

DEHUMIDIFICATION AND WATER COLLECTING DEVICE AND METHODS OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority to U.S. Provisional Application No. 63/479,825, entitled “Dehumidification and Water Collecting Device and Methods of Making the Same,” filed on January 13, 2023, the disclosure of which is hereby incorporated by reference in its entirety.

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FIELD OF THE INVENTION

[0003] The instant application relates to dehumidification and water collection systems and devices. In particular, the instant application relates to membranes and membrane support structures for dehumidification and water collection systems.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0004] This invention was made with government support under DE-EE0009061 awarded by U.S. Department of Energy (DOE). The government has certain rights in this invention.

BACKGROUND

[0005] In a vacuum dehumidification system, water is collected from humid air by driving water across a selective membrane using a vacuum. Free-standing membranes often rupture and deform, limiting the effectiveness and size of membranes in vacuum dehumidification systems.

SUMMARY

[0006] In one aspect, a membrane unit includes a support structure including open space within the support structure for removal of water vapor; and at least one membrane disposed on at least one surface of the support structure, wherein the membrane is water permeable and water selective, wherein the membrane unit is configured such that when a vacuum is applied to the open space of the support structure, water vapor is drawn across the membrane and through the support structure along an axis parallel to an interface between the support structure and the membrane.

[0007] In some embodiments, the open space includes pores within the support structure.

[0008] In some embodiments, the geometry of the pores varies spatially.

[0009] In some embodiments, the geometry of the pores varies in an axis parallel to the interface between the support structure and the membrane.

[0010] In some embodiments, the geometry of the pores varies in an axis perpendicular to the interface between the support structure and the membrane.

[0011] In some embodiments, the open space includes channels within the support structure.

[0012] In some embodiments, the geometry of the channels varies spatially.

[0013] In some embodiments, the geometry of the channels varies in an axis parallel to the interface between the support structure and the membrane.

[0014] In some embodiments, the geometry of the channels varies in an axis perpendicular to the interface between the support structure and the membrane.

[0015] In some embodiments, the chemistry of the support structure varies spatially.

[0016] In some embodiments, the chemistry of the support structure varies in an axis parallel to the interface between the support structure and the membrane.

[0017] In some embodiments, the chemistry of the support structure varies in an axis perpendicular to the interface between the support structure and the membrane.

[0018] In some embodiments, the geometry of the membrane varies spatially.

[0019] In some embodiments, the geometry of the membrane varies in an axis parallel to the interface between the support structure and the membrane.

[0020] In some embodiments, the geometry of the membrane varies in an axis perpendicular to the interface between the support structure and the membrane.

[0021] In some embodiments, the chemistry of the membrane varies spatially.

[0022] In some embodiments, the chemistry of the membrane varies in an axis parallel to the interface between the support structure and the membrane.

- [0023] In some embodiments, the chemistry of the membrane varies in an axis perpendicular to the interface between the support structure and the membrane.
- [0024] In some embodiments, the membrane unit has a planar geometry.
- [0025] In some embodiments, the membrane unit has a non-planar geometry.
- [0026] In some embodiments, the membrane unit has a water vapor permeability of at least 0.01 g H₂O/m²/s.
- [0027] In some embodiments, the membrane unit has a water vapor selectivity H₂O/N₂ of at least 1000 H₂O/N₂.
- [0028] In some embodiments, the membrane includes pores with diameters of less than about 10 nm.
- [0029] In some embodiments, the support structure includes pores with diameters of about 100 μm to about 1 cm.
- [0030] In some embodiments, the membrane unit further includes a membrane support substrate disposed between the membrane and the support structure.
- [0031] In some embodiments, the membrane support substrate includes pores with diameters of about 100 nm to about 10 mm.
- [0032] In some embodiments, the membrane unit further includes an inlet in fluid communication with the open space of the support structure for application of a vacuum.
- [0033] In some embodiments, the membrane unit further includes an outlet in fluid communication with the open space of the support structure for removal of water vapor.
- [0034] In some embodiments, the membrane unit further includes a non-porous frame.
- [0035] In some embodiments, the membrane unit allows passage of visible light.
- [0036] In some embodiments, the membrane unit blocks passage of infrared light.
- [0037] In some embodiments, the membrane unit further includes a membrane overlay disposed on the membrane.
- [0038] In some embodiments, the membrane overlay includes pores.
- [0039] In some embodiments, the membrane overlay includes pores with diameter greater than 10 μm.
- [0040] In some embodiments, the membrane overlay is chemically functionalized.
- [0041] In some embodiments, the membrane overlay has one or more of anti-fouling, dirt repelling, wetting, or antimicrobial characteristics.
- [0042] In some embodiments, the membrane overlay includes a photocatalytic compound.

- [0043] In some embodiments, the photocatalytic compound includes titanium dioxide.
- [0044] In some embodiments, the membrane overlay includes at least one of high surface area particles or high molecular structures.
- [0045] In some embodiments, the at least one of high surface area particles or high molecular structures includes activated carbon, metal organic frameworks, zeolites, or a combination thereof.
- [0046] In some embodiments, the membrane overlay includes a biocidal compound.
- [0047] In some embodiments, the biocidal compound includes silver ions, copper ions, silver nanoparticles, copper nanoparticles, quaternary ammonium compounds, or a combination thereof.
- [0048] In some embodiments, the membrane overlay causes a turbulent mixing or reduces a concentration polarization of a non-water gas species at an interface of the membrane.
- [0049] In some embodiments, the membrane unit further includes at least one non-permeable barrier disposed on at least another surface of the support structure.
- [0050] In some embodiments, the membrane unit further includes a sensible cooling layer disposed on a surface of the non-permeable barrier.
- [0051] In some embodiments, wherein the non-permeable barrier is non-permeable to water vapor.
- [0052] In some embodiments, the non-permeable barrier is non-permeable to gas molecules.
- [0053] In some embodiments, the non-permeable barrier is non-porous.
- [0054] In some embodiments, the non-permeable barrier includes a structural support layer.
- [0055] In some embodiments, the non-permeable barrier includes a metal, an alloy, or a combination thereof.
- [0056] In some embodiments, the non-permeable barrier includes a polymer.
- [0057] In some embodiments, the non-permeable barrier has a thermal conductivity in the range of 0.1-0.5 W/m-K.
- [0058] In some embodiments, the non-permeable barrier has a thermal conductivity in the range of 0.5-10 W/m-K.
- [0059] In some embodiments, the non-permeable barrier has a thermal conductivity in the range of 10-500 W/m-K.

- [0060] In some embodiments, the non-permeable barrier is hydrophobic.
- [0061] In some embodiments, the sensible cooling layer includes a wettable evaporative media.
- [0062] In some embodiments, the sensible cooling layer includes a radiant cooler, a reflective barrier, or combination thereof.
- [0063] In some embodiments, the sensible cooling layer includes pores.
- [0064] In some embodiments, the sensible cooling layer is hydrophilic.
- [0065] In some embodiments, the wettable evaporative media includes a heat transfer fluid.
- [0066] In one aspect, a system includes one or more membrane units described herein; a vacuum pump configured to apply a vacuum to the open spaces of the support structure of the one or more membrane units; and one or more inlets configured to deliver humid feed air to each membrane of the one or more membrane units along an axis parallel to an interface between the support structure and the membrane.
- [0067] In some embodiments, the system includes a plurality of membrane units.
- [0068] In some embodiments, the system further includes a vacuum manifold system.
- [0069] In some embodiments, the system further includes a vacuum reservoir.
- [0070] In some embodiments, the system further includes a plurality of vacuum pumps.
- [0071] In some embodiments, the system further includes a gas-to-liquid heat exchanger.
- [0072] In some embodiments, the system further includes a water circuit.
- [0073] In some embodiments, the system further includes a water pump.
- [0074] In some embodiments, the system further includes a plurality of vacuum gates or valves.
- [0075] In some embodiments, the system further includes a vapor compressor.
- [0076] In some embodiments, the plurality of membrane units are arranged parallel to each other.
- [0077] In some embodiments, at least one membrane unit is arranged perpendicular to another membrane unit.
- [0078] In some embodiments, at least one membrane unit is arranged counter-parallel to another membrane unit.
- [0079] In some embodiments, the inlets are configured to deliver humid feed air to one or more spaces between the plurality of membrane units.

[0080] In some embodiments, at least one membrane unit includes at least one non-permeable barrier disposed on at least another surface of the support structure of the at least one membrane unit.

[0081] In some embodiments, the system further includes one or more first inlets configured to deliver working air adjacent to a surface of each non-permeable barrier of the one or more membrane units along an axis parallel to an interface between the support structure and the non-permeable barrier.

[0082] In some embodiments, the working air includes dehumidified feed air.

[0083] In some embodiments, the system further includes a water mister for distributing water to the working air.

[0084] In some embodiments, the first inlets are configured to deliver working air to one or more spaces between the plurality of membrane units.

[0085] Any one of the embodiments disclosed herein may be properly combined with any other embodiment disclosed herein. The combination of any one of the embodiments disclosed herein with any other embodiments disclosed herein is expressly contemplated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0086] The objects and advantages will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

[0087] FIG. 1 shows a schematic diagram of membrane unit design, according to certain embodiments.

[0088] FIG. 2A shows a schematic of a selective membrane, according to certain embodiments.

[0089] FIG. 2B shows a schematic of a membrane unit, according to certain embodiments.

[0090] FIG. 2C shows a schematic of a vacuum membrane dehumidification system, according to certain embodiments.

[0091] FIG. 2D shows the dry bulb temperature and humidity ratio of an illustrative system for isothermal dehumidification and water collection, according to certain embodiments.

[0092] FIG. 3A shows a schematic of a selective membrane, according to certain embodiments.

[0093] FIG. 3B shows a schematic of a membrane unit including a non-porous barrier and wettable evaporative media, according to certain embodiments.

[0094] FIG. 3C shows a schematic of a vacuum membrane dehumidification and evaporative cooling system, according to certain embodiments.

[0095] FIG. 3D shows the dry bulb temperature and humidity ratio of an illustrative system for dehumidification and evaporative cooling, according to certain embodiments.

[0096] FIGs. 4A-4B show features of a membrane unit and supported membrane assembly, according to certain embodiments.

[0097] FIGs. 5A-5B show features of a membrane unit and supported membrane assembly including a non-porous barrier and sensible cooling layer, according to certain embodiments.

[0098] FIG. 6A shows a vacuum membrane dehumidification system retrofit to a curtain wall system, according to certain embodiments.

[0099] FIG. 6B shows a vacuum manifold system for a vacuum membrane dehumidification system, according to certain embodiments.

[0100] FIG. 6C shows a membrane unit connected to a vacuum manifold, according to certain embodiments.

[0101] FIGs. 7A-7B show features of a supported membrane assembly which includes a planar conformal membrane and porous support structure, according to certain embodiments.

[0102] FIGs. 8A-8D show features of a supported membrane assembly which includes a planar conformal membrane, a non-permeable barrier, a sensible cooling layer, and a porous support structure, according to certain embodiments.

[0103] FIGs. 9A-9B show a supported membrane assembly which includes a nonplanar conformal membrane and porous support structure, according to certain embodiments.

[0104] FIGs. 10A-10B show a supported membrane assembly which includes a conformal membrane and porous support structure with a range of porous interconnected geometries perpendicular to the feed plane, according to certain embodiments.

[0105] FIGs. 11A-11B show a supported membrane assembly which includes a conformal membrane and porous support structure with a range of porous interconnected geometries parallel to the feed plane, according to certain embodiments.

[0106] FIGs. 12A-12B show a supported membrane assembly which includes a conformal membrane and porous support structure with a range of porous interconnected

geometries in a combination of perpendicular and parallel directions to the feed plane, according to certain embodiments.

[0107] FIGs. 13A-13B show a supported membrane assembly which includes a conformal membrane and non-porous support structure with continuous channels, according to certain embodiments.

[0108] FIGs. 14A-14B show a supported membrane assembly which includes a conformal membrane and non-porous support structure with hierarchical continuous channels, according to certain embodiments.

[0109] FIGs. 15A-15B show a supported membrane assembly which includes a conformal membrane, a conformal porous membrane substrate, and porous support structure, according to certain embodiments.

[0110] FIGs. 16A-16B show a supported membrane assembly which includes a conformal membrane overlay, a conformal porous membrane, and a porous support structure, according to certain embodiments.

[0111] FIGs. 17A-17B show a supported membrane assembly which includes a conformal membrane overlay, a conformal porous membrane, a conformal porous membrane substrate, and porous support structure, according to certain embodiments.

[0112] FIGs. 18A-18B show a supported membrane assembly which includes a conformal membrane with a range of membrane chemistries perpendicular to the feed plane and porous support structure, according to certain embodiments.

[0113] FIGs. 19A-19B show a supported membrane assembly which includes a conformal membrane with a range of membrane chemistries parallel to the feed plane and porous support structure, according to certain embodiments.

[0114] FIG. 20 shows a matrix showing various combinations of membranes and support structures, according to certain embodiments.

[0115] FIG. 21 shows a matrix showing various combinations of sensible cooling layer, membrane overlay, membrane, and membrane support substrate, according to certain embodiments.

[0116] FIGs. 22A-22B show a supported membrane assembly with a cylindrical configuration, according to certain embodiments.

[0117] FIGs. 22C-22D show a supported membrane assembly with a cylindrical configuration including a membrane overlay, according to certain embodiments.

- [0118] FIGs. 23A-23B show a supported membrane assembly with a tubular configuration including a non-porous barrier layer, according to certain embodiments.
- [0119] FIGs. 23C-23D show a supported membrane assembly with a tubular configuration including a membrane overlay, according to certain embodiments.
- [0120] FIGs. 24A-24B show a supported membrane assembly with a tubular array configuration, according to certain embodiments.
- [0121] FIGs. 24C-24D show a supported membrane assembly with a tubular array configuration including membrane overlays, according to certain embodiments.
- [0122] FIGs. 25A-25B show a supported membrane assembly with an annular configuration including a non-porous barrier layer and evaporative cooling layer, according to certain embodiments.
- [0123] FIGs. 26A-26B show a supported membrane assembly with an annular configuration including a non-porous barrier layer and evaporative cooling layer, according to certain embodiments.
- [0124] FIGs. 27A-27B show a supported membrane assembly with an annular configuration including a non-porous barrier and radiant cooling layer, according to certain embodiments.
- [0125] FIGs. 28A-28B show a supported membrane assembly with a spiral configuration, according to certain embodiments.
- [0126] FIGs. 28C-28D show a supported membrane assembly with a spiral configuration including a membrane overlay, according to certain embodiments.
- [0127] FIGs. 29A-29B show a supported membrane assembly with a spiral configuration, according to certain embodiments.
- [0128] FIGs. 29C-29D show a supported membrane assembly with a spiral configuration including a membrane overlay, according to certain embodiments.
- [0129] FIG. 30A shows a porous support material made from 3D printed polymer gyroidal structures, according to certain embodiments.
- [0130] FIG. 30B shows a rigid plastic frame with a vacuum inlet for a porous support material, according to certain embodiments.
- [0131] FIG. 30C shows a water selective membrane adhered to a frame for a support material, according to certain embodiments.
- [0132] FIG. 30D shows multiple porous support structures with hierarchical structures having varying porosities and layer thicknesses, according to certain embodiments.

[0133] FIG. 30E shows an experimental set up for a dehumidification system, according to certain embodiments.

[0134] FIG. 31A shows raw water permeance over time for a selection of membranes, including various cellulose tri-acetate (“CA”), Ethylene-methyl acrylate copolymer, silicone rubber (“PDMS”), polyolefin composite, and polyethylene-amide co-block polymer, according to certain embodiments.

[0135] FIG. 31B shows calculated water vapor flux for a selection of membranes, including various cellulose tri-acetate (“CA”), Ethylene-methyl acrylate copolymer, silicone rubber (“PDMS”), polyolefin composite, and polyethylene-amide co-block polymer, according to certain embodiments.

[0136] FIG. 31C shows selectivity values for a selection of membranes, including various cellulose tri-acetate (“CA”), Ethylene-methyl acrylate copolymer, silicone rubber (“PDMS”), polyolefin composite, and polyethylene-amide co-block polymer, according to certain embodiments.

[0137] FIG. 32A shows a porous 3D printed PLA (polylactic acid) support material, according to certain embodiments.

[0138] FIG. 32B shows a non-woven fiber support material, according to certain embodiments.

[0139] FIG. 32C shows a plastic screen mesh support material with corrugated support, according to certain embodiments.

[0140] FIG. 32D shows a stacked plastic screen mesh support material, according to certain embodiments.

[0141] FIG. 32E shows a porous 3D printed PLA (polylactic acid) support material, according to certain embodiments.

[0142] FIG. 32F shows a non-woven fiber support material, according to certain embodiments.

[0143] FIG. 32G shows a plastic screen mesh support material, according to certain embodiments.

[0144] FIG. 32H shows a plastic screen mesh support material with corrugated support, according to certain embodiments.

[0145] FIG. 32I shows a schematic of a porous 3D printed PLA (polylactic acid) support material, according to certain embodiments.

- [0146] FIG. 32J shows a schematic of a non-woven fiber support material, according to certain embodiments.
- [0147] FIG. 32K shows a schematic of a stacked plastic screen mesh support material, according to certain embodiments.
- [0148] FIG. 32L shows a schematic of a plastic screen mesh support material with corrugated support, according to certain embodiments.
- [0149] FIG. 32M shows water mass flux values for panel geometries with various porous support structures, according to certain embodiments.
- [0150] FIG. 33A shows individual panels assembled into arrayed “cassettes” with variable spacing, according to certain embodiments.
- [0151] FIG. 33B shows cassettes installed into ducted air-side flow system with permeate-side vacuum manifold, according to certain embodiments.
- [0152] FIG. 33C shows the impact of panel spacing on water mass flux and pressure drop across the system, according to certain embodiments.
- [0153] FIG. 33D shows a panel with 3mm membrane to membrane spacing, according to certain embodiments.
- [0154] FIG. 33E shows a panel with 6mm membrane to membrane spacing, according to certain embodiments.
- [0155] FIG. 33F shows a panel with 12mm membrane to membrane spacing, according to certain embodiments.
- [0156] FIG. 33G shows experimentally measured mass flux and corresponding water extraction rate and projected coefficient of performance values for panel geometries with variable spacing.
- [0157] FIG. 34A shows a prototype tested in a demonstration building, according to certain embodiments.
- [0158] FIG. 34B shows a prototype installed next to a window AC, according to certain embodiments.
- [0159] FIG. 34C shows a diagram illustrating a prototype system demonstration, according to certain embodiments.
- [0160] FIG. 34D shows a prototype with a vacuum system installed, according to certain embodiments.
- [0161] FIGs. 35A-35C show dehumidification efficiency for three flow configurations field-tested for 24-hour periods, according to certain embodiments.

[0162] FIG. 36A shows relative humidity for a fan assisted air flow at 0.7 to 1.5 m/s air velocity, according to certain embodiments.

[0163] FIG. 36B shows relative humidity for fan assisted air flow configuration at 3.0 m/s air velocity, according to certain embodiments.

[0164] FIG. 36C shows relative humidity for natural ventilation air flow configuration 0.0 to 0.3 m/s air velocity, according to certain embodiments.

[0165] FIG. 36D shows absolute humidity for a fan assisted air flow at 0.7 to 1.5 m/s air velocity, according to certain embodiments.

[0166] FIG. 36E shows absolute humidity for fan assisted air flow configuration at 3.0 m/s air velocity, according to certain embodiments.

[0167] FIG. 36F shows absolute humidity for natural ventilation air flow configuration 0.0 to 0.3 m/s air velocity, according to certain embodiments.

[0168] FIG. 37 shows relationship between indoor and outdoor absolute humidities for the product air velocity of approximately 0.75 m/s, according to certain embodiments.

[0169] FIG. 38 shows the decrease in absolute humidity of the product air as a function of outdoor absolute humidity for the product air velocity of approximately 0.75 m/s, according to certain embodiments.

[0170] FIG. 39 shows the decrease in absolute humidity of the product air for a product air velocity of approximately 0.75 m/s during the 12-hour test, according to certain embodiments.

DETAILED DESCRIPTION

[0171] In one aspect, a membrane unit includes a support structure comprising open space within the support structure for removal of water vapor; and at least one membrane disposed on at least one surface of the support structure, wherein the membrane is water permeable and water selective, wherein the membrane unit is configured such that when a negative pressure (vacuum) is applied to the open space of the support structure, water vapor is drawn across the membrane and through the support structure along an axis parallel to an interface between the support structure and the membrane.

[0172] Disclosed herein is an engineered component of a water-selective vacuum membrane system for energy-efficient, low-carbon emission building dehumidification and water collection. As humid air passes through the system into a target environment, water vapor can be selectively captured using an array of mass exchangers with a specially

developed membrane unit or panel. The chemical composition of the membranes of the membrane panel promotes separation of small molecules ($\text{H}_2\text{O}/\text{N}_2$ selectivity) through preferential absorption and diffusion of water molecules - an isothermal process (*e.g.*, humid air is dried without any temperature change). Vacuum pressure can be applied on one side of a membrane to create a driving force to amplify the water permeation through the membrane, resulting in high water capture rates. The thin membranes (*e.g.*, polymer membranes) used in a membrane unit can be supported by structural support matrices (*e.g.*, a porous support or non-porous support with channels), which are stiff enough to prevent a permanent membrane deformation and rupture and highly porous in such a way to limit or prevent concentration polarization of water vapor flux on both the feed and permeate side to maintain high water vapor permeability across the entire system.

[0173] In some embodiments, a membrane unit or panel includes one or more water selective membranes with uniform or varying geometry and location, and one or more support structures with uniform or varying geometry and location. A membrane unit can alternatively be referred to as a mass exchange unit, a membrane tile, or a membrane panel. In some embodiments, the support structure includes open spaces for removal of permeate, for example a porous substrate, a hollow support structure, a hollow channel structure, or combinations thereof. For example, if support structure materials are not properly sized for the structure and porosity, water diffusion across the membrane can be limited due to the creation of a stagnant boundary layer (*i.e.*, concentration polarization due to localized buildup of water vapor molecules on the permeate-side [*i.e.*, water collection side]) and/or a decrease pressure gradient and concentration gradient across the membrane. A well-designed, interconnected structure enhances the transport of water molecules away from the membrane interface on the permeate side, resulting in improved permeance across the membrane and dehumidification of the target air. In some embodiments, a well-designed, interconnected structure has interconnected open spaces. In some embodiments, the interconnected open spaces can be three-dimensionally connected, for example, to allow vapor to flow in all dimensions. In some embodiments, a well-designed interconnected structure includes open spaces, pores, or voids having a feature size of about 100 μm to 5mm. In some embodiments, a structure includes open spaces, pores, or voids having a feature sizes of about 100 μm to 200 μm , 200 μm to 300 μm , 300 μm to 400 μm , 400 μm to 500 μm , 500 μm to 1 mm, 1 mm to 2mm, 2 mm to 3mm, 3 mm to 4 mm, 4mm to 5 mm, or any feature size within a range bounded by any feature size disclosed herein. In some embodiments, a well-designed

interconnected structure has a porosity of about 20% to 80%. In some embodiments, a well-designed interconnected structure has a porosity of 40% to 60%. In some embodiments, a well-designed interconnected structure has a porosity of 20%-30%, 30%-40%, 40%-50%, 50-60%, 60%-70%, 70%-80%, or any porosity within a range bounded by any porosity disclosed herein. In some embodiments, the percentage surface area of the membrane or a membrane with membrane substrate (e.g. a membrane support substrate) that contacts the well-designed interconnected structure is about 15% to 30%. In some embodiments, the percentage surface area of the membrane or a membrane with membrane substrate (e.g. a membrane support substrate) that contacts the well-designed interconnected structure is about 5-10%, 10%-15%, 15-20%, 20%-30%, or any percentage surface area of the membrane within a range bounded by any percentage surface area of the membrane disclosed.

[0174] In some embodiments, the membrane unit demonstrates high water vapor permeabilities, for example a water flux of at least $0.01 \text{ g H}_2\text{O}/\text{m}^2/\text{s}$ and/or a water permeability of at least $1 \times 10^{-13} \text{ mol} \cdot \text{m}/\text{m}^2 \cdot \text{s} \cdot \text{Pa}$. In some embodiments, the membrane unit demonstrates a water flux of 0.01 to $1.0 \text{ g H}_2\text{O}/\text{m}^2/\text{s}$. In some embodiments, the membrane unit demonstrates high water selectivity, for example, of at least $1000 \text{ H}_2\text{O}/\text{N}_2$. In some embodiments, the membrane unit demonstrates a water selectivity of about 1000-10,000,000 $\text{H}_2\text{O}/\text{N}_2$. In some embodiments, the membrane unit demonstrates a low air permeability, for example, an air permeability of less than about $1 \times 10^{-16} \text{ mol} \cdot \text{m}/\text{m}^2 \cdot \text{s} \cdot \text{Pa}$. In some embodiments, the membrane unit demonstrates a low air permeability, for example, an air permeability of less than about $1 \times 10^{-20} \text{ mol} \cdot \text{m}/\text{m}^2 \cdot \text{s} \cdot \text{Pa}$. In some embodiments, a vacuum pressure is applied to achieve significant driving forces across the membrane. In some embodiments, pressures from about 95,000 to about 105,000 Pa can be applied.

[0175] FIG. 1 shows an example membrane unit and associated design parameters. A membrane unit can alternatively be referred to as a mass exchange unit, a membrane tile, or a membrane panel. As shown in FIG. 1, each membrane unit 101 includes a membrane material 102 and a core material or support structure 103. In this example, each membrane unit includes a planar core material and membrane material on the two opposite surfaces of the planar core material. However, a membrane unit can have any configuration where a core material has a membrane material disposed on at least one surface of the core material. For example, a membrane unit can include a planar core material with a membrane material on the two opposite surfaces of the planar core material. In another example, a membrane unit can be a single-sided membrane unit in which one surface of the planar core material includes

a membrane material. In these embodiments, the other surface of the planar core material without a membrane can provide additional vacuum input locations and/or heat transfer benefits. In another example, the membrane unit can be surrounded or encompassed by a continuous boundary or frame. In some embodiments, the boundary or frame includes an inlet in the planar core material, for example at the center of the channel. In these embodiments, the inlet can provide application of a vacuum on the planar core material. In another example, a membrane unit can include a cylindrical core material with a membrane material on the sides of the cylinder. For example, a core material can have any geometry enclosed by a membrane material. In some embodiments, a membrane is a conformal membrane that covers the support structure completely, for example a membrane covering the outer surfaces of a cylinder or tube. In the example shown in FIG. 1, target air to be dehumidified flows in the space between membrane units 101 (*e.g.*, a feed plane) via a pressure gradient (free or forced), and a low pressure is created within the support structure. In this example, a water selective membrane preferentially absorbs water molecules from a humid air feed stream. Vacuum pressure can provide a pressure and/or concentration gradient sufficient to pull water molecules across the membrane and into a permeate stream (*e.g.*, at pressures below the partial pressure of water vapor, typically less than 4 kPa). As a result, a vapor concentration gradient is created within the support structure. This combination of a pressure gradient and concentration gradient can cause water vapor to move across the membrane and through the support structure, removing water vapor from humid air in the feed plane.

[0176] In some embodiments, a suitable membrane material has high permeability (high solubility and diffusivity of water) and high selectivity (water absorbing while oxygen and nitrogen rejecting). In some embodiments, a suitable core or support material is strong enough to not collapse under vacuum, smooth enough to not pierce the membrane, includes sufficient open space (*e.g.*, pores or channels) to prevent choking of internal vapor flow, is inexpensive, is quick to fabricate, and is in minimal contact with the membrane to maximize active area. Such a support structure material can provide at least two functions (1) structural support of the membrane material, and (2) vapor transport for continuous removal of water. In some embodiments, the support structure material includes open space, *e.g.*, pores or channels, to facilitate vapor flow. In some embodiments, the geometry and chemistry of the support material is selected to create an internal vapor concentration gradient and facilitate vapor flow, for example, by creating a spatial gradient of chemistry, geometry, or

combination thereof. In some embodiments, the thickness of the membrane unit and the spacing of membrane units can be selected to optimize dehumidification. In some embodiments, the membrane tiles can be adjustable to vary the spacing. For example, the membrane tiles can be placed on an adjustable bellows-type structure to vary the spacing and thus dehumidification capacity, while maintaining a fixed or constant flow. In some embodiments, a pressure gradient can be applied to a membrane unit, *e.g.*, by applying a vacuum to the core material or support structure. *e.g.*, via a vacuum inlet, creating a driving force to increase permeation of water across the membrane and into the support structure. In some embodiments, a membrane unit includes one or more inlets in fluid connection with the open spaces of the support structure for application of a vacuum. In some embodiments, the membrane unit includes an inlet with a controllable valve or solenoid valve. In some embodiments, such a valve can be used for diagnostics, membrane unit replacement, and/or adaptable dehumidification throughput control. In some embodiments, the membrane unit includes one or more outlets in fluid connection with the open spaces of the support structure for removal of water vapor from the support structure. In some embodiments, the membrane unit includes one or more outlets with pressure sensors or transducers in fluid connection with the open spaces of the support structure for removal of water vapor from the support structure.

[0177] FIGs. 2A-2C show a schematic of an example vacuum membrane dehumidification system 200. FIG. 2A shows a dense block-copolymer film 202 that demonstrates high water vapor permeability and selectivity based on tailored molecular structure. In the example shown in FIG. 2A, when humid feed air, including oxygen, nitrogen, and water, flows past or parallel to the water-selective membrane, water can pass through the membrane to form the permeate, but oxygen and nitrogen permeate at a much lower rate. Such a film can be used as a selective membrane and is typically thin. Non-limiting examples of the thickness of the selective membrane include a thickness of 1 μm 15 μm , 50 μm , or 100 μm , or any thickness within a range bounded by any thickness disclosed herein. Feed and permeate pathways can be parallel, counter-parallel, perpendicular, or tangential. FIG. 2B shows a membrane unit 201 including a support structure 203 and a membrane 202 on either surface of the support structure. As shown in FIG. 2B, a vacuum applied to the porous support structure can create a vacuum-driven concentration gradient such that water from the feed is captured within the support structure and flows downward as part of the permeate. In the example shown in FIG. 2B, the water vapor concentration can be

optimized by selecting the membrane unit thickness. In some embodiments, the membrane unit thickness can be 5 mm or thinner. In some embodiments, the membrane unit thickness can be 6 mm or thinner. As shown in FIG. 2C, multiple membrane units 201 can be arranged to form a dehumidification system 200. In the example shown in FIG. 2C, humid air enters at (a) as part of the feed and dry air exits at (b) as water vapor is captured within the support structure (e.g., as permeate). In this example, the boundary layer can be optimized by selecting the spacing between membrane units, e.g., 10 mm. As shown in FIG. 2D, this example system can achieve energy efficient isothermal dehumidification and water collection. The example system can remove water vapor from air without altering temperature.

[0178] In some embodiments, the membrane support structure includes a non-permeable interface or barrier that is non-permeable to water vapor. In some embodiments, the membrane support structure's non-permeable interface can be modified to function as an evaporative or radiant cooler. For example, one surface of the membrane support structure can include a water-selective membrane for dehumidification and water collection, while the other surface can include a non-permeable barrier for incorporating cooling via evaporation (e.g., evaporative cooling) or radiation (e.g., radiant cooling). In some embodiments, the non-permeable barrier is non-porous. In some embodiments, a membrane support structure including a non-permeable barrier further includes a sensible cooling layer. In some embodiments, the sensible cooling layer includes a wettable evaporative media for evaporative cooling. In some embodiments, the sensible cooling layer includes a spectrally selective media or reflective barrier for radiant cooling. In some embodiments, the sensible cooling layer includes a wettable evaporative media for evaporative cooling and a spectrally selective media or reflective barrier for radiant cooling.

[0179] FIGs. 3A-3C show a schematic of an example vacuum membrane dehumidification and evaporative cooling system 300. FIG. 3A shows a dense block-copolymer film 302 that demonstrates high water vapor permeability and selectivity based on tailored molecular structure. In the example shown in FIG. 3A, when feed (e.g., warm humid feed air, including oxygen, nitrogen, and water; or gas containing water) flows past or parallel to the water-selective membrane, water can pass through the membrane to form the permeate, but oxygen and nitrogen permeate at a much lower rate. Such a film can be used as a selective membrane and is typically thin. Non-limiting examples of the thickness of the selective membrane include a thickness of 1 μm 15 μm , 50 μm , or 100 μm , or any thickness

within a range bounded by any thickness disclosed herein. Feed and permeate pathways can be parallel, counter-parallel, perpendicular, or tangential. FIG. 3B shows a membrane unit 301 including a support structure 303, a membrane 302 on one surface of support structure 303, and a non-permeable (e.g., non-porous) barrier 304 at the other surface of support structure 303. In some embodiments, membrane 302 can be in contact or exposed to a feed air for dehumidification, while non-porous barrier 304 can be in contact or exposed to working air for cooling. As shown in FIG. 3B, a vacuum applied to the porous support structure can create a vacuum-driven concentration gradient such that water from the feed air is captured within the support structure through membrane 302 and flows downward as part of the permeate. In some embodiments, non-porous barrier 304 can cause evaporative cooling of the working air that is in contact with it. In some embodiments, non-porous barrier 304 can be a non-soluble (e.g., non water soluble) and/or non-porous media. In some embodiments, the other surface of the non-porous barrier 304 (e.g., a surface that is not in contact with the support structure 303) can include a wetted-porous or wettable evaporative media (i.e., a sensible cooling layer) 305. Wettable evaporative media 305 can include a porous or void space for holding water.

[0180] In the example shown in FIG. 3B, the water vapor concentration can be optimized by selecting the membrane unit thickness, e.g., 5 mm. As shown in FIG. 3C, multiple membrane units 301 can be arranged to form a dehumidification and cooling system 300. In the example shown in FIG. 3C, on the membrane side of membrane unit 301, warm humid air enters at (a) as part of the feed and cold dry air exits at (b) as water vapor is captured within the support structure (e.g., as permeate). In this example, on the non-porous barrier side of membrane unit 301, the working air enters at one end and becomes cooler and more humid via evaporative cooling as it travels towards the other end. In some embodiments, to enhance the evaporative cooling of the working air, a water mister can be provided to distribute water with the working air. In this example, the boundary layer can be optimized by selecting the spacing between membrane units, e.g., 10 mm.

[0181] In some embodiments, the example shown in FIG. 3A-3C shows a configuration with dual functionality membrane assembly coupled with sensible cooling via evaporative cooling. In said system, the sensible cooling layer (i.e., wetted-porous media or wettable evaporative media) 305 is cooled by evaporation (phase change of water or other liquid) and transfers heat through the porous support structure away from the dry feed air, which, in turn, both dehumidifies and cools the product supply air. FIG. 3C shows that a portion of the

sensibly cooled and dehumidified product air can be redirected into the wet-working air, further reducing the air temperature through sub-wet bulb cooling. The working and product air channels can be arrayed in a range of configurations, including but not limited to parallel, cross, counter, regenerative, multi-stage, and other heat exchange and flow configurations.

[0182] As shown in FIG. 3D, the dehumidification and evaporative cooling system in the above example shown in FIGs. 3A-3C can achieve energy efficient dehumidification and evaporative cooling. This example system can remove water vapor such that both the temperature and humidity ratio (i.e., the moisture content) of the feed air decrease, resulting in a cooler and drier target air. On the other hand, the temperature of the working air decreases and the humidity ratio of the working air increases, resulting a cooler and more wet working air.

[0183] In some embodiments, a non-porous barrier 304 can be thermally conductive and/or thin. For example, non-porous barrier 304 can offer negligible or minimal thermal resistance. As another example, non-porous barrier 304 can offer negligible or minimal boundary or interface thermal resistance with materials on either surface. In some embodiments, non-porous barrier 304 can include its own support structure, for example, non-porous barrier can include a non-permeable layer and a structural layer. In some embodiments, non-porous barrier 304 can be hydrophobic to mitigate water vapor from entering into wetted-porous media (i.e., sensible cooling layer) 305. In some embodiments, wetted-porous media 305 can be hydrophilic in nature. In some embodiments, wetted-porous media 305 can be a heat transfer fluid.

[0184] In some embodiments, the sensible cooling layer can be modified to function as a radiant cooler or a reflective barrier. In some embodiments, the sensible cooling layer can include a porous reflective coating or spectrally selective media (e.g., instead of a wettable evaporative media).

[0185] In some embodiments, the sensible cooling layer can include both a wettable evaporative media and a radiant cooler. In some embodiments, the sensible cooling layer can include both a wettable evaporative media and a spectrally selective media (e.g., a reflective barrier). In some embodiments, a sensible cooling layer can be act as both a wettable evaporative media and spectrally selective media. For example, a hydrophobic porous polyvinylidene fluoride can be used for both evaporative cooling and radiant cooling.

[0186] In some embodiments, the membrane support structure's non-permeable barrier includes a metal, an alloy, or a combination thereof. In some embodiments, the non-permeable barrier can include a polymer.

[0187] In some embodiments, the membrane support structure's non-permeable barrier can have a thermal conductivity in the range of 0.1-500 W/m-K. In some embodiments, the membrane support structure's non-permeable barrier can have a thermal conductivity in the range of 10-500 W/m-K. In some embodiments, the membrane support structure's non-permeable barrier can have a thermal conductivity in the range of 0.5-10 W/m-K. In some embodiments, the membrane support structure's non-permeable barrier can have a thermal conductivity in the range of 0.1-0.5 W/m-K.

[0188] In some embodiments, the geometry and/or chemistry of the porous membrane support structure can be selected to improve the sensible heat transfer (e.g., via thermal conduction) from the membrane to the non-permeable barrier, thereby increasing the cooling rate of the feed air.

[0189] FIGs. 4A-4B show schematics of features of an example membrane unit or mass exchange unit 401. FIG. 4A shows a cross-section and FIG. 4B shows an isometric view. In this example, the membrane unit includes a supported membrane assembly that includes a support structure (e.g., a porous support structure) 403 and a membrane 402 on opposite surfaces of the porous support structure. A membrane unit can include at least a membrane assembly including a support structure and membrane on at least one surface of the support structure, but a membrane unit can also include other components. For example, the membrane unit shown in FIGs. 4A-4B also includes a non-porous boundary or frame 411, a connection to a negative pressure source 410 (e.g., a vacuum inlet), a region of feed air (target air for water vapor removal, indicated by a white arrow), and a region for permeate (water vapor removed from target air, indicated by a black arrow). A membrane unit can include one or more of the features shown in FIGs. 4A-4B. As shown in FIG. 4A, feed air moves through a space adjacent to the surfaces of the membranes 402 and parallel to the surfaces of the membranes (e.g., in a feed plane), and permeate is removed via the porous substrate material. In some embodiments, the membrane unit includes an inlet 410 for application of a vacuum that is in fluid connection with the pores of the porous support structure. In some embodiments, the membrane unit includes an outlet for removal of permeate that is in fluid connection with the pores of the porous support structure.

[0190] FIGs. 5A-5B show schematics of features of an example membrane unit or mass exchange unit 501 including a non-permeable (e.g., non-porous) barrier 504. FIG. 5A shows a cross-section and FIG. 5B shows an isometric view of membrane unit 501. In this example, the membrane unit includes a supported membrane assembly that includes a porous support structure (e.g., a porous support structure) 503, a membrane 502 on one surface of porous support structure 503 and a non-porous barrier 504 on the other surface of support structure 503. A membrane unit can include at least a membrane assembly including a support structure, a membrane on the one surface of the support structure, and a non-porous barrier on the other surface of the support structure, but a membrane unit can also include other components. For example, the membrane unit shown in FIGs. 5A-5B also includes a sensible cooling layer 505 disposed on the surface of non-porous barrier 504 that is not in direct physical contact with porous support structure 503, a non-porous boundary or frame 511, a connection to a negative pressure source 510 (e.g., a vacuum inlet), a region of feed air (target air for water vapor removal, indicated by a white arrow), and a region for permeate (water vapor removed from target air, indicated by a black arrow). A membrane unit can include one or more of the features shown in FIGs. 5A-5B. As shown in FIG. 5A, feed air moves through a space adjacent to the surfaces of the membrane 502 and parallel to the surface of the membrane (e.g., in a feed plane), and permeate is removed via the porous substrate material. As shown in FIG. 5A, feed air moves through a space adjacent to the surfaces of the membrane 502 and parallel to the surfaces of the membrane (e.g., in a feed plane), and permeate is removed via the porous substrate material. Further, wet working air can move through a space adjacent to the surface of the non-permeable barrier 504 and parallel to the surface of the barrier 504 (e.g., in a working air plane) to produce cold working air.

[0191] In some embodiments, FIGs. 5A-5B show a configuration with a dual functionality (e.g., dehumidification and cooling) membrane assembly coupled with sensible cooling. In said system, the sensible cooling layer transfers heat through the porous support structure away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air (or feed air).

[0192] Energy efficient isothermal dehumidification via membrane-based systems disclosed here rely on at least two primary factors: highly permeable and selective water vapor membranes and significant concentration gradients. Therefore, design parameters can

greatly affect the overall performance of these systems, for example, by creating and maintaining concentration gradients within the membranes or within the support structure.

[0193] For example, performance can be affected by membrane design parameters. A membrane's gas permeance (water vapor or otherwise) can be influenced by its chemical composition, which affects the gas solubility and diffusivity. In addition, membrane gas permeance is inversely proportional to membrane thickness, where thinner membranes can transport more gas molecules over a given time period. Since the overall permeance of vapor across the membrane is also related to the concentration differential, significant negative pressure is induced on the backside of the membrane to maximize flux. The use of thin membranes carries inherent risks of failure from physical damage (tearing, scratches, rupture, etc.). However, chemical modification, coupling of a membrane with a stiff porous support structure, and lamination onto a flexible substrate or support layer all present strategies to enhance the mechanical durability and thus feasibility of thin membranes for vacuum membrane dehumidification. In some embodiments, a flexible or rigid substrate or membrane substrate is porous and can include pores on the range of nano-scale to millimeter scale (100 nm to 10 mm).

[0194] In some embodiments, a water selective membrane is water "soluble." In some embodiments, a water selective membrane includes molecular scale (<10nm) pores. Such pores can be the result of the polymer chemistry of the membrane material.

[0195] In some embodiments, chemical modification of regions within a polymeric membrane, either through additional polymerization, cross-linking, crystallization, or additives, present methods to improve the durability these membranes. The ability to control these properties spatially can permit structural reinforcement at points of high stress. The ability to control these properties spatially can also permit targeted (efficient) removal of water vapor across the feed flow, for example by creating a chemistry gradient within a membrane.

[0196] In some embodiments, a well-designed porous core material or support structure can enable the use of thinner membranes, which can result in improved permeance across the membrane and dehumidification of the target air. For example, a support structure can provide mechanical support. In some embodiments, a support structure can also allow the use of more hydrophilic membranes, which tend to be increasingly soft, which can yield higher water vapor permeance. In some embodiments, the support structure includes metallic, ceramic, polymeric, composite/hybrid materials, and combinations thereof.

[0197] In some embodiments, a well-designed porous support structure can enable improved coupling (adhesion, bonding, etc.) between the membrane, porous substrate, support structure, and/or the non-porous boundary.

[0198] In some embodiments, a support structure includes open spaces in the form of pores, channels, or combinations thereof. In some embodiments, a support structure includes pores on the range of micrometer scale to centimeter scale, *e.g.* 100 μm to 1 cm. In some embodiments, a support structure includes channels on the range of micrometer scale to centimeter scale, *e.g.* 100 μm to 1 cm.

[0199] In some embodiments, a support structure includes surface chemistry, *e.g.*, within pores or channels, that can improve vapor transport within the support structure. For example, a support structure can include variations in chemistry, such as chemistry that varies along an axis perpendicular to or parallel to the feed plane, to facilitate removal of water vapor or permeate.

[0200] In some embodiments, a supported membrane assembly includes a porous support structure with interconnected pores that are single-, double-, or triple periodic to enhance vapor flow and structural strength. Single-periodic refers to periodicity in one direction (*e.g.*, x). Double-periodic refers to periodicity in two directions (*e.g.*, x and y). Triple-periodic refers to periodicity in three directions (*e.g.*, x, y, and z).

[0201] In some embodiments, a supported membrane assembly includes a support structure having a surface geometry or topology which disrupts, separates, mixes, or induces other changes to a feed boundary layer to enhance water vapor contact with membrane surface.

[0202] In some embodiments, a well-designed porous core material or support structure can reduce the “concentration polarization” on the permeate side of the membrane. Concentration polarization can occur when water/gas vapor mixes with a stagnant permeated side boundary layer and limits diffusion by reducing the internal vapor concentration gradient, in effect choking the flow of vapor through the membrane. In some embodiments, a reduction in the concentration polarization can result in improved permeance across the membrane and dehumidification of the target air.

[0203] In some embodiments, a supported membrane assembly includes a support structure having a surface geometry or topology which disrupts, separates, mixes, or induces other changes to the permeate boundary layer to reduce water vapor contact with membrane surface.

[0204] In some embodiments, a supported membrane assembly can be encompassed by a non-porous boundary or frame, for example, to provide additional structural support. The non-porous boundary can include metallic, ceramic, polymeric, or composite/hybrid materials. For example, a membrane can be affixed to a frame using chemical, mechanical, or other bonding methods. In some embodiments, the frame can encompass all but one side of the membrane unit.

In some embodiments, the frame can be attached to a single side of the membrane unit, where the remaining edges are a continuous air-tight seal.

[0205] In some embodiments, the chemistry of the membrane, the geometry of the membrane, the location of the membrane, the location of the membrane substrate, the location of the support structure, or a combination thereof can be designed in a way to selectively control the passage of visible light and/or infrared light through the panel assembly. For example, the membrane unit can be designed to allow passage of visible light. For example, the membrane unit can be designed to block passage of infrared light.

[0206] FIGs. 6A-6C show a non-limiting example of a vacuum membrane dehumidification system. FIG. 6A shows a vacuum membrane dehumidification system retrofit to a curtain wall system in an existing building. In the example shown in FIG. 6A, humid exterior air passes through a plurality of membrane units 601 and dry air is delivered to the interior of the building. In this example, fins 612 shade the membrane units from the sun, reducing UV degradation and heat transfer into the building / feed air. FIG. 6B shows a vacuum manifold system for a vacuum membrane dehumidification system. In the example shown in FIG. 6B, a plurality of membrane units 601 are connected to a manifold 614 that is connected to a vacuum pump 613. In this example, the membrane units are arranged parallel to each other and feed air flows through the spaces between membrane units. Alternatively, membrane units can be arranged counter-parallel or perpendicular to each other, for example, in serpentine, zigzag, spiral, and other configurations. FIG. 6C shows an example membrane unit 601 connected to a vacuum manifold 614. In the example shown in FIG. 6C, each membrane unit includes a porous support structure 603, a support layer 606 on either side of the support structure, and a water selective membrane 602 on the external surface of each support layer, and a structural frame 611. In this example, humid exterior air (*e.g.*, feed air) moves within a plane parallel to the plane of the membrane 602. Water vapor is moved across the water selective membrane and through the porous support structure (*e.g.*, as permeate) to a manifold and can be removed via an outlet.

[0207] In some embodiments, a vacuum dehumidification system includes a vacuum system including one or more vacuum pumps, a plurality of pressure sensors or gauges, and a plurality of vacuum gates or valves.

[0208] In some embodiments, a vapor condenser system includes of one or combinations of gas-to-liquid heat exchangers and a chiller with refrigerant and pump.

[0209] In some embodiments, an indirect evaporative cooler and pump includes a water circuit and a water pump.

[0210] A mass exchange unit or membrane assembly can include various support structure and membrane configurations to create a vapor gradient and improve performance. For example, one or both of the support structure and membrane can include spatial variations in chemistry, geometry, or a combination of chemistry and geometry. In some embodiments, a membrane assembly can have a planar or nonplanar configuration. In some embodiments, a membrane assembly can include a porous support structure with spatial variations in pore geometry (*e.g.*, pore geometry that varies along an axis perpendicular to or parallel to the feed plane). In some embodiments the membrane assembly can include a non-porous support structure with continuous channels with a range of channel width, lengths, heights, and wall thickness. In some embodiments, a membrane assembly can include a support structure with spatial variations in chemistry (*e.g.*, chemistry that varies along an axis perpendicular to or parallel to the feed plane). In some embodiments, a membrane assembly can include a porous membrane substrate. In some embodiments, a membrane assembly can include a membrane with spatial variations in membrane chemistry (*e.g.*, membrane chemistry that varies along an axis perpendicular to or parallel to the feed plane). In some embodiments, a membrane assembly can include a membrane with spatial variations in membrane geometry (*e.g.*, pore geometry that varies along an axis perpendicular to or parallel to the feed plane).

[0211] FIGs. 7A-19B, described below, show various illustrative configurations for a mass exchange unit or membrane assembly. In FIGs. 7A-19B, panel A shows a cross-section of a membrane assembly, and panel B shows an isometric view of a membrane assembly. In each of these figures, feed air (target air for water vapor removal) is indicated by a white arrow, and permeate (water vapor removed from target air) is indicated by a black arrow. As shown in these figures, in these examples, feed air flows parallel to the interface between the membrane and the support structure of the membrane assembly, and permeate is removed via the support structure. Although FIGs. 7A-19B show illustrative combinations of membrane,

support structure, non-porous barrier, sensible cooling layer (e.g., wettable evaporative media or spectrally selective media), membrane substrate, and membrane overlay, the combinations are not limited to those shown in FIGs. 7A-19B. For example, although FIGs. 7A-19B show illustrative configurations of the working and product/feed air channels, the working air and product/feed air channels can be arrayed in a range of configurations, including but not limited to parallel, cross, counter, perpendicular, non-orthogonal, radially oriented, regenerative, multi-stage, and other heat exchange and flow configurations.

[0212] FIGs. 7A-7B show features of a supported membrane assembly 701 which includes a planar membrane (e.g., a conformal membrane) 702 and porous support structure 703. In some embodiments, a conformal membrane covers the support structure completely.

[0213] FIGs. 8A-8D show illustrative configuration for a mass exchange unit or membrane assembly including a non-permeable (e.g., non-porous) barrier and a sensible cooling layer (e.g., wettable evaporative media or spectrally selective media).

[0214] In some embodiments, the sensible cooling layer can be a wettable evaporative media. The example shown in FIGs. 8A-8B illustrates features of a supported membrane assembly 801 which includes a planar membrane (e.g., a conformal membrane) 802, porous support structure 803, planar non-porous or non-permeable barrier 804, and sensible cooling layer 805. In the example shown in FIGs. 8A-8B, the sensible cooling layer 805 is a wettable evaporative media. In some embodiments, a conformal membrane covers one surface of the support structure completely, and a non-permeable barrier covers the other surface of the support structure completely. In the example shown in FIGs. 8A-8B, feed air (target air for water vapor removal), permeate (water vapor removed from target air), and wet working air are indicated by white arrow, a black arrow, and a dotted arrow, respectively. In this example, feed air flows parallel to the interface between the membrane and the support structure of the membrane assembly, working air flows parallel to the interface between the non-permeable barrier and the support structure of the membrane assembly, and permeate is removed via the support structure.

[0215] In some embodiments, FIGs. 8A-8B show configuration with dual functionality membrane assembly 801 coupled with sensible cooling via evaporative cooling. In said system, the sensible cooling layer can be cooled by evaporation (phase change of water or other liquid) and transfers heat through the porous support structure away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air.

[0216] In some embodiments, the sensible cooling layer can be a spectrally selective media. FIGs. 8C-8D show a configuration with dual functionality membrane assembly 801 coupled with sensible cooling via radiant sky cooling. In the example shown in FIGs. 8C-8D, the sensible cooling layer 805 is a spectrally selective media (e.g., a reflective barrier). In said system, the sensible cooling layer can be cooled by spectrally selective radiant exchange with the sky and transfers heat through the porous support structure away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air.

[0217] Additional examples of a mass exchange unit or membrane assembly including a non-permeable (e.g., non-porous) barrier can include illustrative examples similar to FIGs. 7A-7B and 9A-19B, as described below, where one membrane (including the membrane overlay and/or membrane substrate layers) is replaced with the non-permeable barrier and sensible cooling layer (e.g., wettable evaporative media or spectrally selective media), and working air, rather than the feed air, is moved on the space adjacent to the non-permeable barrier.

[0218] FIGs. 9A-9B show a supported membrane assembly 901 which includes a nonplanar membrane (e.g., a conformal membrane) 902 and porous support structure 903. The nonplanar membrane can have any geometry. Non-limiting examples of nonplanar geometries include tubular, annular, spiral, sinusoidal, triangular, sawtooth, square, dimpled, curved, and cylindrical geometries.

[0219] FIGs. 10A-10B show a supported membrane assembly 1001 which includes membrane (e.g., a conformal membrane) 1002 and porous support structure 1003 with a range of porous interconnected geometries perpendicular to the feed plane. In this example, the diameter of pores changes along the axis perpendicular to the feed plane, with increased diameters at the center of the porous support structure and smaller diameters closer to the interface with the membrane. However, geometries can vary in any way to provide a gradient perpendicular to the feed plane. Examples of such variations include size, shape, density, aspect ratio of pores, and any combination thereof.

[0220] FIGs. 11A-11B shows a supported membrane assembly 1101 which includes a membrane (e.g., a conformal membrane) 1102 and porous support structure 1103 with a range of porous interconnected geometries parallel to the feed plane. In this example, the diameter of pores changes along the axis parallel to the feed plane, with diameters decreasing in the direction that feed air is moving and increasing in the direction that permeate is removed. However, geometries can vary in any way to provide a gradient perpendicular to

the feed plane. Examples of such variations include size, shape, density, aspect ratio of pores, and any combination thereof.

[0221] FIGs. 12A-12B show a supported membrane assembly 1201 which includes a membrane (*e.g.*, a conformal membrane) 1202 and porous support structure 1203 with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane. In this example, the diameter of pores changes along the axes perpendicular and parallel to the feed plane. However, geometries can vary in any way to provide a gradient perpendicular to the feed plane. Examples of such variations include size, shape, density, aspect ratio of pores, and any combination thereof.

[0222] FIGs. 13A-13B illustrates a supported membrane assembly 1301 which includes a membrane (*e.g.*, a conformal membrane) 1302 and non-porous support structure 1303 with continuous channels that allow movement of permeate instead of a porous material. In this example, the support structure includes channels parallel to the feed plane such that permeate moves through the channels for removal. A support structure with channels can include channels with a range of channel width, lengths, heights, and wall thickness. In some embodiments, channels can have parallel, spiral, zig-zag, branching, or other configurations.

[0223] FIGs. 14A-14B show a supported membrane 1401 assembly which includes a membrane (*e.g.*, a conformal membrane) 1402 and non-porous support structure 1403 with hierarchical continuous channels. A support structure with channels can include hierarchical channels with a range of channel width, lengths and heights in branching or other configurations. In this example, the support structure includes channels parallel to the feed plane and channels perpendicular to the feed plane (*e.g.*, in three different dimensions).

[0224] FIGs. 15A-15B show a supported membrane assembly 1501 which includes a membrane (*e.g.*, a conformal membrane) 1502, a conformal porous membrane substrate 1506 and porous support structure 1503. In this example the membrane substrate 1506 is disposed between the membrane 1502 and the support structure 1503. In some embodiments, a membrane support structure improves membrane durability.

[0225] FIGs. 16A-16B show a membrane unit 1601 further including a membrane overlay 1607 disposed between the membrane 1602 and the feed air flow (*e.g.*, the overlay 1607 is disposed on the outer surface of the membrane 1602). For example, supported membrane assembly 1601 can include a conformal membrane 1602, a conformal membrane overlay 1607 and porous support structure 1603. In some embodiments, the membrane overlay of the membrane unit can include varying surface functionality, for example

chemical functionalization. For example, the surface of the overlay can be functionalized to provide one or more of an anti-fouling, wetting, dirt repelling, antimicrobial, and filtration characteristics. In some embodiments, the overlay can be functionalized to shed bulk fluid without disrupting the molecular transport across the membrane. In some embodiments, the overlay can be disposable or replaceable. In some embodiments, the overlay is not bonded to the membrane. In some embodiments, the overlay can serve as an additional support layer for the membrane.

[0226] FIGs. 17A-17B show a membrane unit 1701 including a membrane support substrate 1706 disposed between the membrane 1702 and the support structure 1703, and a membrane overlay 1707 disposed between the membrane 1702 and the air flow (i.e., membrane overlayer disposed on the outside face of the membrane assembly with a membrane substrate).

[0227] In some embodiments, the overlay is highly porous with pores $>10\ \mu\text{m}$ or $>50\ \mu\text{m}$, so as to not interfere with the vapor diffusion or molecular transport.

[0228] In some embodiments, the membrane overlay can provide additional performance benefits, such as enhanced water capture via micron-scale geometry-induced condensation and coalescence, higher surface area for water absorption, and/or higher hydrophilicity.

[0229] In some embodiments, the membrane overlay can provide additional performance benefits, such as enhanced turbulent mixing and minimization of concentration polarization of non-transmitted gaseous species at the membrane interface, therefore achieving high levels of water vapor permeability.

[0230] In some embodiments, the membrane overlay can provide additional performance benefits, such as prolonged membrane lifetime via a physical barrier to filter particulates. For example, a physical barrier can both prevent membrane fouling or impact rupture and to improve overall product air quality. In some embodiments, such a protective overlay can be replaced in-situ during regular service intervals without interfering with underlying membrane.

[0231] In some embodiments, the membrane overlay can provide additional performance benefits, such as product air purification via inclusion of photocatalytic compounds for UV-activated decomposition of airborne pollutants. Non-limiting examples of photocatalytic compounds include titanium dioxide. In some embodiments, such a functional and protective overlay could be replaced in-situ during regular service intervals without interfering with underlying membrane.

[0232] In some embodiments, the membrane overlay can provide additional performance benefits, such as air purification via inclusion of high surface area particles/molecular structures for the adsorption of gaseous airborne pollutants. Non-limiting examples of high surface area particles/molecular structures include activated carbon, metal organic frameworks, zeolites, and combinations thereof. Non-limiting examples of pollutants include CO₂, volatile organic compounds, unpleasant odors, hazardous vapors, and combinations thereof. In some embodiments, such a functional and protective overlay could be replaced in-situ during regular service intervals without interfering with underlying membrane.

[0233] In some embodiments, the membrane overlay can provide additional performance benefits, such as air purification resulting from germicidal/anti-microbial treatment via inclusion of biocidal compounds in the membrane overlay. Non-limiting examples of biocidal compounds include silver ions, copper ions, silver nanoparticles, copper nanoparticles, or quaternary ammonium compounds, and combinations thereof. In some embodiments, such a functional and protective overlay could be replaced in-situ during regular service intervals without interfering with underlying membrane.

[0234] In some embodiments, the membrane overlay can provide additional performance benefits, using any combination of the above instances.

[0235] FIGs. 18A-18B show a supported membrane assembly 1801 which includes a membrane (*e.g.*, a conformal membrane) with a range of membrane chemistries (1802a, 1802b, 1802c) perpendicular to the feed plane and porous support structure 1803. In this example, the membrane includes three different membrane chemistries arranged perpendicular to the feed plane, for example as a layered membrane with different membrane chemistry in each layer.

[0236] FIGs. 19A-19B show a supported membrane assembly 1901 which includes a membrane (*e.g.*, a conformal membrane) with a range of membrane chemistries (1902a, 1902b, 1902c) parallel to the feed plane and porous support structure 1903. In this example, the membrane includes three different membrane chemistries arranged so that the membrane chemistry changes along the axis that the feed air is moving. For example, the membrane chemistry can include regions of different H₂O/N₂ selectivity, *e.g.*, regions of lower H₂O/N₂ selectivity. In these embodiments, regions of lower H₂O/N₂ selectivity can be placed at the end of the dry air feed and opposite the vacuum inlet. This configuration can increase the amount of dry air molecules entering the said region producing a dry sweep gas that can improve the removal of water/gas vapor on the permeate side of the membrane, resulting in

an improved permeance across the membrane. In this example, the additional dry air can result in dehumidification at higher vacuum pressures and improved pump energy performance.

[0237] In another example, not shown, a supported membrane assembly can include a membrane (*e.g.*, a conformal membrane) with a range of membrane chemistries in a combination of perpendicular and parallel directions to the feed plane and porous support structure.

[0238] FIG. 20 shows a matrix showing various illustrative combinations of membranes and support structures. Row 1 shows various illustrative support structure configurations (as shown in FIGs. 7A-7B, 9A-14B), while Column 1 shows various illustrative membrane configuration (as shown in FIGs. 7A-7B, 15A-15B, 18A-19B). Any support structure configuration in Row 1 can be combined with any membrane configuration in Column 1. Although FIG. 20 shows illustrative combinations, combinations of membrane and support structure configurations are not limited to those shown in FIG. 20.

[0239] For example, as shown in row 2 of FIG. 20, a membrane with a porous membrane substrate (FIGs. 15A-15B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0240] For example, as shown in Row 3 of FIG. 20, a membrane with a range of membrane chemistries perpendicular to the feed plane (FIGs. 18A-18B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous

support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0241] For example, as shown in Row 4 of FIG. 20, a membrane with a range of membrane chemistries parallel to the feed plane (FIGs. 19A-19B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0242] For example, a membrane with a range of membrane chemistries in a combination of perpendicular and parallel directions to the feed plane can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0243] FIG. 21 shows a matrix showing various illustrative combinations of sensible cooling layer, non-permeable barrier, membrane overlay, and combination of a membrane overlay and membrane substrate with different porous support structures. Row 1 shows various illustrative support structure configurations (e.g., corresponding to FIGs. 7A-7B, 9A-14B), while Column 1 shows various illustrative membrane configurations, including a configuration in which one face of the membrane unit includes a non-porous barrier and sensible cooling layer, a configuration including a membrane overlay, and a configuration including a membrane overlay with a membrane substrate (as shown in FIGs. 8A-8B, 16A-17B, 17A-17B). Any support structure configuration in Row 1 can be combined with any membrane configuration in Column 1. In some embodiments, the sensible cooling layer can be an evaporative cooling layer. In some embodiments, the sensible cooling layer can be a

radiant cooling layer. Although FIG. 21 shows illustrative combinations, combinations of sensible cooling layer, membrane overlay and membrane substrate configurations are not limited to those shown in FIG. 21.

[0244] For example, as shown in row 2 of FIG. 21, a membrane configuration in which one face of the membrane unit includes a membrane while the other face includes a non-porous barrier and sensible cooling layer (FIGs. 8A-8B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0245] For example, as shown in row 3 of FIG. 21, a membrane with a membrane overlay (FIGs. 16A-16B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0246] For example, as shown in row 4 of FIG. 21, a membrane with a membrane overlay and supported on a membrane substrate (FIGs. 17A-17B) can be combined with a planar porous support structure (FIGs. 7A-7B), a nonplanar porous support structure (FIGs. 9A-9B), a porous support structure with a range of porous interconnected geometries perpendicular to the feed plane (FIGs. 10A-10B), a porous support structure with a range of porous interconnected geometries parallel to the feed plane (FIGs. 11A-11B), a porous support structure with a range of porous interconnected geometries in a combination of perpendicular and parallel directions to the feed plane (FIGs. 12A-12B), a non-porous support structure

with continuous channels (FIGs. 13A-13B), a non-porous support structure with hierarchical continuous channels (FIGs. 14A-14B), or any combination thereof.

[0247] FIGs. 22A-29D show illustrative non-planar configurations for a mass exchange unit or membrane assembly. Non-limiting non-planar configurations include cylindric, tubular, annular, spiral, spiral-wound, circular, rectangular, and combinations thereof. Non-limiting non-planar configurations include a twisted, bent, transformed, or morphed geometry, or any combination thereof to improve membrane exchange. In FIGs. 22A-29D, panel A shows a cross-section of a membrane assembly, and panel B shows an isometric view of a membrane assembly. In each of these figures, feed air (target air for water vapor removal) is indicated by a white arrow and permeate (water vapor removed from target air) is indicated by a black arrow. Although FIGs. 22A-29D show illustrative combinations of membrane, support structure, non-porous barrier, sensible cooling layer (e.g., wettable evaporative media or spectrally selective media), membrane substrate, and membrane overlay, the combinations are not limited to those shown in FIGs. 22A-29D. Although FIGs. 22A-29D show illustrative configurations of the working and product/feed air channels, the working air and product/feed air channels can be arrayed in a range of configurations, including but not limited to parallel, cross, counter, perpendicular, non-orthogonal, radially oriented, regenerative, multi-stage, and other heat exchange and flow configurations.

[0248] FIGs. 22A-22B show a supported membrane assembly 2201 with a cylindrical configuration that includes a membrane 2202 and a porous support structure 2203. In this example, the support structure is cylindrical, and the membrane is disposed on the outer surface of the cylinder. FIGs. 22C-22D show an example in which the supported membrane assembly 2201 further includes a membrane overlay 2207 disposed on the membrane 2202. In these examples, feed air flows over the membrane on the outer surface of the cylinder and permeate is removed via the cylindrical support structure, for example, along the long axis of the cylinder.

[0249] FIGs. 23A-23B show a supported membrane assembly 2301 with a tubular configuration that includes a membrane 2302 and a porous support structure 2303. In this example, the support structure is tubular, and the membrane is disposed on the inner surface of the tube and a non-permeable (e.g., non-porous) barrier layer 2304 is disposed on the outer surface of tube (i.e., the barrier layer is disposed on outer surface of the porous support structure). FIGs. 23C-23D show an example in which the supported membrane assembly 2301 further includes a membrane overlay 2307 disposed on the inner surface of membrane

2302. In these examples, feed air flows through the tube, over the membrane on the inner surface of the tube, and permeate is removed via the tubular support structure, for example, along the long axis of the tube.

[0250] FIGs. 24A-24B show a “unit cell” with a membrane tube that includes a membrane 2402 and a porous support structure “shell” 2403, for example, in a “shell and tube” configuration of the supported membrane assembly 2401. FIGs. 24C-24D show an example in which the supported membrane assembly 2401 further includes a membrane overlay 2407 disposed on the inner surface of membrane 2302. In some embodiments, the “tube” can have any arbitrary cross-sectional geometry, for example, circle, hexagon, square, or triangle. In this configuration, vacuum can be applied to a volume with a continuous porous support structure with membrane tubes arrayed in periodic unit cell patterns. Non-limiting examples of unit cell patterns include triangular, square, hexagonal, or other unit cell patterns. In some embodiments, a non-porous boundary is assumed to be at the extent of the porous structure as a shell structure. In some embodiments, an inlet is included at the non-porous boundary to apply a vacuum.

[0251] FIGs. 25A-25B show an annular configuration with dual functionality membrane assembly 2501, including a membrane 2502 disposed on the inner surface of the membrane support 2503, coupled with sensible cooling via evaporative cooling. In said system, a sensible cooling layer 2505 (e.g., a wettable evaporative media) is disposed on a non-permeable (e.g., non-porous) barrier 2504 that is disposed on the outside surface of a porous membrane support 2503. In said system, the sensible cooling layer 2505 is cooled by evaporation (phase change of water or other liquid) and transfers heat through the porous support structure 2503 away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air.

[0252] FIGs. 26A-26B show an annular configuration with dual functionality membrane assembly 2601, including a membrane 2602 disposed on the outer surface of the membrane support 2603, coupled with sensible cooling via evaporative cooling. In said system, the sensible cooling layer 2605 is disposed on the inside surface of a non-permeable (e.g., non-porous) barrier 2604 that is disposed on the inside surface of a porous membrane support 2603. In said system, the sensible cooling layer 2605 (e.g., a wettable evaporative media) is cooled by evaporation (phase change of water or other liquid) and transfers heat through the porous support structure 2603 away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air which is supplied on inner surface of the membrane assembly.

In some embodiments, the non-permeable barrier 2604 can seal off the low pressure vacuum environment for efficient dehumidification and prevent moisture from the sensible cooling layer 2605 from entering the low pressure environment.

[0253] FIGs. 27A-27B show an annular configuration with dual functionality membrane assembly 2701, including a membrane 2702 disposed on the inner surface of the membrane support 2703, coupled with sensible cooling via radiant sky cooling. In said system, the sensible cooling layer 2705 (e.g., a spectrally selective media) is disposed on the outside surface of a non-porous barrier 2704 that is disposed on the outside surface of a porous membrane support 2703. In said system, the sensible cooling layer 2705 is cooled by spectrally selective radiant exchange with the sky and transfers heat through the porous support structure 2703 away from the dry feed air, which, in turn, both dehumidifies and cools the target supply air. In said system, the membrane 2702 is disposed on the inner surface of the porous membrane support 2703.

[0254] FIGs. 28A-28B show a supported membrane assembly 2801 with a spiral configuration that includes a membrane 2802 and a porous support structure 2803. In this example, the support structure is a spiral, and the membrane is disposed on the outer surface of the spiral. In this example, feed air flows over the membrane on the outer surface of the spiral and permeate is removed via the spiral support structure, for example, along the long axis of the spiral. FIGs. 28C-28D show an example in which the supported membrane assembly 2801 further includes a membrane overlay 2807 disposed on membrane 2802.

[0255] FIGs. 29A-29B show a supported membrane assembly 2901 with a spiral configuration that includes a membrane 2902 and a porous support structure 2903. In this example, the support structure is a spiral, and the membrane is disposed on the inner surface of the spiral. In this example, feed air flows over the membrane on the inner surface of the spiral and permeate is removed via the spiral support structure, for example, along the long axis of the spiral. FIGs. 29C-29D show an example in which the supported membrane assembly 2901 further includes a membrane overlay 2907 disposed on membrane 2902.

EXAMPLES

[0256] Certain embodiments will now be described in the following non-limiting examples.

[0257] A lab-scale experimental test setup was employed as shown in FIGs. 30A-30E. The vacuum membrane units in this set up included various components shown in FIGs.

30A-30C: a highly porous support material, shown here are 3D printed polymer gyroidal structures with 60% open volume (FIG. 30A); a plastic frame designed to encompass the support matrix with vacuum inlet (FIG. 30B); and a water-selective membrane adhered around the perimeter to both sides of the support frame, membrane pictured measures 150 mm x 150 mm (FIG. 30C). FIG. 30D depicts multiple porous support structures with hierarchical structures of varying porosities and layer thicknesses (related to, for example, FIG. 10A-10B). Individual panels and assemblies of multiple panels were tested in the lab with a custom experimental setup, shown in FIG. 30E with systems diagram overlay.

[0258] The experimental design was configured to allow a plurality of test samples with varying geometries. Generally, the test setup included the following: a ducted housing allowing interchangeable panel “cassettes” (labeled sample), a programmable blower fan (Retrotec 300) controlling the air flow at the inlet of the panel cassette and differential pressure across the cassettes. To control the air-side humidity, a humidity sensor was placed at the cassette inlet. This humidity sensor signaled a solenoid valve with a compressed air supply that was fed into the headspace of a heated water tank with an atomizing mister. The upstream humid air speed was set to 1 m/s for the bulk of experiments, while differential pressure varied depending on configuration. Inlet air-side speed, pressure, relative humidity and temperatures were spot measured and logged using an anemometer (TSI 9535). Inlet and outlet air-side relative humidity and temperature were also measured and logged using stationary sensors (Sensiron SHT31-D). For each test, vacuum pressure is applied to the panel using a dry scroll pump (Edwards nXDS20i) with energy monitoring (Reed R5090). Permeate-side vacuum pressure is measured using a transducer (Edwards ASG2). Water vapor in the permeate-side is collected from the vacuum pump exhaust using a liquid-to-air exchange element connected to a recirculating chiller (VWR 89202-978) with a water-glycol solution at 1 °C and glass coiled condenser. A secondary trap in an insulated ice bath is used in series at the permeate-side exhaust to capture residue water vapor not collected by the chiller and condenser. Collected water is logged using a digital balance or scale (Cole-Parmer Symmetry SP5001). Tests are run for a minimum of four hours. Seal tests were performed to ensure that all panel samples were able to achieve a vacuum pressure below 1 mbar. For determining membrane selectivity, air permeability is approximated by the pressure rise of an evacuated membrane panel no longer under active vacuum.

[0259] Various polymer films were evaluated for water vapor permeance and selectivity to demonstrate the variability in membrane performance. These included, but were not

limited to, cellulose tri-acetate, Ethylene-methyl acrylate copolymer, expanded polytetrafluoroethylene, silicone rubber ('PDMS'), polyolefin composite, and polyethylene-amide co-block polymer ('PEBAX'). Membranes are primarily evaluated on two performance criteria: the water vapor permeance (P , [$\text{mol}/\text{m}^2 \cdot \text{s} \cdot \text{Pa}$]) with resulting mass flux [$\text{g}/\text{s}/\text{m}^2$] and water selectivity (S , [$\text{mol H}_2\text{O} / \text{mol N}_2$]). FIGs. 31A-31C present a snapshot of the membrane material characterization and down-selection process. FIGs. 31A-31C show water permeance over time (FIG. 31A), calculated water vapor flux (FIG. 31B), and selectivity values (FIG. 31C) for a selection of various membranes: cellulose tri-acetate ("CA"), ethylene-methyl acrylate copolymer, polyethylene-amide co-block polymer ("Pebax"), silicone rubber ("PDMS"), polyolefin composite, cellulose acetate (microporous, "CA2"). Experiment parameters were fixed with a 1 m/s air speed, 85% RH, 28°C, and 0.045 m² surface area. A minimum of three samples were tested, error bars represent one standard deviation. The summarized mass flux and water selectivity results for single (double-sided) panel samples with dimensions of 150mm x 150mm (0.045 m²) with a 6 mm porous support material.

[0260] Upon demonstrating high water vapor permeance and selectivity, polyethylene-amide co-block polymer membranes were used as a basis for variations in membrane support configurations. A high mass flux allows for less membrane material to be implemented for the same amount of latent heat removal, whereas a high selectivity minimizes the amount of energy the vacuum pump exerts in air compression.

[0261] Experimental results for the optimization of the mass exchange unit geometry (including support structure geometry), including those shown in FIGs. 32A-32L, indicate that there is a significant relationship between the geometrical configuration of the mass exchange geometry and the mechanical robustness, as well as permeation properties. Panel spacing, support material, and thickness of modules have been adjusted to enable intended geometry. FIGs. 32A-32L show example porous, hollow, and channel support materials including porous 3D printed polylactic acid ('PLA') (FIGs. 32A, 32E, 32I), non-woven fiber (non-porous fiber pads) (FIGs. 32B, 32F, 32J), plastic screen mesh (stacked mesh) (FIGs. 32D, 32G, 32K), and plastic screen mesh with corrugated support (hybrid channels + mesh faces) (FIGs. 32C, 32H, 32L). This series of porous support materials tested for mechanical stability under vacuum pressure and mass flux of polyethylene-amide co-block polymer membrane panels incorporating the various porous support materials. Experiment parameters were fixed with a 1 m/s air speed, 85% RH, 28°C, and 0.045 m² surface area. It is

hypothesized that the support material porosity/density, compressibility, and cavity thickness can decrease the permeate diffusion by limiting the permeate-side vapor concentration gradient. FIG. 32M shows mass flux values for polyethylene-amide co-block polymer panel geometries with the various porous support materials. Based on these results, a fused deposition PLA printed geometry with 60% void space and open cell pore structure was used systematically for lab tests and prototype development.

[0262] A series of experiments, shown in FIGs. 33A-33G, evaluated the relationship between panel thickness, air gap spacing, pressure drop, and humidity removal. The first series of tests evaluated the relationship between mass flux on the permeate-side and pressure loss on the air-side. A cassette of 4 panels (each including a porous support with a membrane on one or both sides) was tested with variable spacing and a fixed air velocity. Individual panels were assembled into arrayed “cassettes” with variable spacing (FIG. 33A) and installed into the ducted air-side flow systems with permeate-side vacuum manifold (FIG. 33B) to evaluate the impact on mass flux and pressure drop across the system (FIG. 33C). Altered panel geometries with varied membrane to membrane spacing were tested (3mm, 6mm, 12mm depths; FIGs. 33D-33F from top to bottom respectively). Experimentally measured mass flux and corresponding water extraction rate and projected coefficient of performance (COP) values for panel geometries with variable depths (FIG. 33G). Data on Y2-axis is calculated for a field site full 1 m² area window prototype. On X-axis, samples labeled “x1” include a membrane on one side, whereas “x2” labeled samples are double-sided (e.g. the membrane to membrane spacing is halved). All geometries use a porous support material with 60% porosity and open cell geometry. Experiment parameters are fixed with a 1 m/s air speed, 85% RH, 28°C, and 0.045 m² surface area.

[0263] The results in FIGs. 33C and 33G show that a panel spacing below 5mm (5mm between panels) incurs a sizable pressure drop without a meaningful increase in mass flux. This result is in line with boundary layer studies and the Nusselt analogy for heat exchange devices, therefore a 5mm panel-to-panel spacing was selected for the geometry specification. The results in FIGs. 33C and 33G also show that there is a significant reduction in mass flux as the unit (frame) thickness is reduced. Meaning cavity thickness can decrease the permeate diffusion by limiting the permeate-side vapor concentration gradient. Optimal cavity thickness for the materials tested in this example is above 6 mm. However, additional structural considerations can be varied to improve performance.

[0264] The vacuum field-tested prototype, shown in FIGs. 34A-34D, included a primary mass exchanger cassette with 60 units within an aluminum framing system. The prototype was tested in a demonstration building with an enormous potential for retrofit, shown in FIG. 34A, and the demonstration units installed next to the conventional window AC, as shown in FIG. 34B. FIG. 34C shows a diagram illustrating the system demonstration, including an aluminum frame secured to the window header and sill and a pump, water tray, and chiller on a cart. FIG. 34D shows a vacuum system installed, demonstrating installation and the transmission of light and fresh air through the system unlike the standard AC used as a baseline.

[0265] The panels of the vacuum field-tested prototype were a composite system with 3D printed PLA support with open cell pore structure, a plastic frame with a single barbed, vacuum port at the bottom, and two 20 μm thick polyethylene-amide co-block polymer membranes taped to the frame, on either side of the PLA support. The active exchange area of the double-sided panel is 0.07 m^2 for a total of 4.14 m^2 across all 60. A vacuum manifold, shown in FIG. 34D, connects all panels to a configurable “pod” at the base of the window wall, which houses the vacuum pump and connections. There is a removable set of axial fans placed on the interior face of the cassette to provide tunable air flow across the exchanger, and that can be removed to test the device under naturally ventilated conditions.

[0266] FIGs. 35A-35C show results for three flow configurations that were tested for 24-hour periods: Fan assisted air flow with a high measured velocities of 3 m/s , or a differential pressure of roughly 4 Pa (i.e., high flow mode); Fan assisted air flow with a low measured velocities of 0.7 to 1.5 m/s , or a differential pressure of roughly 2 Pa (i.e., medium flow mode); and a naturally ventilated air flow with measured velocities of 0.0 to 0.3 m/s (0.7 m/s peak), or a differential pressures in the range of 0.2 Pa (i.e., a low flow mode). FIG. 35A shows absolute indoor humidity as a function of absolute outdoor humidity. FIG. 35A shows that the medium and high flow modes generally do not generate any considerable reduction in the absolute humidity of the indoors (i.e., the product or treated air) relative to the outdoor air in this capacity, while the low flow mode leads to a substantial decrease in the absolute humidity of the indoor air when compared to the outside air. FIGs. 35B and 35C show the decrease in the absolute humidity of the product air relative to the outdoor air, which is a measure of the dehumidification efficiency, as a function of absolute humidity of the outdoor air (FIG. 35B), and pressure difference between the indoor and the outdoor (FIG. 35C), respectively. FIGs. 35B and 35C show that the medium and high flow modes generated

lower dehumidification efficiency ($\Delta AH \leq 0.5$ g of H₂O/kg air, while a high dehumidification was achieved at the low flow mode ($\Delta AH_{\text{Max}} = 3.5$ g of H₂O/kg_{air}). At flow velocity of 0.25 m/s (0.019 m³/s), approx. 0.2 L/h of water vapor was removed from the outdoor air.

[0267] FIGs. 36A-36F show the outdoor and inlet relative humidity and absolute humidity measurements across a 24-hour period for each of the three configurations. FIGs. 36A-36F show 24-hour relative and absolute humidity for fan assisted air flow configuration at 0.7 to 1.5 m/s air velocity (FIGs. 36A, 36D), fan assisted air flow configuration at 3.0 m/s air velocity (FIGs. 36B, 36E), natural ventilation (NV) air flow configuration 0.0 to 0.3 m/s air velocity (FIGs. 36C, 36F).

[0268] For the fan-assisted air flow modes (FIGs. 36A-36B and 36D-36E), the system achieves average relative humidity reductions of 9% (11% peak) and 6% (7% peak) corresponding to a 0.27 and 0.21 g/kg specific humidity reduction for the low and high velocity tests, respectively. This results in an estimated 0.018 g/s to 0.027 g/s and 0.044 g/s water removal rate (mass flux) for the medium and high velocity tests, respectively. For the naturally ventilated air flow (FIGs. 36C, 36F) the system achieves an average relative humidity reduction of 26% (39% peak) corresponding to a 2.15 g/kg. This results in an average estimate of 0.036 g/s water removal rate (mass flux) for the naturally ventilated air flow test.

[0269] Under naturally ventilated operation with a low air flow velocity the inaugural pilot prototype achieved high dehumidification rates, up to a 39% reduction. FIGs. 36A-36F indicate that during the morning and mid-afternoon, when the unit receives direct solar exposure, the system may no longer capture water but instead evaporates off residual water in the panels. Alternate configurations can address whole building solutions to mitigate direct radiant heat gain on the mass exchanger cassette. In the natural ventilation test, the target building became positively pressurized during the daytime. Future retrofit solutions can address opportunities to maintain negative pressure through whole building mechanical or buoyancy driven ventilation strategies. During lab testing, panels were tested under a 1 mbar (0.1kPa) vacuum pressure. Average vacuum pressure measurements during the field study was around 4 +/- 3mbar, potentially reducing the vapor pressure concentration gradient across the panel and therefore reducing the mass flux. The increased pressure is likely due to fabrication errors for the bespoke assembly.

[0270] The physical installation of the retrofit units shows that the water selective vacuum membrane mass exchanger cassette and pod system provides a highly configurable and extensible façade integrated dehumidification system. The optimized panel geometry provides a suitable depth for typical wall construction, roughly 150 mm, while the panel width and height provide the ability to stack or array multiple cassettes to achieve desired wall opening area, comfort levels, and ventilation rates. Further, the pod approach for the remaining systems, specifically vacuum pump and possible condenser unit, require minimum installation setup and have a single connection point to the mass exchanger cassette, the vacuum line. Therefore, embodiments of the pod can be adapted to fit with a casement or other buildout and, within limits, may not need to be placed directly adjacent to the mass exchanger cassette.

[0271] FIGs. 37-39 show a compilation of dehumidification field data collected across three consecutive days (8:00 AM – 8:00 PM).

[0272] The dehumidification unit included a parallel array of 62 individual dehumidification cartridges spaced 5 millimeters apart. Each rectangular cartridge measured 250 x 170 x 5 mm (H x W x D) and was composed of a 20 µm thick co-block polymer membrane (230 x 150 mm) on the exterior surfaces in contact with the flow of outdoor air (“feed side”). The interior surfaces of the membranes (“permeate side”) were faced with a porous non-woven cellulose substrate film. A 3D-printed gyroidal structure with 40% interconnected porosity was used as a stiff, rigid membrane support structure. Each membrane was attached to a rigid, non-porous acrylic frame, which provided a continuous border width of 1 centimeter around the perimeter of the membrane support structure. A singular barbed fitting was affixed to one edge of the cartridge to serve as a vacuum inlet port. This vacuum port is in fluid connection with the pores of the membrane support structure. All of the cartridges were connected to a central vacuum manifold, which was connected to a dry scroll vacuum pump, which established a low-pressure environment on the permeate side of the system.

[0273] For field testing data accumulation, the dehumidification unit was affixed to the interior side of a window opening on the top floor of a retrofitted residential house. The testing was performed in forced convection mode with airflow controlled by four axial DC fans positioned on the interior side of the unit. Treated air was delivered at a mass flow rate of 165 (±60) kilograms/hour. FIG. 37 shows a plot of the absolute humidity of the product (“treated”) air as a function of the absolute humidity of the outdoor air. A downshift in the

absolute humidity of the product air from the $X=Y$ diagonal line (i.e., the line with a slope of 1) demonstrates the degree of dehumidification that increases as the absolute humidity of the outdoor air increases (i.e., a higher moisture removal achieved in conditions of higher absolute humidity). For a product air velocity of approximately 0.75 m/s, the removed moisture corresponded to suppression of wet-bulb temperature by 1-2 °C. FIG. 38 shows a plot of the decrease in the absolute humidity of the air caused by the dehumidification unit (i.e., degree of dehumidification of the dehumidification unit) as a function of the absolute humidity of the outdoor air. The degree of dehumidification is found to generally increase with an increasing absolute humidity of the outdoor air. FIG. 39 shows a plot of the difference in the absolute humidity of the product and the indoor air over time during the three testing days.

[0274] It will be appreciated that while one or more particular materials or steps have been shown and described for purposes of explanation, the materials or steps may be varied in certain respects, or materials or steps may be combined, while still obtaining the desired outcome. Additionally, modifications to the disclosed embodiment and the invention as claimed are possible and within the scope of this disclosed invention.

CLAIMS

1. A membrane unit comprising
a support structure comprising open space within the support structure for removal of water vapor; and
at least one membrane disposed on at least one surface of the support structure, wherein the membrane is water permeable and water selective,
wherein the membrane unit is configured such that when a vacuum is applied to the open space of the support structure, water vapor is drawn across the membrane and through the support structure along an axis parallel to an interface between the support structure and the membrane.
2. The membrane unit of claim 1, wherein the open space comprises pores within the support structure.
3. The membrane unit of claim 2, wherein the geometry of the pores varies spatially.
4. The membrane unit of any of claims 2-3, wherein the geometry of the pores varies in an axis parallel to the interface between the support structure and the membrane.
5. The membrane unit of any of claims 2-4, wherein the geometry of the pores varies in an axis perpendicular to the interface between the support structure and the membrane.
6. The membrane unit of any of claims 1-5, wherein the open space comprises channels within the support structure.
7. The membrane unit of claim 6, wherein the geometry of the channels varies spatially.
8. The membrane unit of any of claims 6-7, wherein the geometry of the channels varies in an axis parallel to the interface between the support structure and the membrane.
9. The membrane unit of any of claims 6-8, wherein the geometry of the channels varies in an axis perpendicular to the interface between the support structure and the membrane.
10. The membrane unit of any of claims 1-9, wherein the chemistry of the support structure varies spatially.
11. The membrane unit of any of claims 1-10, wherein the chemistry of the support structure varies in an axis parallel to the interface between the support structure and the membrane.
12. The membrane unit of any of claims 1-11, wherein the chemistry of the support structure varies in an axis perpendicular to the interface between the support structure and the membrane.

13. The membrane unit of any of claims 1-12, wherein the geometry of the membrane varies spatially.
14. The membrane unit of any of claims 1-13, wherein the geometry of the membrane varies in an axis parallel to the interface between the support structure and the membrane.
15. The membrane unit of any of claims 1-14, wherein the geometry of the membrane varies in an axis perpendicular to the interface between the support structure and the membrane.
16. The membrane unit of any of claims 1-15, wherein the chemistry of the membrane varies spatially.
17. The membrane unit of any of claims 1-16, wherein the chemistry of the membrane varies in an axis parallel to the interface between the support structure and the membrane.
18. The membrane unit of any of claims 1-17, wherein the chemistry of the membrane varies in an axis perpendicular to the interface between the support structure and the membrane.
19. The membrane unit of any of claims 1-18, wherein the membrane unit has a planar geometry.
20. The membrane unit of any of claims 1-19, wherein the membrane unit has a non-planar geometry.
21. The membrane unit of any of claims 1-20, wherein the membrane unit has a water vapor permeability of at least $0.01 \text{ g H}_2\text{O}/\text{m}^2/\text{s}$.
22. The membrane unit of any of claims 1-21, wherein the membrane unit has a water vapor selectivity $\text{H}_2\text{O}/\text{N}_2$ of at least 1000 $\text{H}_2\text{O}/\text{N}_2$.
23. The membrane unit of any of claims 1-22, wherein the membrane comprises pores with diameters of less than about 10 nm.
24. The membrane unit of any of claims 1-23, wherein the support structure comprises pores with diameters of about $100 \text{ }\mu\text{m}$ to about 1 cm.
25. The membrane unit of any of claims 1-24, further comprising a membrane support substrate disposed between the membrane and the support structure.
26. The membrane unit of claim 25, wherein the membrane support substrate comprises pores with diameters of about 100 nm to about 10 mm.
27. The membrane unit of any of claims 1-26, further comprising an inlet in fluid communication with the open space of the support structure for application of a vacuum.

28. The membrane unit of any of claims 1-27, further comprising an outlet in fluid communication with the open space of the support structure for removal of water vapor.
29. The membrane unit of any of claims 1-28, further comprising a non-porous frame.
30. The membrane unit of any of claims 1-29, wherein the membrane unit allows passage of visible light.
31. The membrane unit of any of claims 1-30, wherein the membrane unit blocks passage of infrared light.
32. The membrane unit of any of claims 1-31, further comprising a membrane overlay disposed on the membrane.
33. The membrane unit of claim 32, wherein the membrane overlay comprises pores.
34. The membrane unit of claim 32, wherein the membrane overlay comprises pores with diameter greater than 10 μm .
35. The membrane unit of any of claims 32-34, wherein the membrane overlay is chemically functionalized.
36. The membrane unit of any of claims 32-35, wherein the membrane overlay has one or more of anti-fouling, dirt repelling, wetting, or antimicrobial characteristics.
37. The membrane unit of any of claims 32-36, wherein the membrane overlay comprises a photocatalytic compound.
38. The membrane unit of claim 37, wherein the photocatalytic compound includes titanium dioxide.
39. The membrane unit of any of claims 32-38, wherein the membrane overlay comprises at least one of high surface area particles or high molecular structures.
40. The membrane unit of claim 39, wherein the at least one of high surface area particles or high molecular structures includes activated carbon, metal organic frameworks, zeolites, or a combination thereof.
41. The membrane unit of any of claims 32-40, wherein the membrane overlay comprises a biocidal compound.
42. The membrane unit claim 41, wherein the biocidal compound includes silver ions, copper ions, silver nanoparticles, copper nanoparticles, quaternary ammonium compounds, or a combination thereof.
43. The membrane unit of any of claims 32-42, wherein the membrane overlay causes a turbulent mixing or reduces a concentration polarization of a non-water gas species at an interface of the membrane.

44. The membrane unit of any of claims 1-43, further comprising at least one non-permeable barrier disposed on at least another surface of the support structure.
45. The membrane unit of claim 44, further comprising a sensible cooling layer disposed on a surface of the non-permeable barrier.
46. The membrane unit of any of claims 44-45, wherein the non-permeable barrier is non-permeable to water vapor.
47. The membrane unit of any of claims 44-46, wherein the non-permeable barrier is non-permeable to gas molecules.
48. The membrane unit of any of claims 44-47, wherein the non-permeable barrier is non-porous.
49. The membrane unit of any of claims 44-48, wherein the non-permeable barrier comprises a structural support layer.
50. The membrane unit of any of claims 44-49, wherein the non-permeable barrier comprises a metal, an alloy, or a combination thereof.
51. The membrane unit of any of claims 44-50, wherein the non-permeable barrier comprises a polymer.
52. The membrane unit of any of claims 44-51, wherein the non-permeable barrier has a thermal conductivity in the range of 0.1-0.5 W/m-K.
53. The membrane unit of any of claims 44-51, wherein the non-permeable barrier has a thermal conductivity in the range of 0.5-10 W/m-K.
54. The membrane unit of any of claims 44-51, wherein the non-permeable barrier has a thermal conductivity in the range of 10-500 W/m-K.
55. The membrane unit of any of claims 44-54, wherein the non-permeable barrier is hydrophobic.
56. The membrane unit of any of claims 44-55, wherein the sensible cooling layer comprises a wettable evaporative media.
57. The membrane unit of any of claims 44-56, wherein the sensible cooling layer comprises a radiant cooler, a reflective barrier, or combination thereof.
58. The membrane unit of any of claims 44-57, wherein the sensible cooling layer comprises pores.
59. The membrane unit of any of claims 44-58, wherein the sensible cooling layer is hydrophilic.

60. The membrane unit of any of claims 44-59, wherein the wettable evaporative media comprises a heat transfer fluid.
61. A system comprising
one or more membrane units of any of claims 1-60;
a vacuum pump configured to apply a vacuum to the open spaces of the support structure of the one or more membrane units; and
one or more inlets configured to deliver humid feed air to each membrane of the one or more membrane units along an axis parallel to an interface between the support structure and the membrane.
62. The system of claim 61, comprising a plurality of membrane units.
63. The system of any of claims 61-62, further comprising a vacuum manifold system.
64. The system of any of claims 61-63, further comprising a vacuum reservoir.
65. The system of any of claims 61-64, further comprising a plurality of vacuum pumps.
66. The system of any of claims 61-65, further comprising a gas-to-liquid heat exchanger.
67. The system of any of claims 61-66, further comprising a water circuit.
68. The system of any of claims 61-67, further comprising a water pump.
69. The system of any of claims 61-68, further comprising a plurality of vacuum gates or valves.
70. The system of any of claims 61-69, further comprising a vapor compressor.
71. The system of any of claims 62-70, wherein the plurality of membrane units are arranged parallel to each other.
72. The system of any of claims 62-71, wherein at least one membrane unit is arranged perpendicular to another membrane unit.
73. The system of any of claims 62-72, wherein at least one membrane unit is arranged counter-parallel to another membrane unit.
74. The system of any of claims 62-73, wherein the inlets are configured to deliver humid feed air to one or more spaces between the plurality of membrane units.
75. The system of any of claims 62-74, wherein at least one membrane unit comprises at least one non-permeable barrier disposed on at least another surface of the support structure of the at least one membrane unit.
76. The system of claim 75, further comprising one or more first inlets configured to deliver working air adjacent to a surface of each non-permeable barrier of the one or more

membrane units along an axis parallel to an interface between the support structure and the non-permeable barrier.

77. The system of claim 76, wherein the working air comprises dehumidified feed air.

78. The system of any of claims 76-77, further comprising a water mister for distributing water to the working air.

79. The system of any of claims 76-78, wherein the first inlets are configured to deliver working air to one or more spaces between the plurality of membrane units.