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(54) SYSTEM AND METHOD FOR EFFICIENT AIR DEHUMIDIFICATION AND LIQUID RECOVERY WITH EVAPORATIVE COOLING

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

(52) **U.S. Cl.**
USPC **95/43**; 95/45; 95/52; 96/4; 96/7; 96/9; 96/10

(58) **Field of Classification Search**
CPC B01D 53/22; B01D 53/228; B01D 63/06
USPC 95/43, 45, 52; 96/4, 7, 9, 10
See application file for complete search history.

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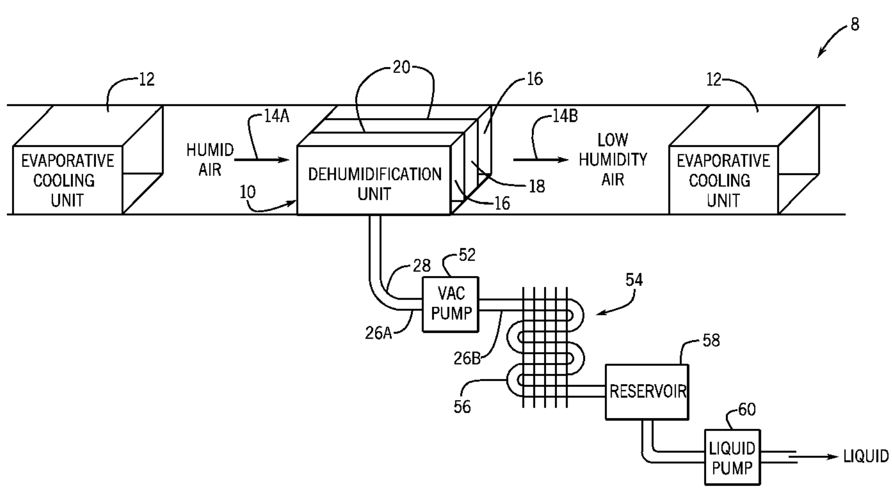
(57) **ABSTRACT**

The present invention relates to systems and methods for dehumidifying air by establishing humidity gradients in one or more dehumidification units. Water vapor from relatively humid atmospheric air entering the dehumidification units is extracted by the dehumidification units without substantial condensation into low pressure water vapor vacuum volumes. The water vapor is extracted through water vapor permeable membranes of the dehumidification units into the low pressure water vapor vacuum volumes. The air exiting the dehumidification units is less humid than the air entering the dehumidification units. The low pressure water vapor extracted from the air is compressed to a slightly higher pressure, condensed, and removed from the system at ambient conditions. In addition, each of the dehumidification units may be associated with one or more evaporative cooling units through which the air will be directed, with the evaporative cooling units being upstream and/or downstream of the dehumidification units.

21 Claims, 11 Drawing Sheets



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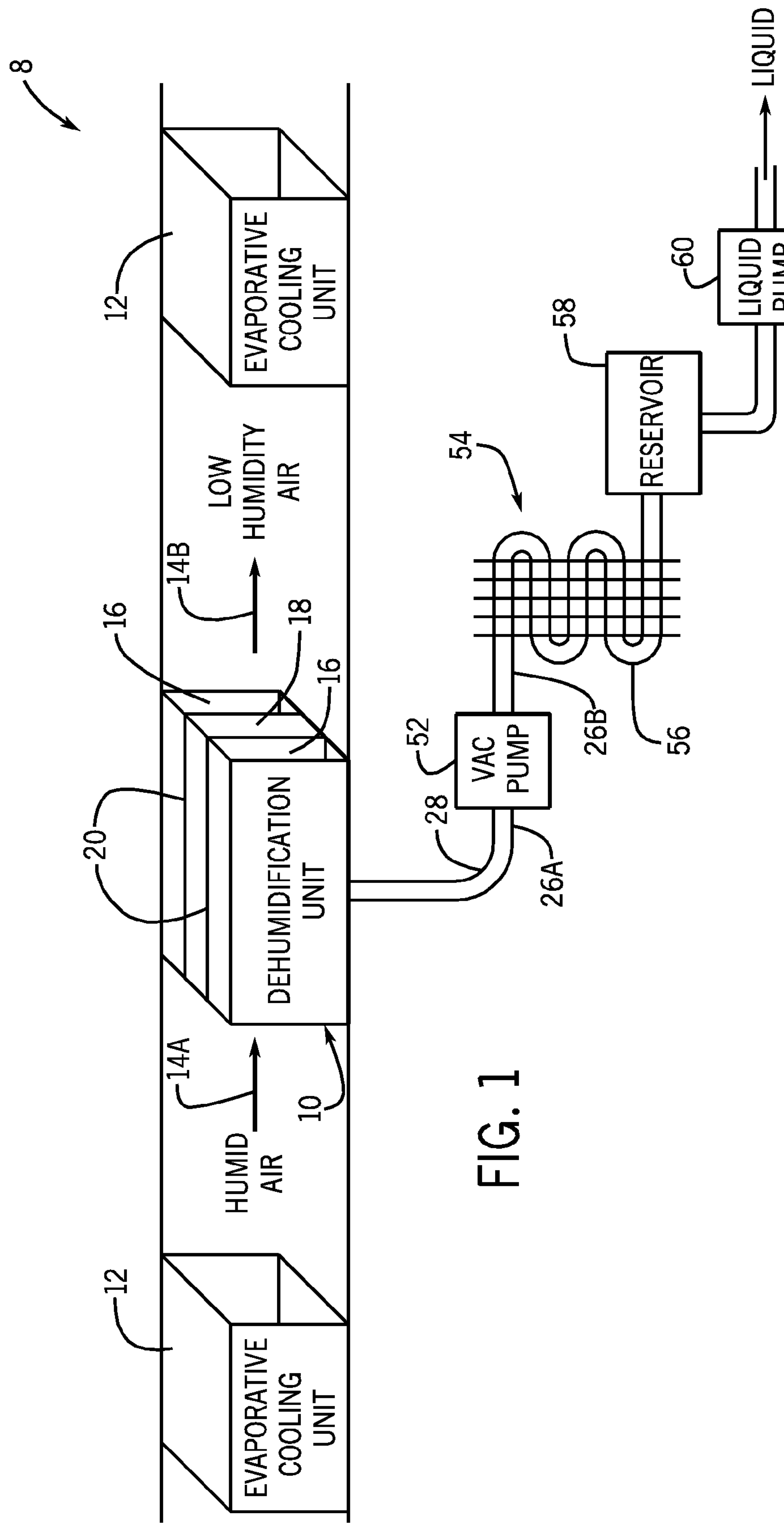
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12
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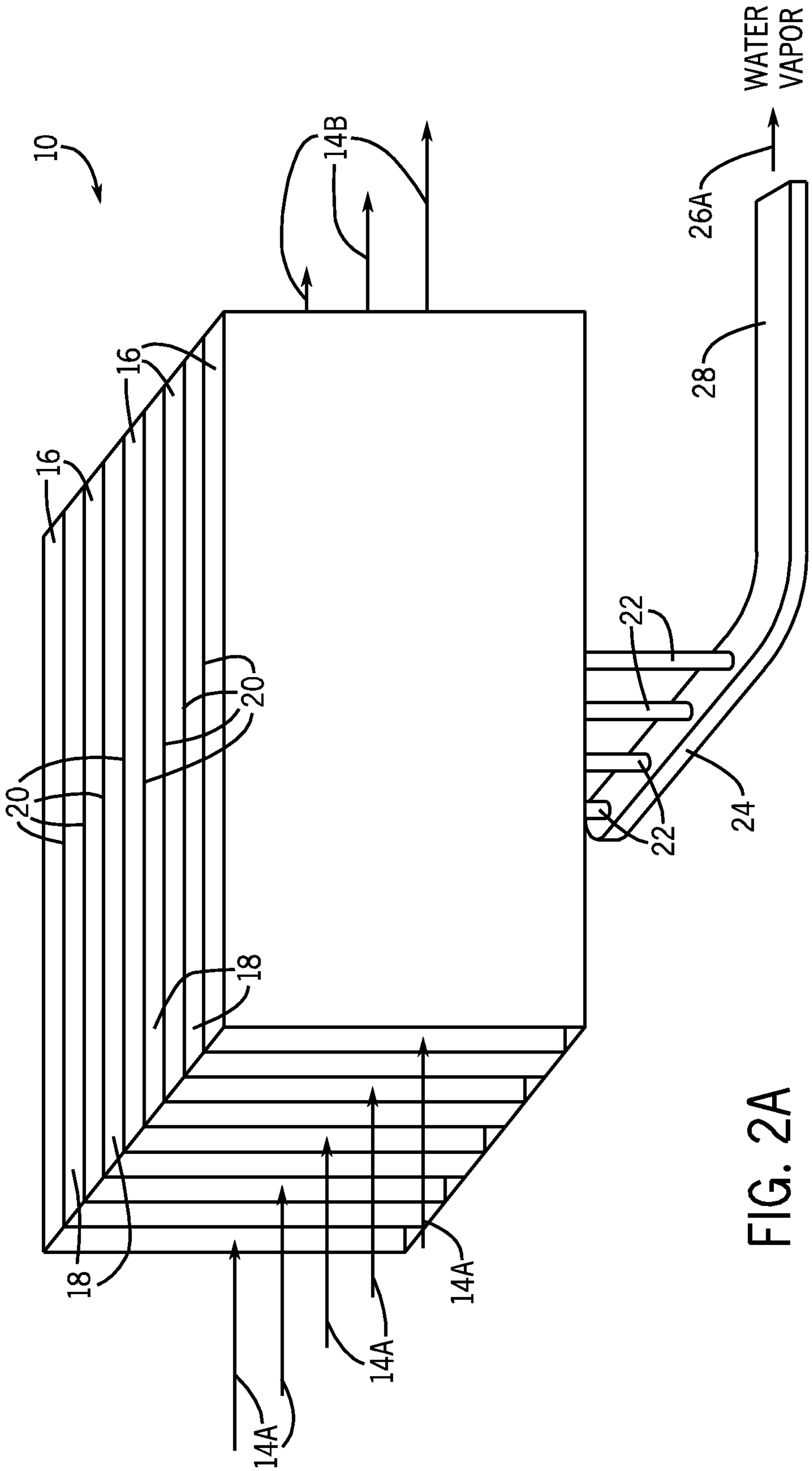
LOW HUMIDITY AIR
14B
16
18
16
20
DEHUMIDIFICATION UNIT
14A
10
HUMID AIR
12
EVAPORATIVE COOLING UNIT
28
52
VAC PUMP
26A
26B
56
54
RESERVOIR
58
60
LIQUID PUMP
LIQUID

FIG. 1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14B
WATER VAPOR
26A
16
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28
20
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20
22
22
22
24
18
18
14A
14A
14A

FIG. 2A

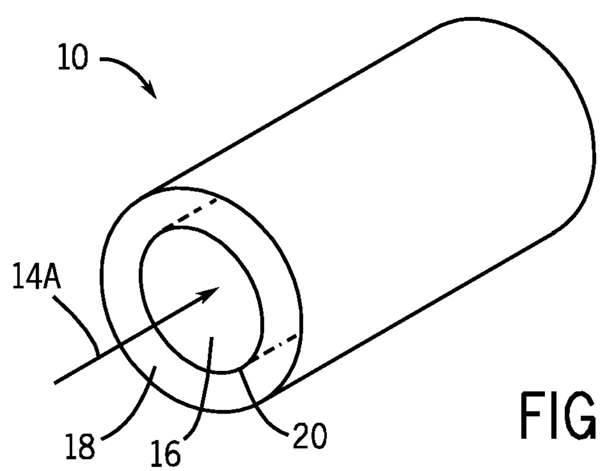


FIG. 2B

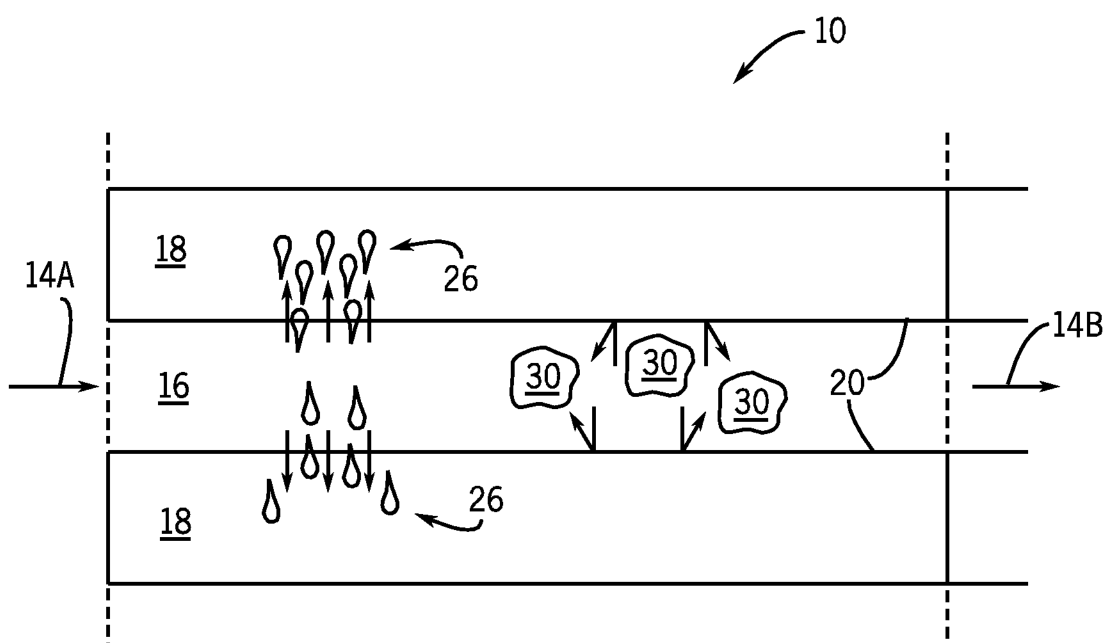


FIG. 3

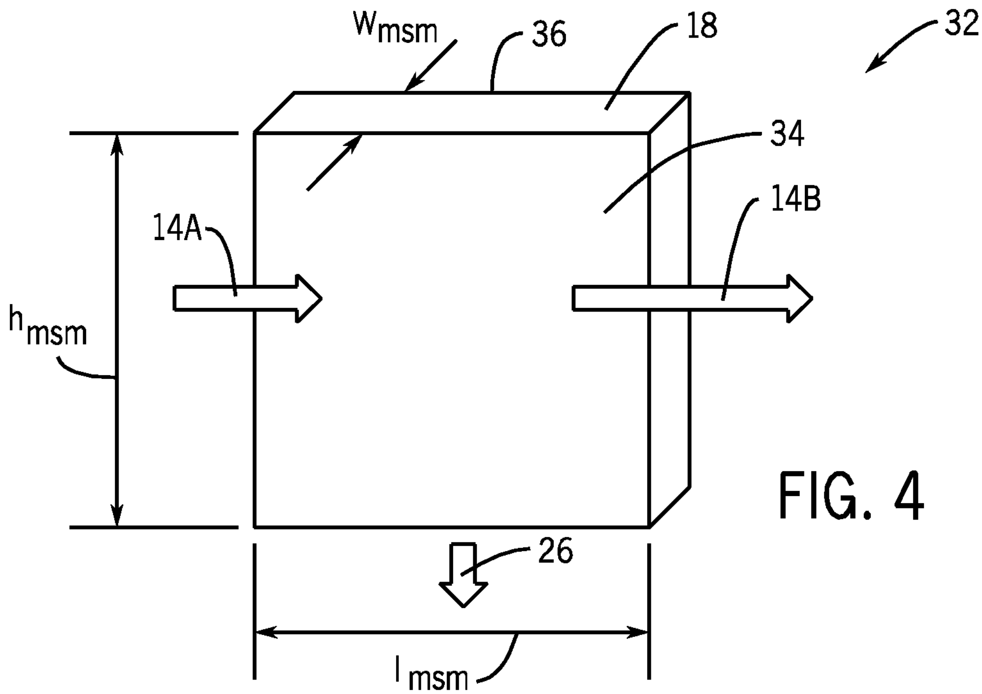


FIG. 4

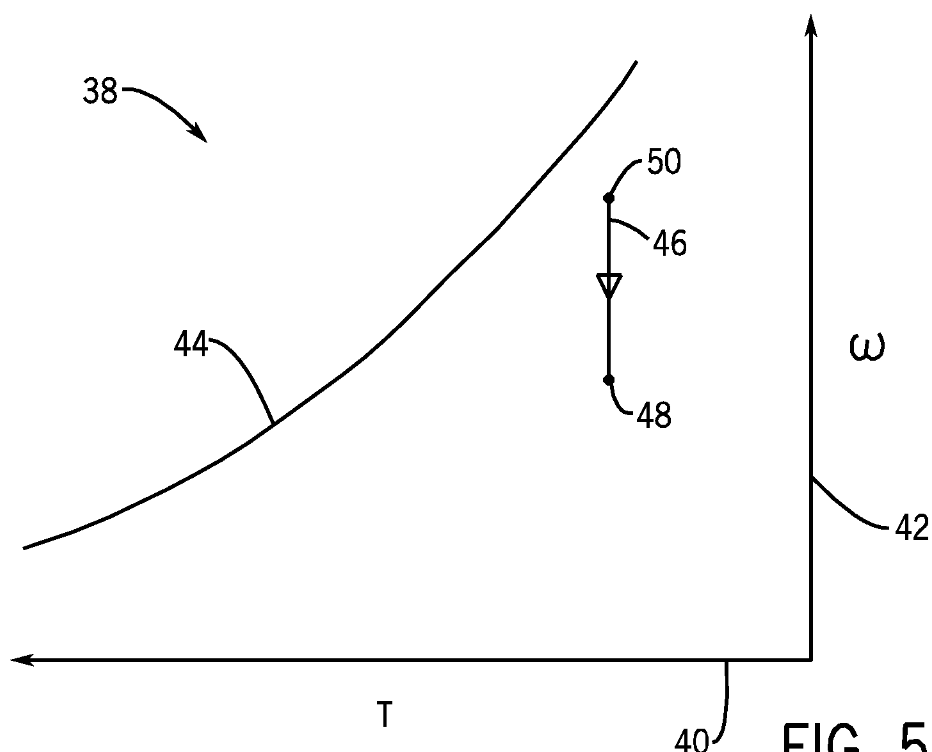


FIG. 5

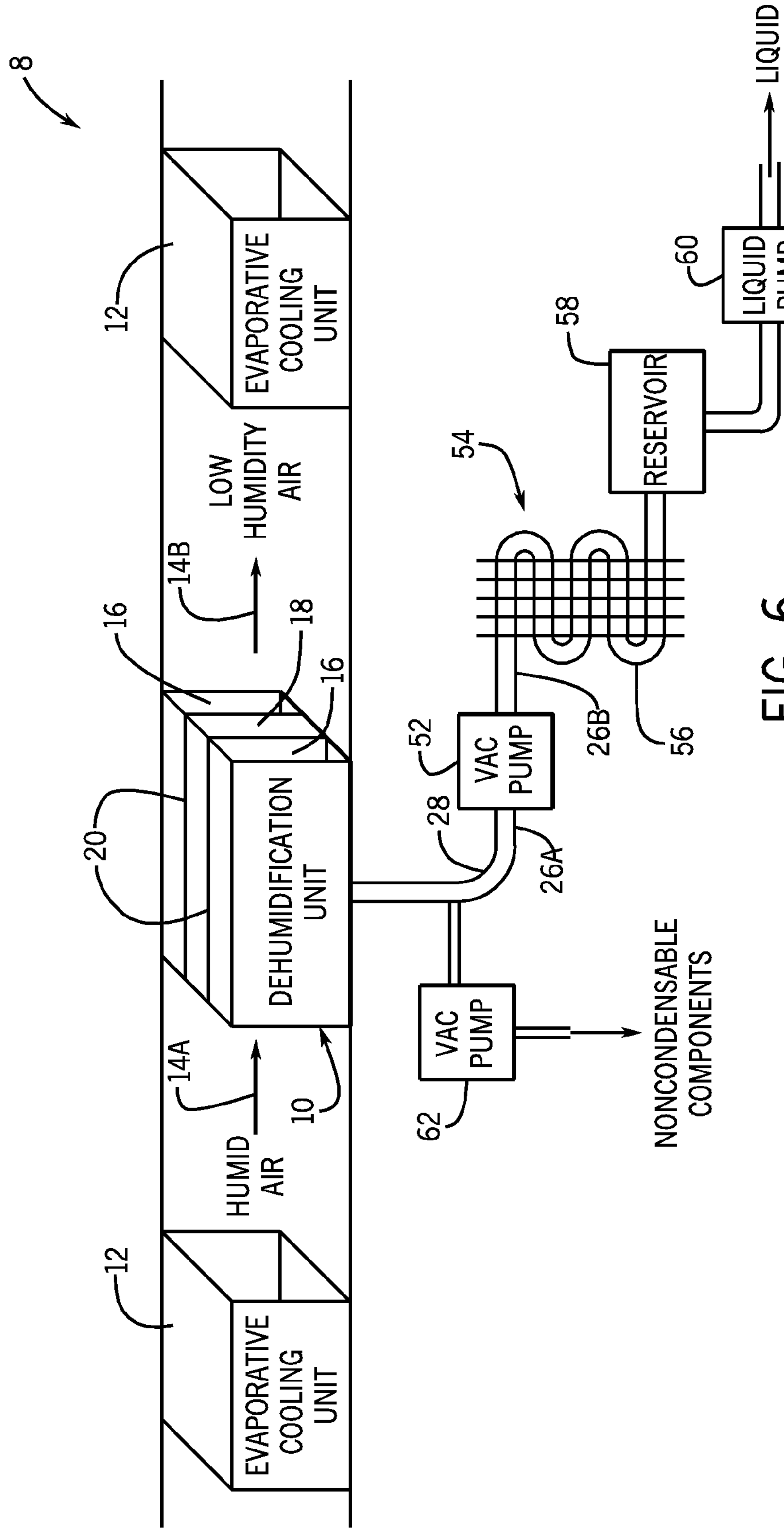
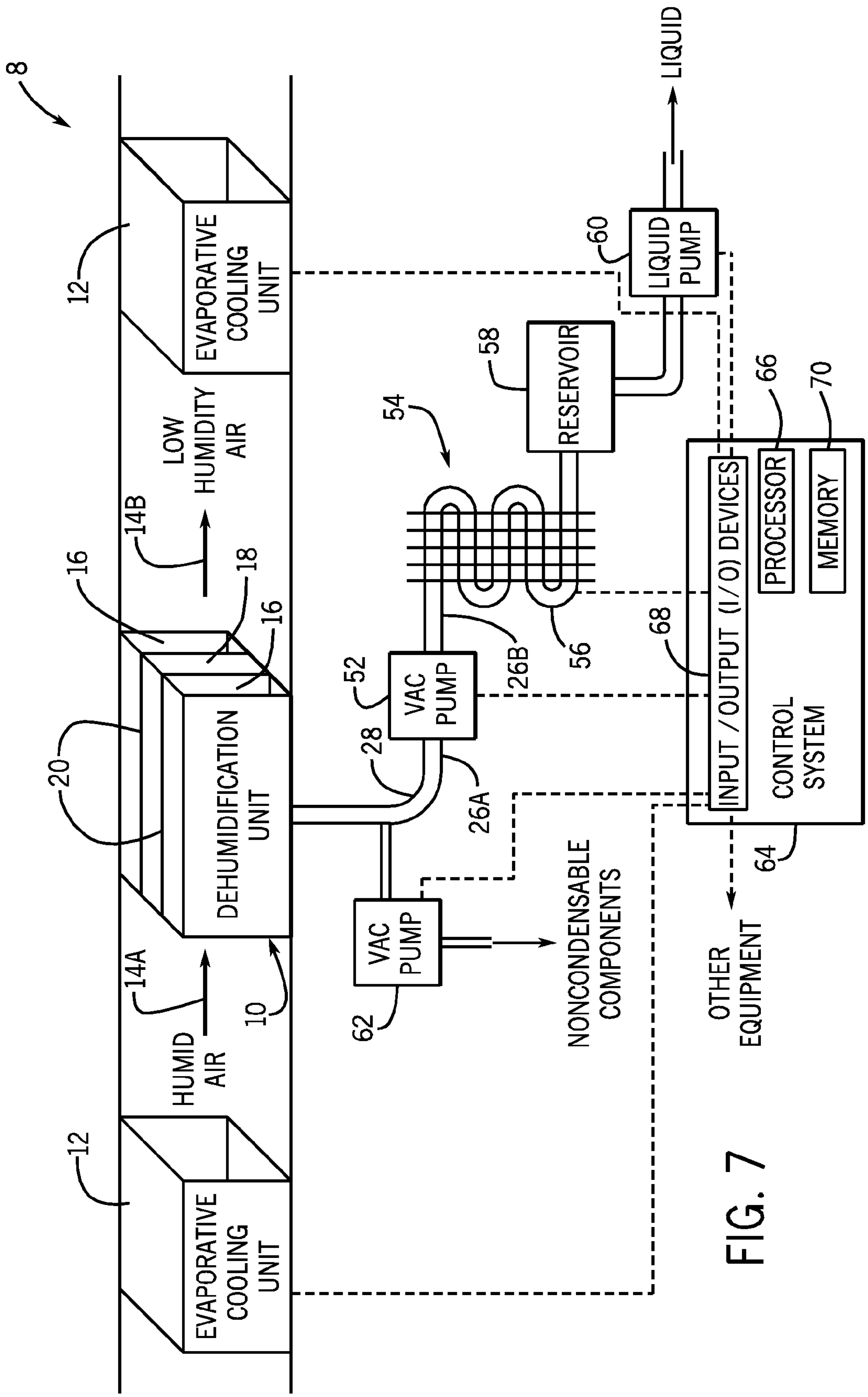

8
12
EVAPORATIVE COOLING UNIT
LOW HUMIDITY AIR
14B
16
18
16
20
DEHUMIDIFICATION UNIT
14A
10
HUMID AIR
12
EVAPORATIVE COOLING UNIT
28
26A
52
VAC PUMP
26B
56
54
58
RESERVOIR
60
LIQUID PUMP
LIQUID
62
VAC PUMP
NONCONDENSABLE COMPONENTS

FIG. 6



8
12
EVAPORATIVE COOLING UNIT
LOW HUMIDITY AIR
14B
16
18
16
20
DEHUMIDIFICATION UNIT
HUMID AIR
14A
10
12
EVAPORATIVE COOLING UNIT
LIQUID
60
LIQUID PUMP
58
RESERVOIR
66
70
54
INPUT / OUTPUT (I/O) DEVICES
PROCESSOR
MEMORY
56
68
26B
52
VAC PUMP
28
26A
CONTROL SYSTEM
64
VAC PUMP
62
NONCONDENSABLE COMPONENTS
OTHER EQUIPMENT

FIG. 7

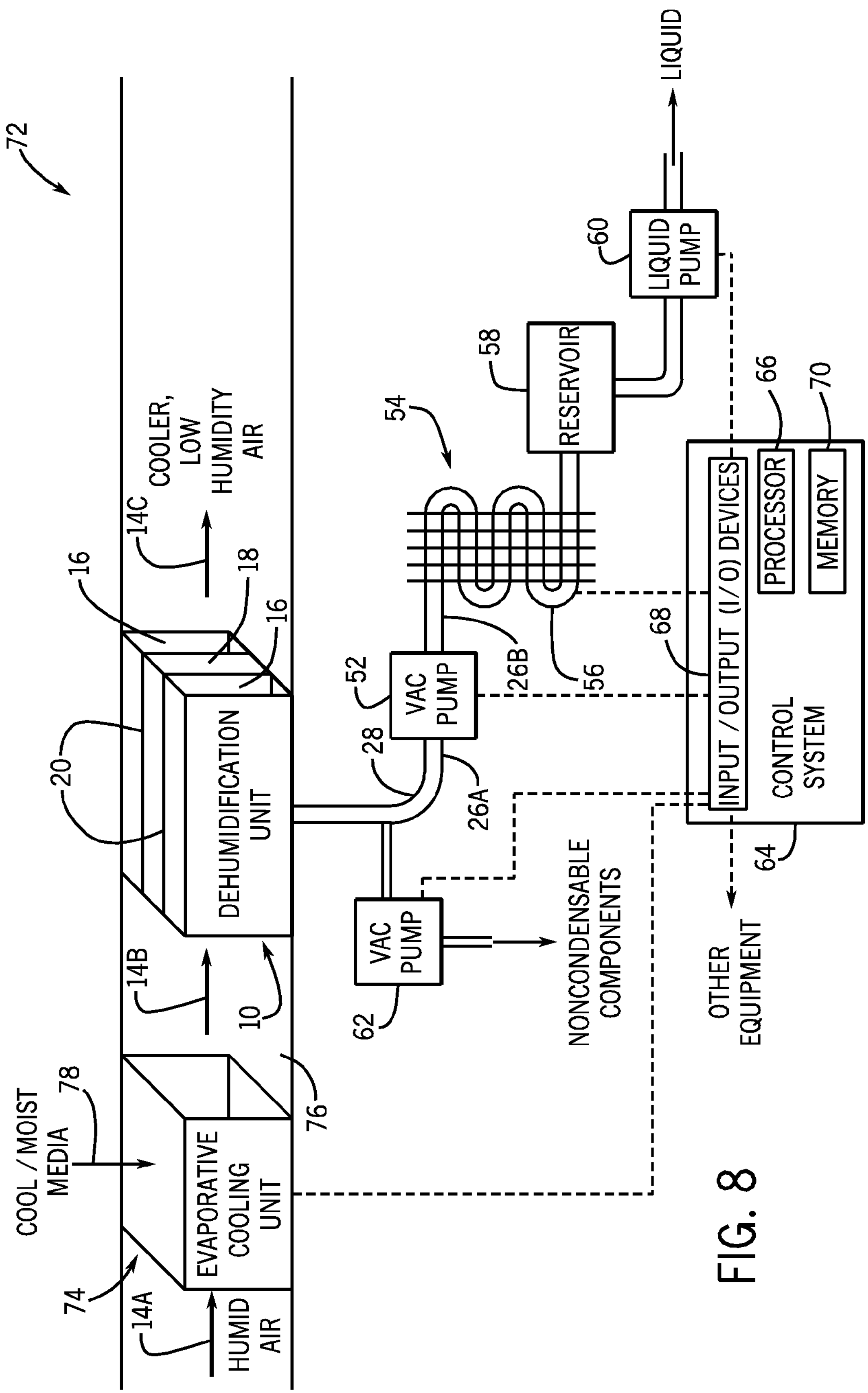

72
LIQUID
60
LIQUID PUMP
58
RESERVOIR
54
66
70
COOLER, LOW HUMIDITY AIR
14C
16
18
16
INPUT / OUTPUT (I/O) DEVICES
PROCESSOR
MEMORY
68
52
VAC PUMP
26B
56
20
DEHUMIDIFICATION UNIT
28
26A
CONTROL SYSTEM
64
NONCONDENSABLE COMPONENTS
VAC PUMP
62
14B
10
OTHER EQUIPMENT
COOL / MOIST MEDIA
78
76
EVAPORATIVE COOLING UNIT
74
14A
HUMID AIR

FIG. 8

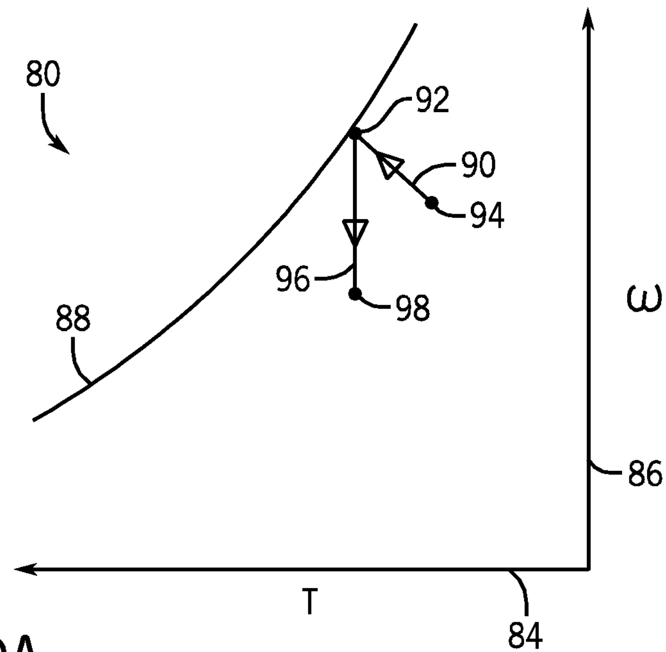


FIG. 9A

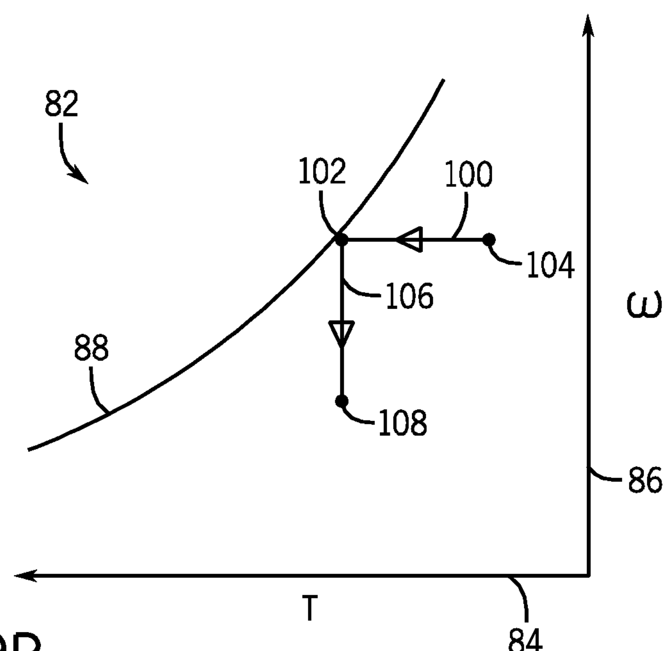


FIG. 9B

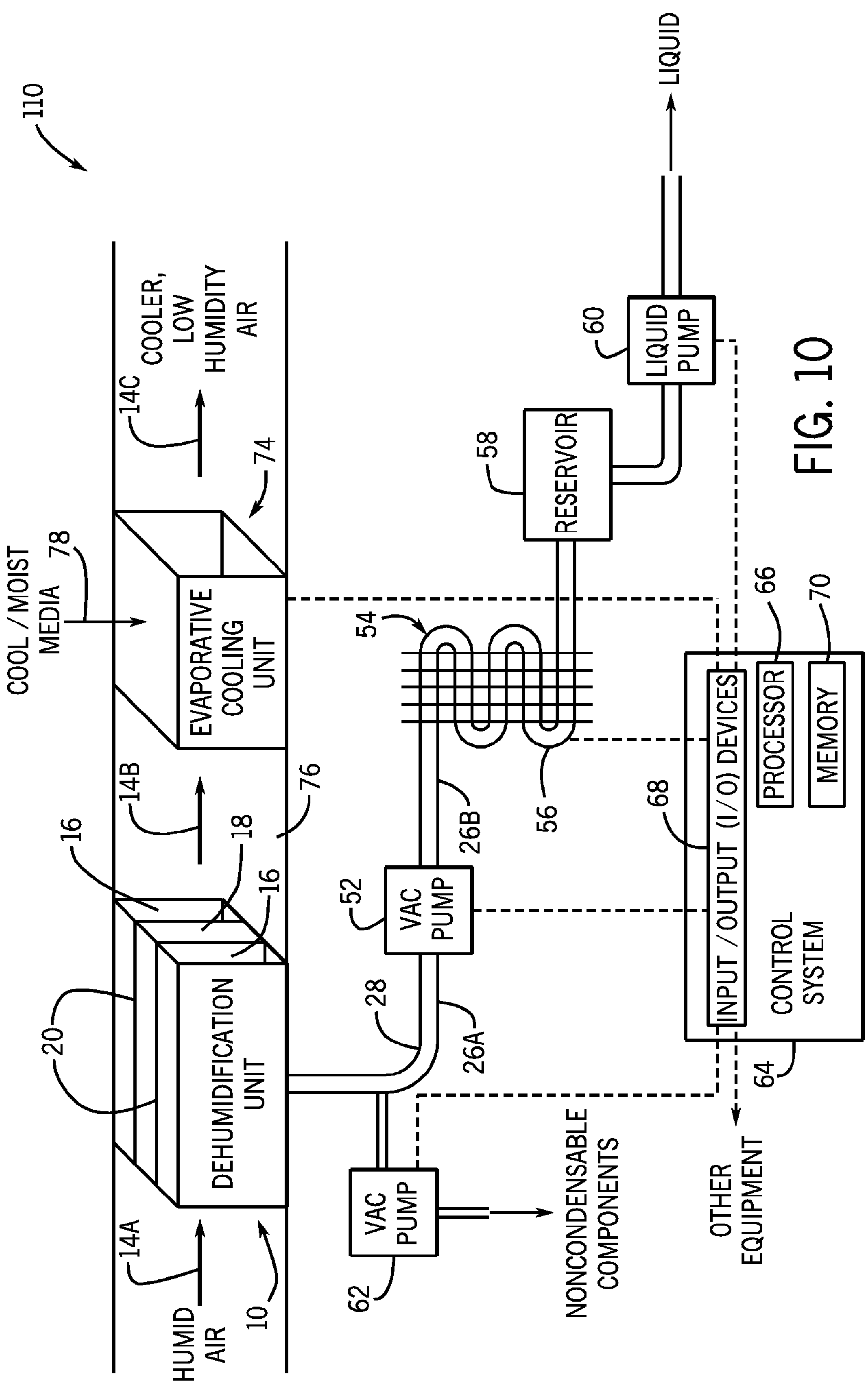

110
HUMID AIR
14A
10
DEHUMIDIFICATION UNIT
20
16
18
16
14B
76
EVAPORATIVE COOLING UNIT
COOL / MOIST MEDIA
78
74
14C
COOLER, LOW HUMIDITY AIR
VAC PUMP
62
NONCONDENSABLE COMPONENTS
28
26A
VAC PUMP
52
26B
54
56
RESERVOIR
58
LIQUID PUMP
60
LIQUID
INPUT / OUTPUT (I/O) DEVICES
68
PROCESSOR
66
MEMORY
70
CONTROL SYSTEM
64
OTHER EQUIPMENT

FIG. 10

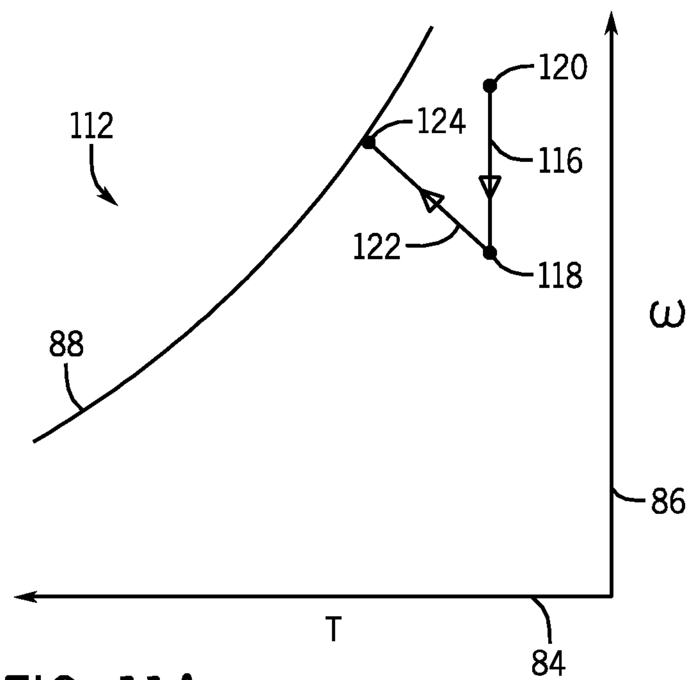


FIG. 11A

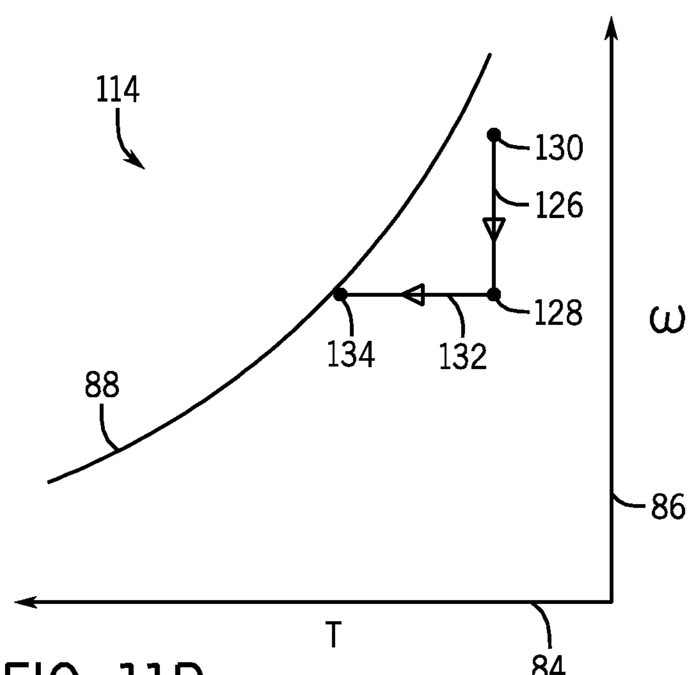


FIG. 11B

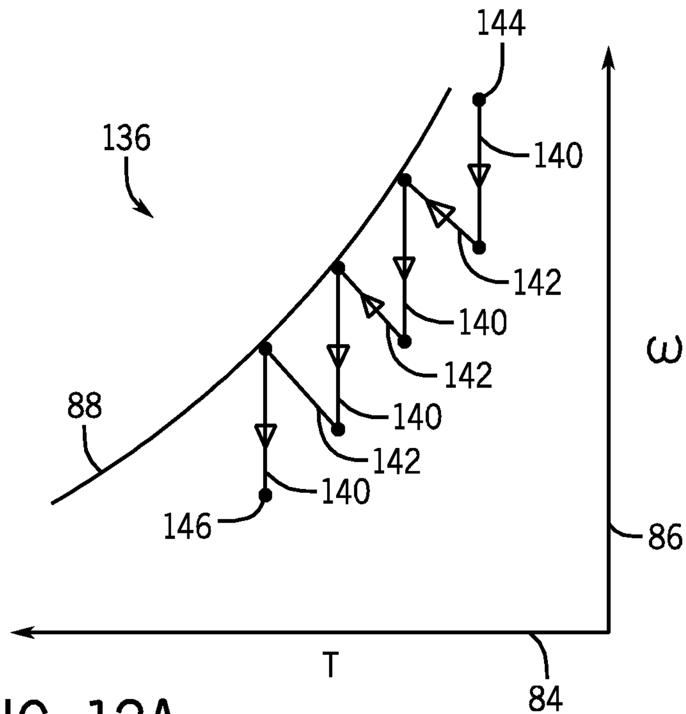


FIG. 12A

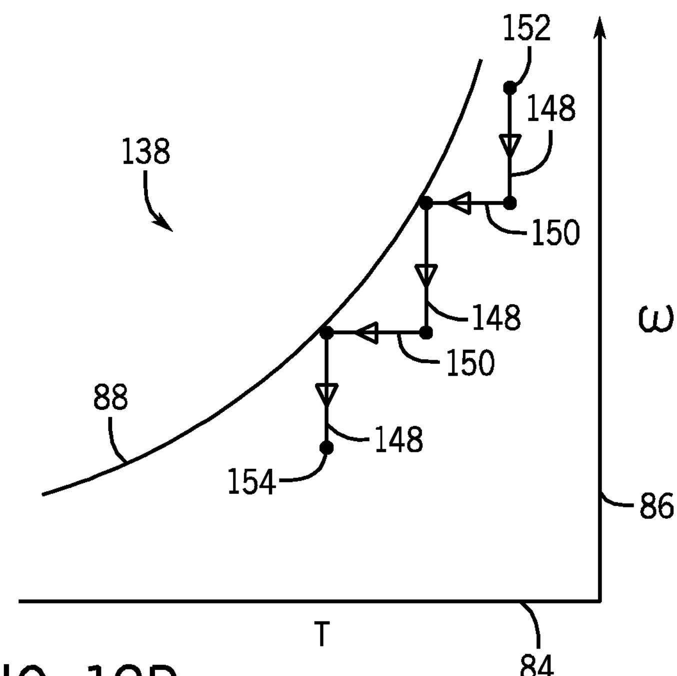


FIG. 12B

SYSTEM AND METHOD FOR EFFICIENT AIR DEHUMIDIFICATION AND LIQUID RECOVERY WITH EVAPORATIVE COOLING

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_2O 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_2O 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_2O 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 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_2O 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 system also includes an evaporative cooling unit configured to cool the airstream. The system further 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_2O 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.

In a second embodiment, a system includes a dehumidification unit for removing H_2O vapor from an airstream. The dehumidification unit includes an air channel configured to receive an inlet airstream and discharge an outlet airstream. The dehumidification unit also includes an H_2O permeable material adjacent to the air channel. The H_2O permeable material is configured to selectively enable H_2O from H_2O vapor in the inlet airstream to pass through the H_2O permeable material to a suction side of the H_2O permeable material and substantially block other components in the inlet airstream from passing through the H_2O permeable material to the suction side of the H_2O permeable material. The system also includes an evaporative cooling unit configured to cool the airstream. The system further includes a pressure increasing device configured to create a lower partial pressure of H_2O vapor of the H_2O permeable material than the partial pressure of the H_2O vapor in the inlet airstream to drive passage of the H_2O from the H_2O vapor in the inlet airstream through the H_2O permeable material, and to increase the pressure at an outlet of the pressure increasing device to a partial pressure of H_2O vapor suitable for condensing H_2O vapor on the suction side into liquid H_2O.

In a third embodiment, a method includes receiving an airstream including H_2O vapor into an air channel of a dehumidification unit, wherein the airstream has a first partial pressure of H_2O vapor. The method also includes cooling the airstream via an evaporative cooling unit. The method further includes suctioning H_2O into an H_2O vapor channel of the dehumidification unit through an H_2O permeable material of the dehumidification unit using a pressure differential across the H_2O permeable material. The H_2O vapor channel has a second partial pressure of H_2O vapor lower than the first partial pressure of H_2O vapor of the airstream. In addition, the method includes receiving H_2O vapor from the H_2O vapor channel into a pressure increasing device and increasing the pressure of the H_2O vapor from the pressure increasing device to a third partial pressure of H_2O vapor that is higher than the second partial pressure of H_2O vapor.

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 and one or more evaporative cooling units in accordance with an embodiment of the present disclosure;

FIG. **2**A 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. **2**B 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**, **2**A, and **2**B 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 and the one or more evaporative cooling units 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;

FIG. **7** is a schematic diagram of the HVAC system and the dehumidification unit and the one or more evaporative cooling units 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;

FIG. **8** is a schematic diagram of an HVAC system having an evaporative cooling unit disposed upstream of the dehumidification unit in accordance with an embodiment of the present disclosure;

FIG. **9**A is a psychrometric chart of the temperature and the humidity ratio of the air flowing through a direct evaporative cooling unit and the dehumidification unit of FIG. **8** in accordance with an embodiment of the present disclosure;

FIG. **9**B is a psychrometric chart of the temperature and the humidity ratio of the air flowing through an indirect evaporative cooling unit and the dehumidification unit of FIG. **8** in accordance with an embodiment of the present disclosure;

FIG. **10** is a schematic diagram of an HVAC system having the evaporative cooling unit disposed downstream of the dehumidification unit in accordance with an embodiment of the present disclosure;

FIG. **11**A is a psychrometric chart of the temperature and the humidity ratio of the air flowing through the dehumidification unit and a direct evaporative cooling unit of FIG. **10** in accordance with an embodiment of the present disclosure;

FIG. **11**B is a psychrometric chart of the temperature and the humidity ratio of the air flowing through the dehumidification unit and an indirect evaporative cooling unit of FIG. **10** in accordance with an embodiment of the present disclosure;

FIG. **12**A is a psychrometric chart of the temperature and the humidity ratio of the air flowing through a plurality of dehumidification units and a plurality of direct evaporative cooling units in accordance with an embodiment of the present disclosure; and

FIG. **12**B is a psychrometric chart of the temperature and the humidity ratio of the air flowing through a plurality of dehumidification units and a plurality of indirect evaporative cooling units 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 certain embodiments, the dehumidification unit may be used in conjunction with one or more evaporative cooling units. For example, in certain embodiments, an evaporative cooling unit may be disposed upstream of the dehumidification unit, with the air expelled from the evaporative cooling unit directed into an inlet of the dehumidification unit. Conversely, in other embodiments, the dehumidification unit may be disposed upstream of the evaporative cooling unit, with the air expelled from the dehumidification unit directed into an inlet of the evaporative cooling unit. Indeed, in other embodiments, multiple dehumidification units may be used with multiple evaporative cooling units disposed in between the dehumidification units. Using multiple dehumidification units and multiple evaporative cooling units enables a "saw-tooth" progression on a psychrometric chart from initial conditions of temperature and humidity ratio of inlet air to desired final conditions of temperature and humidity ratio of outlet air. In other words, each of the dehumidification units successively dehumidifies the air at substantially constant temperature, while each of the evaporative cooling units successively cools (and humidifies, in the case of direct evaporative cooling) the air until the desired final conditions of temperature and humidity ratio are achieved.

In operation, the water vapor permeable material allows the flow of H_2O (which may refer to H_2O 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_2O 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_2O 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_2O 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_2O components from air. For example, in certain embodiments, instead of a water vapor permeable material, an H_2O permeable material may be used. As such, the H_2O permeable material may allow the flow of one, all, or any combination of H_2O components (i.e., water molecules, gaseous water vapor, liquid water, adsorbed/desorbed water molecules, absorbed/desorbed water molecules, and so forth) through the H_2O 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_2O 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_2O (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 **8** having a dehumidification unit **10** and one or more evaporative cooling units **12** in accordance with an embodiment of the present disclosure. As illustrated, in certain embodiments, the dehumidification unit **10** may receive inlet air **14**A having a relatively high humidity from a first evaporative cooling unit **12** on an inlet side of the dehumidification unit **10**. Furthermore, in certain embodiments, the dehumidification unit **10** may expel outlet air **14**B having a relatively low humidity into a second evaporative cooling unit **12** positioned on an outlet side of the dehumidification unit **10**. Aspects of the evaporative cooling units **12** and their positioning in the HVAC system **8** will be discussed in further detail herein. In particular, while FIG. **1** shows evaporative cooling units **12** at the inlet side and the outlet side of the dehumidification unit **10**, in other embodiments, the HVAC system **8** may include only an evaporative cooling unit **12** upstream of the dehumidification unit **10**, or only an evaporative cooling unit **12** downstream of the dehumidification unit **10**. Furthermore, in more complex arrangements, multiple dehumidification units **10** may be used with multiple evaporative cooling units **12**.

The dehumidification unit **10** may include one or more air channels **16** through which the air **14** (i.e., the inlet air **14**A and the outlet air **14**B) flows. In addition, the dehumidification unit **10** 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 pulls the water vapor from the air **14** in the air channels **16** through the interfaces **20** as H_2O (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_2O 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_2O (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_2O, an interface **20** that blocks 99.5% of components other than H_2O will experience a reduction in efficiency of approximately 2-4%. As such, the components other than H_2O may be periodically purged to minimize these adverse effects on efficiency.

FIG. **2**A is a perspective view of the dehumidification unit **10** 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. **2**A, 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 **26**A 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 **14**A (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 **14**B 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. **2**A, 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. **2**A, in certain embodiments, the water vapor channel outlets **22** may be connected via a water vapor outlet manifold **24**, wherein the water vapor **26**A 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. **2**B is a perspective view of the dehumidification unit **10** of FIG. **1** having a single air channel **16** located inside a single water vapor channel **18** in accordance with an 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. **2**A and **2**B 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 **10** of FIGS. **1**, **2**A, and **2**B 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_2O (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**). 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_2O through permeable volumes of the membranes while blocking the flow of the other components **30**. Again, it should be noted that when the H_2O 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, absorbed/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 **14**A 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 **14**A location to the outlet air **14**B location.

In certain embodiments, the water vapor channels **18** are evacuated before use of the dehumidification unit **10**, 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 **14**A to the outlet air **14**B.

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 **10** 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_2O 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_2O 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 **10**. 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 **10** 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 **10** 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_2O 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^2/h (e.g., in a range of approximately 0.5-2.0 kg/m^2/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^2 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 **10**, 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 **14**B (i.e., point **48**) from the dehumidification unit **12** of FIGS. **1-3** is lower than the humidity ratio of the inlet air **14**A (i.e., point **50**) into the dehumidification unit **12** of FIGS. **1-3**, while the temperature of the outlet air **14**B and the inlet air **14**A 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 **10** to further facilitate the passage of H_2O 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. **2**A. 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 **10** may be distinguished between the water vapor **26**A in the water vapor vacuum volume **28** (i.e., the suction side of the vacuum pump **52**) and the water vapor **26**B expelled from an exhaust side (i.e., an outlet) of the vacuum pump **52** (i.e., the water vapor **26**B delivered to a condensation unit). In general, the water vapor **26**B expelled from the vacuum pump **52** will have a slightly higher pressure and a higher temperature than the water vapor **26**A 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 **26**A 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 **26**A typically be in the range of approximately 65-75° F. However, in other embodiments, the water vapor **26**A 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 **26**A 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 **26**B 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 **26**B 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_2O per pounds of dry air. The system may be set to remove 0.005 pounds of H_2O per pounds of dry air from the air **14**. Pressure differentials across the interfaces **20** may be used to create a flow of H_2O 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 **26**B is increased by the vacuum pump **52** in a primarily adiabatic process, and as the pressure of the water vapor **26**B 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 **26**B 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 **26**B at a temperature of approximately 72-73° F., and the temperature of the water vapor **26**B 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 **26**A and the downstream water vapor **26**B to ensure that the water vapor **26**B 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 **26**A entering the vacuum pump **52** to the water vapor **26**B exiting the vacuum pump **52** increases, the efficiency of the dehumidification unit **10** decreases. For example, in a preferred embodiment, the vacuum pump **52** will be set to adjust the pressure of the water vapor **26**B 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 **26**B. In another embodiment, the temperature of the water vapor **26**B may be used to control the pressure in the condensation unit **54**. The temperature of the water vapor **26**B expelled from the vacuum pump **52** may be substantially warmer than the humid air **14**A (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 **26**B to a point where condensation of the water vapor **26**B 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 **10**.

Once the water vapor **26**B has been slightly pressurized (i.e., compressed) by the vacuum pump **52**, the water vapor **26**B is directed into the condensation unit **54**, wherein the water vapor **26**B 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 **26**B. 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 **26**B 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_2O 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_2), nitrogen (N_2), 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. **2**A). 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**).

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 **8** and the dehumidification unit **10** and the one or more evaporative cooling units **12** of FIG. **1** having a vacuum pump **62** for removing noncondensable components **30** from the water vapor **26**A in the water vapor vacuum volume **28** of the dehumidification unit **10** 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_2O 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 **10** described herein may also be controlled between various operating states, and modulated based on operating conditions of the dehumidification unit **10**. For example, FIG. **7** is a schematic diagram of the HVAC system **8** and the dehumidification unit **10** and the one or more evaporative cooling units **12** of FIG. **6** having a control system **64** for controlling various operating conditions of the HVAC system **8** and the dehumidification unit **10** and the one or more evaporative cooling units **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 **10** (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 **14**A through the dehumidification unit **10**, sensors configured to generate signals related to characteristics of the inlet and outlet air **14**A, **14**B, and so forth) and the one or more evaporative cooling units **12**. The processors **66** may take these signals as inputs and calculate how to control the functionality of these components of the dehumidification unit **10** and the one or more evaporative cooling units **12** to most efficiently cool the air **14** while also removing the water vapor **26** from the air **14** flowing through the dehumidification unit **10**. 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 **26**A from the water vapor vacuum volume **28** of the dehumidification unit **10** 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 **26**A. 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 **26**A 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 components (i.e., both the noncondensable components **30** as well as H_2O, 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 **10** 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 **26**A 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 **10**. 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 **14**A, **14**B, among other things. The control system **64** may use this information to determine how to modulate the lower partial pressure of the water vapor **26**A (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 **26**A 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 **26**A 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 **10**. More specifically, under certain operating conditions, the dehumidification unit **10** may function more efficiently at higher rates of water vapor removal. As such, in certain embodiments, the dehumidification unit **10** 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 **10** 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 **10**.

The dehumidification unit **10** and the evaporative cooling units **12** may be designed and operated in many various modes, and at varying operating conditions. In general, the dehumidification unit **10** 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 **10** and the evaporative cooling units **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 **10** and the evaporative cooling units **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%. Similarly, in certain embodiments, the dehumidification unit **10** and the evaporative cooling units **12** may be optimized for dehumidifying outside air in commercial building recirculated air systems, which dehumidifies the inlet air **14**A 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 **14**B has less humidity and about the same temperature as the inlet air **14**A, unless cooling is performed on the outlet air **14**B.

The dehumidification unit **10** described herein requires less operating power than conventional dehumidification systems because of the relatively low pressures that are required to dehumidify the air **14**A. 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 **10** includes only the fan power required to move the air **14** through the dehumidification unit **10**, 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 **10**. As such, the only relatively major power component required to operate the dehumidification unit **10** 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 **10** is relatively inexpensive as opposed to conventional refrigeration compression dehumidification systems. Moreover, calculations for an embodiment indicate that the dehumidification unit **10** 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 **10** 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.

In certain embodiments, as indicated previously, the dehumidification unit **10** described with respect to FIGS. **1** through **7** may be used in conjunction with one or more evaporative cooling units **12**. For example, FIG. **8** is a schematic diagram of an HVAC system **72** having an evaporative cooling unit **74** disposed upstream of the dehumidification unit **10** in accordance with an embodiment of the present disclosure. The

HVAC system **72** of FIG. **8** generally functions the same as the HVAC system **8** of FIGS. **1**, **6**, and **7**. However, as illustrated in FIG. **8**, the HVAC system **72** specifically includes the evaporative cooling unit **74** disposed upstream of the dehumidification unit **10**. Thus, the HVAC system **72** first receives the relatively humid inlet air **14**A into the evaporative cooling unit **74**, instead of the dehumidification unit **10**. The evaporative cooling unit **74** reduces the temperature of the relatively humid inlet air **14**A and expels cooler (but still relatively humid) air **14**B, which is directed into the dehumidification unit **10** via a duct **76**. As described previously, the cooler (but still relatively humid) air **14**B is then dehumidified in the dehumidification unit **10** and expelled as relatively dry air **14**C into the conditioned space.

The evaporative cooling unit **74** of FIG. **8** may either be a direct evaporative cooling unit or an indirect evaporative cooling unit. In other words, when the evaporative cooling unit **74** uses direct evaporative cooling techniques, a relatively cool and moist media **78** (e.g., relatively cool water) is directly added to the relatively humid inlet air **14**A. However, when the evaporative cooling unit **74** uses indirect evaporative cooling techniques, the relatively humid air **14**A may, for example, flow across one side of a plate of a heat exchanger while the relatively cool and moist media **78** flows across another side of the plate of the heat exchanger. In other words, generally speaking, some of the relatively cool moisture from the relatively cool and moist media **78** is indirectly added to the relatively humid air **14**A. Whether direct or indirect evaporative cooling techniques are used in the evaporative cooling unit **74** affects the rate of humidity removal and temperature reduction of the air **14** that flows through the HVAC system **72** of FIG. **8**. In general, however, the evaporative cooling unit **74** of FIG. **8** initially cools the air **14** to a temperature as low as possible for the particular application, and the dehumidification unit **10** lowers the humidity ratio at approximately constant temperature.

As illustrated, many of the components of the HVAC system **72** of FIG. **8** may be considered identical to the components of the HVAC system **8** of FIGS. **1**, **6**, and **7**. For example, as described previously, HVAC system **72** of FIG. **8** includes the condensation unit **54** that receives water vapor **26**B having a partial pressure just high enough to facilitate condensation, as described previously. In certain embodiments, the HVAC system **72** of FIG. **8** may also include the reservoir **58** for temporary storage of saturated vapor and liquid water. However, as described previously, in other embodiments, no reservoir may be used. In either case, the liquid water from the condensation unit **54** may be directed into the liquid pump **60**, 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.

In addition, the control system **64** of FIG. **7** may also be used in the HVAC system **72** of FIG. **8** to control the operation of the HVAC system **72** in a similar manner as described previously with respect to FIG. **7**. For example, as described previously, the control system **64** may be configured to control the rate of removal of the noncondensable components **30** of the water vapor **26**A in the water vapor vacuum volume **28** by turning the vacuum pump **52** (or separate vacuum pump **62**) on or off, or by modulating the rate at which the vacuum pump **52** (or separate vacuum pump **62**) removes the noncondensable components **30**. More specifically, in certain embodiments, the control system **64** may receive signals from sensors in the water vapor vacuum volume **28** that detect when too many noncondensable components **30** are present in the water vapor **26**A contained in the water vapor vacuum volume **28**.

In addition, the control system **64** may modulate the lower partial pressure of the water vapor **26**A in the water vapor vacuum volume **28** to modify the water vapor removal capacity and efficiency ratio of the dehumidification unit **10**. For example, the control system **64** may receive signals from pressure sensors in the water vapor vacuum volume **28**, the water vapor channels **18**, as well as signals generated by sensors relating to characteristics (e.g., temperature, pressure, flow rate, relative humidity, and so forth) of the air **14** in the evaporative cooling unit **74**, the dehumidification unit **10**, or both, among other things.

The control system **64** may use this information to determine how to modulate the lower partial pressure of the water vapor **26**A in the water vapor vacuum volume **28** 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** of the dehumidification unit **10** as H_2O (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**). For example, if more water vapor removal is desired, the lower partial pressure of the water vapor **26**A 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 **26**A in the water vapor vacuum volume **28** may be increased. Furthermore, as described above, the amount of dehumidification (i.e., water vapor removal) may be cycled to improve the efficiency of the dehumidification unit **10**. More specifically, under certain operating conditions, the dehumidification unit **10** may function more efficiently at higher rates of water vapor removal. As such, in certain embodiments, the dehumidification unit **10** 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 **10** 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.

Furthermore, the control system **64** may also be configured to control operation of the evaporative cooling unit **74**. For example, the control system **64** may selectively modulate how much (direct or indirect) evaporative cooling occurs in the evaporating cooling unit **74**. As an example, valves may be actuated to control the flow rate of the relatively cool and moist media **78** through the evaporative cooling unit **74**, thereby directly affecting the amount of (direct or indirect) evaporative cooling in the evaporative cooling unit **74**. In addition, operation of the evaporative cooling unit **74** and the dehumidification unit **10** may be controlled simultaneously. Furthermore, the control system **64** may be configured to control start-up and shutdown sequencing of the evaporative cooling unit **74** and the dehumidification unit **10**.

FIGS. **9**A and **9**B are psychrometric charts **80**, **82** of the temperature and the humidity ratio of the air **14** flowing through the evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8** in accordance with an embodiment of the present disclosure. More specifically, FIG. **9**A is the psychrometric chart **80** of the temperature and the humidity ratio of the air **14** flowing through a direct evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8** in accordance with an embodiment of the present disclosure, and FIG. **9**B is the psychrometric chart **82** of the temperature and the humidity ratio of the air **14** flowing through an indirect evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8** in accordance with an embodiment of the present disclosure. In particular, in each chart **80**, **82**, the x-axis **84** corresponds to the temperature of the air **14** flowing through the evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8**, the y-axis **86** corresponds to the humidity ratio of the air **14** flowing through the evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8**, and the curve **88** represents the water vapor saturation curve for a given relative humidity of the air **14** flowing through the evaporative cooling unit **74** and the dehumidification unit **10** of FIG. **8**.

As illustrated by line **90** in FIG. **9**A, because the relatively cool and moist media **78** is directly introduced into the air **14** flowing though the direct evaporative cooling unit **74**, the humidity ratio of the air **14**B (i.e., point **92**) out of the direct evaporative cooling unit **74** is substantially higher than the humidity ratio of the inlet air **14**A (i.e., point **94**) into the direct evaporative cooling unit **74**. However, the temperature of the air **14**B (i.e., point **92**) out of the direct evaporative cooling unit **74** is substantially lower than the temperature of the inlet air **14**A (i.e., point **94**) into the evaporative cooling unit **74**. As illustrated by line **96** of FIG. **9**A, because water vapor **26** is removed from the air **14**B flowing through the dehumidification unit **10**, the humidity ratio of the outlet air **14**C (i.e., point **98**) from the dehumidification unit **10** is lower than the humidity ratio of the air **14**B (i.e., point **92**) into the dehumidification unit **10**, while the temperature of the outlet air **14**C and the air **14**B are substantially the same. Indeed, the direct evaporative cooling unit **74** humidifies and cools the air **14**, while the dehumidification unit **10** subsequently dehumidifies the air **14** at substantially constant temperature.

As illustrated by line **100** in FIG. **9**B, because the relatively cool and moist media **78** indirectly cools the air **14** flowing through the indirect evaporative cooling unit **74**, the humidity ratio of the air **14**B (i.e., point **102**) out of the indirect evaporative cooling unit **74** is substantially the same as the humidity ratio of the inlet air **14**A (i.e., point **104**) into the indirect evaporative cooling unit **74**. However, the temperature of the air **14**B (i.e., point **102**) out of the indirect evaporative cooling unit **74** is substantially lower than the temperature of the inlet air **14**A (i.e., point **104**) into the indirect evaporative cooling unit **74**. As illustrated by line **106** of FIG. **9**B, because water vapor **26** is removed from the air **14**B flowing through the dehumidification unit **10**, the humidity ratio of the outlet air **14**C (i.e., point **108**) from the dehumidification unit **10** is lower than the humidity ratio of the air **14**B (i.e., point **102**) into the dehumidification unit **10**, while the temperature of the outlet air **14**C and the air **14**B are substantially the same. Indeed, the indirect evaporative cooling unit **74** cools (without substantially humidifying) the air **14**, while the dehumidification unit **10** subsequently dehumidifies the air **14** at substantially constant temperature.

As described previously, the control system **64** of FIG. **8** may be configured to control the operation of the evaporative cooling unit **74** and the dehumidification unit **10**. For example, the control system **64** may be configured to adjust where points **92**, **94**, **98** and points **102**, **104**, **108** of the air **14** fall in the psychrometric charts **80**, **82** of FIGS. **9**A and **9**B when direct and indirect evaporative cooling techniques, respectively, are used in the evaporative cooling unit **74** of FIG. **8**.

FIG. **10** is a schematic diagram of an HVAC system **110** having the evaporative cooling unit **74** disposed downstream of the dehumidification unit **10** in accordance with an embodiment of the present disclosure. The HVAC system **110** of FIG. **10** generally functions the same as the HVAC system **8** of FIGS. **1**, **6**, and **7** and the HVAC system **72** of FIG. **8**. However, as illustrated in FIG. **10**, the HVAC system **110** first receives the relatively humid inlet air **14**A into the dehumidification unit **10**. As described previously, the relatively humid inlet air **14**A is first dehumidified in the dehumidification unit **10** and expelled as relatively dry air **14**B into the duct **76**. The evaporative cooling unit **74** then reduces the temperature of the dry air **14**B and expels cooler dry air **14**C into the conditioned space.

As described previously with respect to FIG. **8**, the evaporative cooling unit **74** of FIG. **10** may either be a direct evaporative cooling unit or an indirect evaporative cooling unit. In other words, when the evaporative cooling unit **74** uses direct evaporative cooling techniques, the relatively cool and moist media **78** (e.g., relatively cool water) is directly added to the relatively dry air **14**B in the duct **76**. However, when the evaporative cooling unit **74** uses indirect evaporative cooling techniques, the relatively dry air **14**B may, for example, flow across one side of a plate of a heat exchanger while the relatively cool and moist media **78** flows across another side of the plate of the heat exchanger. In other words, generally speaking, some of the relatively cool moisture from the relatively cool and moist media **78** is indirectly added to the relatively dry air **14**B in the duct **76**. Whether direct or indirect evaporative cooling techniques are used in the evaporative cooling unit **74** affects the rate of humidity removal and temperature reduction of the air **14** that flows through the HVAC system **110** of FIG. **10**. In general, however, the dehumidification unit **10** initially lowers the humidity ratio at approximately constant temperature, and the evaporative cooling unit **74** cools the air **14** to a temperature as low as possible for the particular application.

As illustrated, many of the components of the HVAC system **110** of FIG. **10** may be considered identical to the components of the HVAC system **8** of FIGS. **1**, **6**, and **7** and the HVAC system **72** of FIG. **8**. For example, as described previously, HVAC system **110** of FIG. **10** includes the condensation unit **54** that receives water vapor **26**B having a partial pressure just high enough to facilitate condensation, as described previously. In certain embodiments, the HVAC system **110** of FIG. **10** may also include the reservoir **58** for temporary storage of saturated vapor and liquid water. However, as described previously, in other embodiments, no reservoir may be used. In either case, the liquid water from the condensation unit **54** may be directed into the liquid pump **60**, 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.

In addition, the control system **64** of FIGS. **7** and **8** may also be used in the HVAC system **110** of FIG. **10** to control the operation of the HVAC system **110** in a similar manner as described previously with respect to FIGS. **7** and **8**. For example, as described previously, the control system **64** may be configured to control the rate of removal of the noncondensable components **30** of the water vapor **26**A in the water vapor vacuum volume **28** by turning the vacuum pump **52** (or separate vacuum pump **62**) on or off, or by modulating the rate at which the vacuum pump **52** (or separate vacuum pump **62**) removes the noncondensable components **30**. More specifically, in certain embodiments, the control system **64** may receive signals from sensors in the water vapor vacuum volume **28** that detect when too many noncondensable components **30** are present in the water vapor **26**A contained in the water vapor vacuum volume **28**.

In addition, the control system **64** may modulate the lower partial pressure of the water vapor **26**A in the water vapor vacuum volume **28** to modify the water vapor removal capacity and efficiency ratio of the dehumidification unit **10**. For example, the control system **64** may receive signals from pressure sensors in the water vapor vacuum volume **28**, the water vapor channels **18**, as well as signals generated by sensors relating to characteristics (e.g., temperature, pressure, flow rate, relative humidity, and so forth) of the air **14** in the dehumidification unit **10**, the evaporative cooling unit **74**, or both, among other things.

The control system **64** may use this information to determine how to modulate the lower partial pressure of the water vapor **26**A in the water vapor vacuum volume **28** 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** of the dehumidification unit **10** as H_2O (i.e., as atomic water, gaseous water vapor, liquid water, and so forth, adsorbed or absorbed through the interfaces **20**). For example, if more water vapor removal is desired, the lower partial pressure of the water vapor **26**A 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 **26**A in the water vapor vacuum volume **28** may be increased. Furthermore, as described above, the amount of dehumidification (i.e., water vapor removal) may be cycled to improve the efficiency of the dehumidification unit **10**. More specifically, under certain operating conditions, the dehumidification unit **10** may function more efficiently at higher rates of water vapor removal. As such, in certain embodiments, the dehumidification unit **10** 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 **10** 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.

Furthermore, the control system **64** may also be configured to control operation of the evaporative cooling unit **74**. For example, the control system **64** may selectively modulate how much (direct or indirect) evaporative cooling occurs in the evaporating cooling unit **74**. As an example, valves may be actuated to control the flow rate of the relatively cool and moist media **78** through the evaporative cooling unit **74**, thereby directly affecting the amount of (direct or indirect) evaporative cooling in the evaporative cooling unit **74**. In addition, operation of the dehumidification unit **10** and the evaporative cooling unit **74** may be controlled simultaneously. Furthermore, the control system **64** may be configured to control start-up and shutdown sequencing of the dehumidification unit **10** and the evaporative cooling unit **74**.

FIGS. **11**A and **11**B are psychrometric charts **112**, **114** of the temperature and the humidity ratio of the air **14** flowing through the dehumidification unit **10** and the evaporative cooling unit **74** of FIG. **10** in accordance with an embodiment of the present disclosure. More specifically, FIG. **11**A is the psychrometric chart **112** of the temperature and the humidity ratio of the air **14** flowing through the dehumidification unit **10** and a direct evaporative cooling unit **74** of FIG. **10** in accordance with an embodiment of the present disclosure, and FIG. **11**B is the psychrometric chart **114** of the temperature and the humidity ratio of the air **14** flowing through the dehumidification unit **10** and an indirect evaporative cooling unit **74** of FIG. **10** in accordance with an embodiment of the present disclosure. In particular, as described previously with respect to FIGS. **9**A and **9**B, the x-axis **84** corresponds to the temperature of the air **14** flowing through the dehumidification unit **10** and the evaporative cooling unit **74** of FIG. **10**, the y-axis **86** corresponds to the humidity ratio of the air **14** flowing through the dehumidification unit **10** and the evaporative cooling unit **74** of FIG. **10**, and the curve **88** represents the water vapor saturation curve for a given relative humidity of the air **14** flowing through the dehumidification unit **10** and the evaporative cooling unit **74** of FIG. **10**.

As illustrated by line **116** in FIG. **11**A, because water vapor **26** is removed from the relatively humid inlet air **14**A flowing through the dehumidification unit **10**, the humidity ratio of the relatively dry air **14**B (i.e., point **118**) from the dehumidification unit **10** is lower than the humidity ratio of the relatively humid inlet air **14**A (i.e., point **120**) into the dehumidification unit **10**, while the temperature of the relatively dry air **14**B and the relatively humid inlet air **14**A are substantially the same. As illustrated by line **122** of FIG. **11**A, because the relatively cool and moist media **78** is directly introduced into the relatively dry air **14**B flowing through the direct evaporative cooling unit **74**, the humidity ratio of the outlet air **14**C (i.e., point **124**) from the direct evaporative cooling unit **74** is substantially higher than the humidity ratio of the relatively dry air **14**B (i.e., point **118**) into the direct evaporative cooling unit **74**. However, the temperature of the outlet air **14**C (i.e., point **124**) from the direct evaporative cooling unit **74** is substantially lower than the temperature of the relatively dry air **14**B (i.e., point **118**) into the direct evaporative cooling unit **74**. Indeed, the dehumidification unit **10** dehumidifies the air **14** at substantially constant temperature, while the direct evaporative cooling unit **74** subsequently humidifies and cools the air **14**.

As illustrated by line **126** in FIG. **11**B, because water vapor **26** is removed from the relatively humid inlet air **14**A flowing through the dehumidification unit **10**, the humidity ratio of the relatively dry air **14**B (i.e., point **128**) from the dehumidification unit **10** is lower than the humidity ratio of the relatively humid inlet air **14**A (i.e., point **130**) into the dehumidification unit **10**, while the temperature of the relatively dry air **14**B and the relatively humid inlet air **14**A are substantially the same. As illustrated by line **132** of FIG. **11**B, because the relatively cool and moist media **78** indirectly cools the relatively dry air **14**B flowing though the indirect evaporative cooling unit **74**, the humidity ratio of the outlet air **14**C (i.e., point **134**) from the indirect evaporative cooling unit **74** is substantially the same as the humidity ratio of the relatively dry air **14**B (i.e., point **128**) into the indirect evaporative cooling unit **74**. However, the temperature of the outlet air **14**C (i.e., point **134**) from the indirect evaporative cooling unit **74** is substantially lower than the temperature of the relatively dry air **14**B (i.e., point **128**) into the indirect evaporative cooling unit **74**. Indeed, the dehumidification unit **10** dehumidifies the air **14** at substantially constant temperature, while the indirect evaporative cooling unit **74** cools (without substantially humidifying) the air **14**.

As described previously, the control system **64** of FIG. **10** may be configured to control the operation of the dehumidification unit **10** and the evaporative cooling unit **74**. For example, the control system **64** may be configured to adjust where points **118**, **120**, **124** and points **128**, **130**, **134** of the air **14** fall in the psychrometric charts **112**, **114** of FIGS. **11**A and **11**B when direct and indirect evaporative cooling techniques, respectively, are used in the evaporative cooling unit **74** of FIG. **10**.

The embodiments of the HVAC systems **72**, **110** of FIGS. **8** and **10** are not the only ways in which dehumidification units **10** may be combined with evaporative cooling units **74**. More specifically, whereas FIGS. **8** and **10** illustrate the use of a single dehumidification unit **10** and a single evaporative cooling unit **74** in series with each other, in other embodiments, any number of dehumidification units **10** and evaporative cooling units **74** may be used in series with each other. For example, FIG. **1** illustrates the dehumidification unit **10** having evaporative cooling units disposed on both sides (i.e., both upstream and downstream) of the dehumidification unit **10**. As another example, in one embodiment, a first dehumidification unit **10** may be followed by a first evaporative cooling unit **74**, which is in turn followed by a second dehumidification unit **10**, which is in turn followed by a second evaporative cooling unit **74**, and so forth. However, any number of dehumidification units **10** and evaporative cooling units **74** may indeed be used in series with each other, wherein the air **14** exiting each unit **10**, **74** is directed into the next downstream unit **10**, **74** in the series (except from the last unit **10**, **74** in the series, from which the air **14** is expelled into the conditioned space). In other words, the air **14** exiting each dehumidification unit **10** in the series is directed into a downstream evaporative cooling unit **74** (or to the conditioned space, if it is the last unit in the series), and the air **14** exiting each evaporative cooling unit **74** in the series is directed into a downstream dehumidification unit **10** (or to the conditioned space, if it is the last unit in the series). As such, the temperature of the air **14** may be successively lowered in each evaporative cooling unit **74** between dehumidification units **10** in the series, and the humidity ratio of the air **14** may be successively lowered in each dehumidification unit **10** between evaporative cooling units **74** in the series. This process may be continued within any number of dehumidification units **10** and evaporative cooling units **74** until the desired final temperature and humidity ratio conditions of the air **14** are achieved.

FIGS. **12**A and **12**B are psychrometric charts **136**, **138** of the temperature and the humidity ratio of the air **14** flowing through a plurality of dehumidification units **10** and a plurality of evaporative cooling units **74** in accordance with an embodiment of the present disclosure. More specifically, FIG. **12**A is a psychrometric chart **136** of the temperature and the humidity ratio of the air **14** flowing through a plurality of dehumidification units **10** and a plurality of direct evaporative cooling units **74** in accordance with an embodiment of the present disclosure, and FIG. **12**B is a psychrometric chart **138** of the temperature and the humidity ratio of the air **14** flowing through a plurality of dehumidification units **10** and a plurality of indirect evaporative cooling units **74** in accordance with an embodiment of the present disclosure. In particular, in each chart **136**, **138**, the x-axis **84** corresponds to the temperature of the air **14** flowing through the plurality of dehumidification units **10** and the plurality of evaporative cooling units **74**, the y-axis **86** corresponds to the humidity ratio of the air **14** flowing through the plurality of dehumidification units **10** and the plurality of evaporative cooling units **74**, and the curve **88** represents the water vapor saturation curve for a given relative humidity of the air **14** flowing through the plurality of dehumidification units **10** and the plurality of evaporative cooling units **74**.

As illustrated by lines **140** in FIG. **12**A, because water vapor **26** is removed from relatively humid air **14** flowing through each of the plurality of dehumidification units **10**, the humidity ratio of the air **14** substantially decreases while the temperature of the air **14** remains substantially the same in each of the plurality of dehumidification units **10**. As illustrated by lines **142** in FIG. **12**A, because the relatively cool and moist media **78** is directly introduced into the relatively dry air **14** flowing though each of the direct evaporative cooling units **74**, the humidity ratio of the air **14** increases while the temperature of the air **14** substantially decreases in each of the plurality of direct evaporative cooling units **74**. In other words, each of the plurality of dehumidification units **10** successively dehumidifies the air **14** at substantially constant temperature, while each of the plurality of direct evaporative cooling units **74** successively humidifies and cools the air **14** until the desired final conditions of temperature and humidity ratio are achieved. More specifically, as illustrated in FIG. **12**A, the lines **140**, **142** generally form a “step function” progression from the initial conditions of temperature and humidity ratio of the inlet air **14** (i.e., point **144**) to the final conditions of temperature and humidity ratio of the outlet air **14** (i.e., point **146**).

As illustrated by lines **148** in FIG. **12**B, because water vapor **26** is removed from relatively humid air **14** flowing through each of the plurality of dehumidification units **10**, the humidity ratio of the air **14** substantially decreases while the temperature of the air **14** remains substantially the same in each of the plurality of dehumidification units **10**. As illustrated by lines **150** in FIG. **12**B, because the relatively cool and moist media **78** indirectly interacts with the relatively dry air **14** flowing though each of the indirect evaporative cooling units **74**, the humidity ratio of the air **14** remains substantially the same while the temperature of the air **14** substantially decreases in each of the plurality of indirect evaporative cooling units **74**. In other words, each of the plurality of dehumidification units **10** successively dehumidifies the air **14** at substantially constant temperature, while each of the plurality of indirect evaporative cooling units **74** successively cools the air **14** at substantially constant humidity ratio until the desired final conditions of temperature and humidity ratio are achieved. More specifically, as illustrated in FIG. **12**B, the lines **148**, **150** generally form a “sawtooth” progression from the initial conditions of temperature and humidity ratio of the inlet air **14** (i.e., point **152**) to the final conditions of temperature and humidity ratio of the outlet air **14** (i.e., point **154**).

Because evaporative cooling units **74** are used between dehumidification units **10**, each dehumidification unit **10** will receive air **14** that is cooler and at a lower partial pressure of water vapor than the upstream dehumidification units **10**. As such, each of the dehumidification units **10** will operate at substantially different operating conditions. Accordingly, the control system **64** may be used to modulate the operating parameters (e.g., the partial pressures of water vapor in the water vapor vacuum volumes **28**, among other things) of the dehumidification units **10** to take into account the variations between dehumidification units **10**. Similarly, because dehumidification units **10** are used between evaporative cooling units **74**, each evaporative cooling unit **74** will also receive air **14** that is cooler and at a lower partial pressure of water vapor than the upstream evaporative cooling units **74**. As such, each of the evaporative cooling units **74** will also operate at substantially different operating conditions. Accordingly, the control system **64** may also be used to modulate the operating parameters (e.g., the flow rates of the relatively cool and moist media **78**, among other things) of the evaporative cooling units **74** to take into account the variations between evaporative cooling units **74**. In addition, the control system **64** may also simultaneously coordinate operation of the plurality of dehumidification units **10** and the plurality of evaporative cooling units **74** to take the variations into account.

The evaporative cooling units **74** of FIGS. **8** and **10** not only serve to lower the temperature of the air **14**, but also serve to clean the air **14** by, for example, passing the air **14** through a moist, fibrous mat. In addition, the dehumidification units **10** and the evaporative cooling units **14** may be operated at variable speeds or fixed speeds for optimal operation between different initial temperature and humidity conditions (i.e., operating points **144** and **152** in FIGS. **12**A and **12**B, respectively) and the final temperature and humidity conditions (i.e., operating points **146** and **154** in FIGS. **12**A and **12**B, respectively). Furthermore, the evaporative cooling units **74** are relatively low-energy units, thereby minimizing overall operating costs.

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 dehumidification system for removing water vapor from an airstream, comprising:
- a first and second channel separated by a membrane, wherein the membrane is configured to facilitate removal of water vapor from an airstream flowing through the first channel by facilitating passage of H_2O 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;
- a first evaporative cooling unit configured to cool the airstream downstream of the membrane;
- a second evaporative cooling unit configured to cool the airstream upstream of the membrane;
- 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_2O moves through the membrane to the second channel, wherein 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, and
- a controller comprising a microprocessor configured to control operations of the dehumidification system.

2. The system of claim **1**, wherein the operations comprise a first evaporative cooling operation provided by the first evaporative cooler, a first dehumidification operation provided by the pressure increasing device, and a second evaporative cooling operation provided by the second evaporative cooler during the operations.

3. The system of claim **2**, wherein the controller is configured to control the operations of the dehumidification system so as to result in psychrometric chart control of the dehumidification system.

4. The system of claim **1**, comprising a condensation device configured to receive water vapor from the pressure increasing device and condense the water vapor into liquid water.

5. The system of claim **4**, comprising a water transport device configured to transport the liquid water from the condensation device.

6. The system of claim **1**, wherein the membrane comprises zeolite.

7. A system, comprising:
- a dehumidification unit for removing H_2O vapor from an airstream, comprising:
  - an air channel configured to receive an inlet airstream and discharge an outlet airstream; and
  - an H_2O permeable material adjacent to the air channel, wherein the H_2O permeable material is configured to selectively enable H_2O from H_2O vapor in the inlet airstream to pass through the H_2O permeable material to a suction side of the H_2O permeable material and substantially block other components in the inlet airstream from passing through the H_2O permeable material to the suction side of the H_2O permeable material;
- an evaporative cooling unit configured to cool the airstream;
- a pressure increasing device configured to create a lower partial pressure of H_2O vapor on the suction side of the H_2O permeable material than the partial pressure of the H_2O vapor in the inlet airstream to drive passage of the H_2O from the H_2O vapor in the inlet airstream through the H_2O permeable material, and to increase the pressure at an outlet of the pressure increasing device to a partial pressure of H_2O vapor suitable for condensing H_2O vapor into liquid H_2O; and
- a controller comprising a microprocessor configured to control a first operation of the dehumidification unit.

8. The system of claim **7**, comprising a second evaporative cooling unit disposed upstream of the dehumidification unit.

9. The system of claim **7**, wherein the controller is configured to control a second operation of the evaporative cooling unit.

10. The system of claim **7**, comprising a condensation device configured to receive H_2O vapor from the outlet of the pressure increasing device, and to condense the H_2O vapor into liquid H_2O.

11. The system of claim **10**, comprising a liquid pump configured to transport the liquid H_2O from the condensation device.

12. The system of claim **7**, wherein the H_2O permeable material comprises an H_2O permeable membrane.

13. The system of claim **7**, wherein the H_2O permeable material comprises zeolite.

14. The system of claim **7**, wherein the dehumidification unit is a variable speed dehumidification unit, and the evaporative cooling unit is a variable speed evaporative cooling unit.

15. A method, comprising:
- receiving an airstream including H_2O vapor into an air channel of a dehumidification unit, wherein the airstream has a first partial pressure of H_2O vapor;
- cooling the airstream via an evaporative cooling unit;
- suctioning H_2O into an H_2O vapor channel of the dehumidification unit through an H_2O permeable material of the dehumidification unit using a pressure differential across the H_2O permeable material, wherein the H_2O permeable material comprises zeolite and the H_2O vapor channel has a second partial pressure of H_2O vapor lower than the first partial pressure of H_2O vapor of the airstream; and
- receiving H_2O vapor from the H_2O vapor channel into a pressure increasing device and increasing the pressure of the H_2O vapor from the pressure increasing device to a third partial pressure of H_2O vapor that is higher than the second partial pressure of H_2O vapor.

16. The method of claim **15**, comprising cooling the airstream via the evaporative cooling unit before directing the airstream into the dehumidification unit.

17. The method of claim **15**, comprising cooling the airstream via the evaporative cooling unit after receiving the airstream from the dehumidification unit.

18. The method of claim **15**, comprising cooling the airstream via a first evaporative cooling unit before directing the airstream into the dehumidification unit, and cooling the airstream via a second evaporative cooling unit after receiving the airstream from the dehumidification unit.

19. The method of claim **15**, comprising receiving H_2O vapor from the pressure increasing device into a condensation device and condensing the H_2O vapor into liquid H_2O.

20. The method of claim **19**, wherein the airstream has a first partial pressure of H_2O vapor in a range of approximately 0.2-1.0 psia, the second partial pressure of H_2O vapor is in a range of approximately 0.1-1.0 psia, and the third partial pressure of H_2O vapor is in a range of approximately 0.25-1.1 psia.

21. The system of claim **3**, wherein the psychrometric chart control comprises adjusting at least one point on a psychrometric chart.

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