor **26** from the air channels **16** to the water vapor channels **18** through the interfaces **20**.

For example, if more water vapor removal is desired, the lower partial pressure of the water vapor **26A** in the water vapor vacuum volume **28** may be reduced and, conversely, if less water vapor removal is desired, the lower partial pressure of the water vapor **26A** in the water vapor vacuum volume **28** may be increased. Furthermore, in certain embodiments, the amount of dehumidification (i.e., water vapor removal) may be cycled to improve the efficiency of the dehumidification unit **12**. More specifically, under certain operating conditions, the dehumidification unit **12** may function more efficiently at higher rates of water vapor removal. As such, in certain embodiments, the dehumidification unit **12** may be cycled to remove a maximum amount of water vapor from the air **14** for a while, then to remove relatively no water vapor from the air **14** for a while, then to remove a maximum amount of water vapor from the air **14** for a while, and so forth. In other words, the dehumidification unit **12** may be operated at full water vapor removal capacity for periods of time alternating with other periods of time where no water vapor is removed. In addition, the control system **64** may be configured to control start-up and shutdown sequencing of the dehumidification unit **12**.

The dehumidification unit **12** may be designed and operated in many various modes, and at varying operating conditions. In general, the dehumidification unit **12** will be operated with the water vapor vacuum volume **28** (as well as the water vapor channels **18**, the water vapor outlets **22**, and the water vapor manifold **24**) at a water vapor partial pressure below the water vapor partial pressure of the air **14** flowing through the air channels **16**. In certain embodiments, the dehumidification unit **12** may be optimized for dedicated outside air system (DOAS) use, wherein the air **14** may have a temperature in the range of approximately 55-100° F., and a relative humidity in the range of approximately 55-100%. In other embodiments, the dehumidification unit **12** may be optimized for residential use for recirculated air having a temperature in the range of approximately 70-85° F., and a relative humidity in the range of approximately 55-65%.

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Similarly, in certain embodiments, the dehumidification unit 12 may be optimized for dehumidifying outside air in commercial building recirculated air systems, which dehumidifies the inlet air 14A having a temperature in the range of approximately 55-110° F., and a relative humidity in the range of approximately 55-100%. The outlet air 14B has less humidity and about the same temperature as the inlet air 14A, unless cooling is performed on the outlet air 14B.

The dehumidification unit 12 described herein requires less operating power than conventional dehumidification systems because of the relatively low pressures that are required to dehumidify the air 14A. This is due at least in part to the ability of the interfaces 20 (i.e., water vapor permeable membranes) to remove the water vapor 26 from the air 14 efficiently without requiring excessive pressures to force the water vapor 26 through the interfaces 20. For example, in one embodiment, the minimal power needed to operate the dehumidification unit 12 includes only the fan power required to move the air 14 through the dehumidification unit 12, the compressive power of the vacuum pump 52 to compress the water vapor 26 to approximately the saturation pressure (for example, to approximately 1.0 psia, or to a saturation pressure that corresponds to a given condensation temperature, for example, approximately 100° F.), the pumping and/or fan power of the condensation unit 54 (e.g., depending on whether cooling tower water or ambient air is used as the cooling medium), the pumping power of the liquid pump 60 to reject the liquid water from the condensation unit 54 at ambient conditions, and the power of the vacuum pump 62 to purge noncondensable components 30 that leak into the water vapor vacuum volume 28 of the dehumidification unit 12. As such, the only relatively major power component required to operate the dehumidification unit 12 is the compressive power of the vacuum pump 52 to compress the water vapor 26 to approximately the saturation pressure (for example, only to approximately 1.0 psia, or to a saturation pressure that corresponds to a given condensation temperature, for example, approximately 100° F.). As mentioned previously, this power is relatively low and, therefore, operating the dehumidification unit 12 is relatively inexpensive as opposed to conventional refrigeration compression dehumidification systems. Moreover, calculations for an embodiment indicate that the dehumidification unit 12 has a coefficient of performance (COP) at least twice as high (or even up to five times as high, depending on operating conditions) as these conventional dehumidification systems. In addition, the dehumidification unit 12 enables the dehumidification of air without reducing the temperature of the air below the temperature at which the air is needed, as is often done in conventional dehumidification systems.

While the present disclosure may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and tables and have been described in detail herein. However, it should be understood that the embodiments are not intended to be limited to the particular forms disclosed. Rather, the disclosure is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure as defined by the following appended claims. Further, although individual embodiments are discussed herein, the disclosure is intended to cover all combinations of these embodiments.

The invention claimed is:

1. A system, comprising:

a dehumidification system for removing H<sub>2</sub>O vapor from an airstream, comprising:

an air channel configured to receive an inlet airstream and discharge an outlet airstream;

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an H<sub>2</sub>O permeable material adjacent to the air channel, wherein the H<sub>2</sub>O permeable material is configured to selectively enable H<sub>2</sub>O from H<sub>2</sub>O vapor in the inlet airstream to pass through the H<sub>2</sub>O permeable material to a suction side of the H<sub>2</sub>O permeable material and substantially block other components in the inlet airstream from passing through the H<sub>2</sub>O permeable material to the suction side of the H<sub>2</sub>O permeable material;

a pressure increasing device configured to create a lower partial pressure of H<sub>2</sub>O vapor on the suction side of the H<sub>2</sub>O permeable material than the partial pressure of the H<sub>2</sub>O vapor in the inlet airstream to drive passage of the H<sub>2</sub>O from the H<sub>2</sub>O vapor in the inlet airstream through the H<sub>2</sub>O permeable material, and to increase the pressure at an outlet of the pressure increasing device to a partial pressure of H<sub>2</sub>O vapor suitable for condensing H<sub>2</sub>O vapor into liquid H<sub>2</sub>O, wherein the pressure increasing device comprises a vacuum pump;

a condensation device configured to receive the H<sub>2</sub>O vapor from the outlet of the pressure increasing device, and to condense the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O; and a controller configured to periodically purge the suction side of the H<sub>2</sub>O permeable material.

2. The system of claim 1, comprising a liquid pump configured to transport the liquid H<sub>2</sub>O from the condensation device.

3. The system of claim 1, wherein the H<sub>2</sub>O permeable material comprises an H<sub>2</sub>O permeable membrane.

4. The system of claim 1, wherein the H<sub>2</sub>O permeable material comprises zeolite.

5. The system of claim 1, wherein the condensation device comprises a condensation coil that condenses the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O.

6. The system of claim 1, wherein the dehumidification system comprises a vacuum pump that removes noncondensable components from H<sub>2</sub>O vapor on the suction side of the H<sub>2</sub>O permeable material.

7. The system of claim 1, comprising a controller configured to modulate the lower partial pressure of H<sub>2</sub>O vapor on the suction side of the H<sub>2</sub>O permeable material to modify the H<sub>2</sub>O removal capacity and efficiency of the dehumidification system.

8. A method, comprising:

using a pressure differential across an H<sub>2</sub>O permeable material to provide a force to move H<sub>2</sub>O through the H<sub>2</sub>O permeable material into an H<sub>2</sub>O vapor channel, wherein the H<sub>2</sub>O permeable material comprises zeolite; receiving H<sub>2</sub>O vapor from the H<sub>2</sub>O permeable material into the H<sub>2</sub>O vapor channel;

receiving the H<sub>2</sub>O vapor from the H<sub>2</sub>O vapor channel into a pressure increasing device and expelling the H<sub>2</sub>O vapor from the pressure increasing device at a slightly increased partial pressure of H<sub>2</sub>O vapor;

receiving the H<sub>2</sub>O vapor from the pressure increasing device into a condensation device and condensing the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O; and transporting the liquid H<sub>2</sub>O from the condensation device to ambient conditions.

9. The method of claim 8, comprising receiving an airstream including the H<sub>2</sub>O into an air inlet channel, and using the pressure differential across the H<sub>2</sub>O permeable material to provide the force to move H<sub>2</sub>O from the airstream through the H<sub>2</sub>O permeable material into the H<sub>2</sub>O vapor channel.

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10. The method of claim 8, comprising substantially blocking passage of other components of the airstream through the H<sub>2</sub>O permeable material.

11. The method of claim 10, wherein the H<sub>2</sub>O permeable material comprises an H<sub>2</sub>O permeable membrane.

12. The method of claim 8, wherein the H<sub>2</sub>O vapor channel has a partial pressure of H<sub>2</sub>O vapor in a range of approximately 0.1-0.25 psia.

13. A system, comprising:  
a dehumidification system for removing H<sub>2</sub>O vapor from an airstream, comprising:

an air channel configured to receive an inlet airstream and discharge an outlet airstream;

an H<sub>2</sub>O permeable material adjacent to the air channel, wherein the H<sub>2</sub>O permeable material is configured to selectively enable H<sub>2</sub>O from H<sub>2</sub>O vapor in the inlet airstream to pass through the H<sub>2</sub>O permeable material to a suction side of the H<sub>2</sub>O permeable material and substantially block other components in the inlet air-

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stream from passing through the H<sub>2</sub>O permeable material to the suction side of the H<sub>2</sub>O permeable material;

a pressure increasing device configured to create a lower partial pressure of H<sub>2</sub>O vapor on the suction side of the H<sub>2</sub>O permeable material than the partial pressure of the H<sub>2</sub>O vapor in the inlet airstream to drive passage of the H<sub>2</sub>O from the H<sub>2</sub>O vapor in the inlet airstream through the H<sub>2</sub>O permeable material, and to increase the pressure at an outlet of the pressure increasing device to a partial pressure of H<sub>2</sub>O vapor suitable for condensing H<sub>2</sub>O vapor into liquid H<sub>2</sub>O, wherein the pressure increasing device comprises a vacuum pump;

a condensation device configured to receive the H<sub>2</sub>O vapor from the outlet of the pressure increasing device, and to condense the H<sub>2</sub>O vapor into liquid H<sub>2</sub>O, wherein the H<sub>2</sub>O permeable material comprises zeolite.

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