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(54) Title: HYBRIDIZATION OF HUMIDIFICATION-DEHUMIDIFICATION AND PRESSURE-RETARDED OSMOSIS

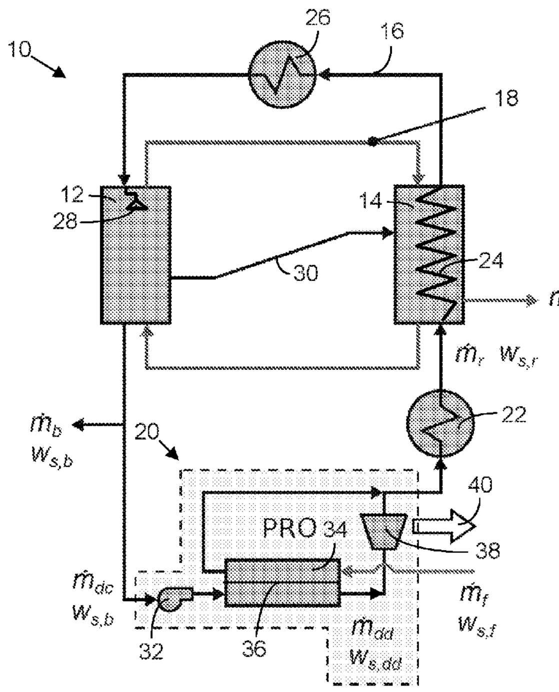

FIG. 2

(57) Abstract: A carrier gas and a combined feed liquid are directed through a humidifier, where water vaporizes from the combined feed liquid into the carrier gas, and through a dehumidifier, where the combined feed liquid cools the carrier gas to condense water from the carrier gas. At least a portion of the concentrated brine stream from the humidifier is directed through a pressure-retarded osmosis unit, while an initial feed solution is directed, in counter-flow, through the osmosis unit. Water from the initial feed solution flows through a membrane in the osmosis chamber into the concentrated brine stream to dilute and increase the volumetric flow rate of the brine stream. The diluted brine stream is extracted from the osmosis chamber and depressurized to produce power, while the concentrated initial feed solution is combined with the depressurized, diluted brine stream to form the combined feed liquid.

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HYBRIDIZATION OF HUMIDIFICATION-DEHUMIDIFICATION AND PRESSURE-RETARDED OSMOSIS

GOVERNMENT SUPPORT

This invention was made with government support under Grant No. 1122374 awarded by the National Science Foundation. The U.S. Government has certain rights in the invention.

BACKGROUND

Humidification-dehumidification (HDH), which is shown schematically in FIG. 1, is a desalination process that uses air as a carrier gas to evaporate water from a saline feed stream. This HDH system 10 includes a humidifier 12 and a dehumidifier 14. In the humidifier 12, a warm liquid feed humidifies a cool, dry carrier-gas (*e.g.*, air) stream in counterflow. The warm, moist carrier-gas stream exits the humidifier and is cooled and dehumidified in the dehumidifier 14, producing a pure water condensate. A liquid-feed conduit 16 circulates the liquid feed through the system, while a carrier-gas conduit 18 circulates the carrier-gas stream through the system.

The cooled carrier gas is either recirculated in a closed loop (closed-air cycle) via conduit 18 or exhausted to the surroundings (in an open-air cycle). HDH can be particularly advantageous (*e.g.*, in comparison with reverse osmosis) for small-scale applications, for high-salinity feeds, and where the feed liquid presents a high scaling potential. HDH systems are further described in US Patent No. 8,292,272 B2; US Patent No. 8,252,092 B2; and US Patent No. 8,647,477 B2.

In pressure-retarded osmosis (PRO), a concentrated (higher-salinity) draw stream and a lower-salinity feed stream are separated by a semi-permeable membrane in counterflow. The semi-permeable membrane selectively admits water but rejects dissolved salts. The difference in osmotic pressure on either side of the membrane causes a flow of pure water from the feed stream into the pre-pressurized draw, thereby increasing the volumetric flow rate of the pressurized draw stream, which can be depressurized in a turbine to produce electrical work. Apparatus and methods for pressure-retarded osmosis are described in 3,906,250 (S. Loeb, Univ. Ben

Gurion). An apparatus referred to as a salinity gradient power unit (SGPU) is described in US Patent No. 8,695,343 B2 (N. Moe, General Electric Co.).

In brine-recirculation HDH (HDH-BR), which is also known as a "closed-water" cycle, a portion of the concentrated brine from the humidifier is recirculated, cooled, and mixed with the feed. This technique, which can be important in brine concentration applications, is used to achieve higher recovery ratios, which are calculated as $RR = \dot{m}_p / \dot{m}_f$, than are obtainable in a single-pass, or open-water HDH arrangement. As the brine and feed streams are mixed, however, exergy is destroyed.

SUMMARY

Apparatus and methods for hybridized humidification-dehumidification, pressure-retarded osmosis are described herein, where various embodiments of the apparatus and methods may include some or all of the elements, features and steps described below.

A hybrid of humidification-dehumidification (HDH) desalination and pressure-retarded osmosis can be used to produce clean water and power in brine concentration applications. In brine concentration applications, HDH is generally configured in a manner that recirculates a portion of the brine produced in a single evaporative pass so that greater recoveries of product (fresh) water can be achieved from the feed stream. When a portion of this high-salinity brine (*e.g.*, with 26% NaCl and/or other salt--*i.e.*, 260 grams of salt per kilogram of solution) is mixed with incoming feed, large irreversibilities are generated. The exergy destroyed in this mixing process can be instead recovered in a pressure-retarded osmosis system, producing electrical power, which could be used to drive auxiliary equipment and eliminate the need for onsite power generation in off-grid areas.

A method for hybridized humidification-dehumidification and pressure-retarded osmosis includes: directing a flow of a carrier gas through a humidifier; directing the flow the carrier gas from the humidifier through a dehumidifier; directing a flow of a combined feed liquid through the humidifier, where water vaporizes from the combined feed liquid into the carrier gas; directing the flow of the combined feed liquid from the humidifier through the dehumidifier, wherein the combined feed liquid cools the carrier gas to condense water from the carrier gas; extracting a concentrated brine stream from the humidifier, wherein the concentrated brine stream is a remnant of the combined feed liquid after water is vaporized from the combined feed liquid in the humidifier; directing at least a portion of the concentrated brine stream through an osmosis chamber of a pressure-retarded osmosis unit on a first side of a membrane; directing an initial feed solution through the osmosis chamber on a second side of the membrane in counterflow to the concentrated brine stream, wherein water from the initial feed solution flows through the membrane into the concentrated brine stream to dilute and increase the volumetric flow of the brine stream; extracting the diluted brine stream from the pressure-retarded osmosis unit and depressurizing the diluted brine stream to produce power; and extracting the initial feed solution from the pressure-retarded osmosis unit and combining the depressurized, diluted brine stream with the initial feed solution to form the combined feed liquid.

The combined feed liquid and the carrier gas can be circulated with pumps, and the pumps can be powered with the power produced by depressurizing the diluted brine stream. In additional embodiments, a light, a computer for controlling the operation of the humidifier and dehumidifier, and pumps that circulate the feed liquid, brine and the carrier gas can be powered with the power produced by depressurizing the brine stream.

In particular embodiments, the initial feed solution comprises at least 1% or at least 10% by mass dissolved solute. For example, the initial feed solution can include flowback or produced water from production of oil and/or gas or can include sea water.

In additional embodiments, the combined feed liquid is heated as it is passed from the dehumidifier to the humidifier.

In yet more embodiments, heat from the combined feed liquid is extracted before the feed liquid passes through the dehumidifier.

Further still, the concentrated brine stream can be pre-pressurized by a pump before entering the osmosis chamber.

A hybrid humidification-dehumidification and pressure-retarded osmosis system includes: a humidifier; a dehumidifier; gas-flow conduits configured to circulate a carrier gas through the humidifier and through the dehumidifier; liquid-flow conduits configured to circulate a combined feed liquid through the dehumidifier and through the humidifier; and a pressure-retarded osmosis unit. The pressure-retarded osmosis unit includes: an osmosis chamber; a semi-permeable membrane, wherein the pressure-retarded osmosis unit is coupled with one of the liquid-flow conduits to feed concentrated brine stream from the humidifier through the osmosis chamber on a first side of the semi-permeable membrane and is coupled with an initial-feed-solution source to pass initial feed solution from the initial-feed-solution source through the osmosis chamber on a second side of the semi-permeable membrane; and a turbine and generator coupled with an outlet from the osmosis chamber on the second side of the semi-permeable membrane. The system further includes a junction configured to combine flow of the brine flow from the turbine with feed liquid from an outlet from the first side of the semi-permeable membrane, wherein one of the liquid-flow conduits provides fluid communication between the junction and the humidifier.

In particular embodiments, the system further includes pumps positioned and configured to pump fluids through the gas-flow conduits and through the liquid-flow conduits, wherein the pumps are configured to receive power from the turbine and generator.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of a traditional humidification-dehumidification (HDH) system that uses a carrier gas to evaporate water from a saline feed stream.

FIG. 2 is a schematic illustration of a hybrid humidification-dehumidification and pressure-retarded osmosis (HDH-PRO hybrid) system.

FIG. 3 is a plot of mass ratio (MR) versus recovery ratio (RR) for HDH-PRO.

FIG. 4 is a plot of maximum work versus feed salinity for HDH-PRO.

In the accompanying drawings, like reference characters refer to the same or similar parts throughout the different views; and apostrophes are used to differentiate multiple instances of the same or similar items sharing the same reference numeral. The drawings are not necessarily to scale; instead, emphasis is placed upon illustrating particular principles in the exemplifications discussed below.

DETAILED DESCRIPTION

The foregoing and other features and advantages of various aspects of the invention(s) will be apparent from the following, more-particular description of various concepts and specific embodiments within the broader bounds of the invention(s). Various aspects of the subject matter introduced above and discussed in greater detail below may be implemented in any of numerous ways, as the subject matter is not limited to any particular manner of implementation. Examples of specific implementations and applications are provided primarily for illustrative purposes.

Unless otherwise herein defined, used or characterized, terms that are used herein (including technical and scientific terms) are to be interpreted as having a meaning that is consistent with their accepted meaning in the context of the relevant art and are not to be interpreted in an idealized or overly formal sense unless expressly so defined herein. For example, if a particular composition is referenced, the composition may be substantially, though not perfectly pure, as practical and imperfect realities may apply; *e.g.*, the potential presence of at least trace impurities (*e.g.*, at less than 1 or 2%) can be understood as being within the scope of the description; likewise, if a particular shape is referenced, the shape is intended to include imperfect variations from ideal shapes, *e.g.*, due to manufacturing tolerances. Percentages or concentrations expressed herein can represent either by weight or by volume. Processes, procedures and phenomena described below can occur at ambient pressure (*e.g.*, about 50-120 kPa—for example, about 90-110 kPa) and temperature (*e.g.*, -20 to 50°C—for example, about 10-35°C) unless otherwise specified.

Although the terms, first, second, third, *etc.*, may be used herein to describe various elements, these elements are not to be limited by these terms. These terms are simply used to distinguish one element from another. Thus, a first element, discussed below, could be termed a second element without departing from the teachings of the exemplary embodiments.

Spatially relative terms, such as “above,” “below,” “left,” “right,” “in front,” “behind,” and the like, may be used herein for ease of description to describe the relationship of one element to another element, as illustrated in the figures. It will be understood that the spatially relative terms, as well as the illustrated configurations, are intended to encompass different orientations of the apparatus in use or operation in addition to the orientations described herein and depicted in the figures. For example, if the apparatus in the figures is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the exemplary term, “above,” may encompass both an orientation of above and below. The apparatus may be otherwise oriented (*e.g.*, rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

Further still, in this disclosure, when an element is referred to as being “on,” “connected to,” “coupled to,” “in contact with,” *etc.*, another element, it may be directly on, connected to, coupled to, or in contact with the other element or intervening elements may be present unless otherwise specified.

The terminology used herein is for the purpose of describing particular embodiments and is not intended to be limiting of exemplary embodiments. As used herein, singular forms, such as “a” and “an,” are intended to include the plural forms as well, unless the context indicates otherwise. Additionally, the terms, “includes,” “including,” “comprises” and “comprising,” specify the presence of the stated elements or steps but do not preclude the presence or addition of one or more other elements or steps.

Additionally, the various components identified herein can be provided in an assembled and finished form; or some or all of the components can be packaged together and marketed as a kit with instructions (*e.g.*, in written, video or audio form) for assembly and/or modification by a customer to produce a finished product.

The humidification-dehumidification, pressure-retarded osmosis (HDH-PRO) hybrid system shown schematically in FIG. 2 recovers the irreversibility lost in the mixing process and generates a useful electrical work output 40. The top half of the apparatus in FIG. 2 is the HDH system 10, which includes a carrier-gas loop 18 (shown as the inner loop) for flow of a carrier gas (*e.g.*, air) through the humidifier 12, where it picks up water vapor from a combined feed liquid, and through the condenser (dehumidifier) 14, where the water vapor is condensed to produce pure water, before being directed back through the humidifier 12 again. In other embodiments, the carrier-gas loop 18 can be open-ended; in an open-air system, air from the surroundings can be drawn into the humidifier 12 and exhausted from the bottom of the dehumidifier 14 without being recirculated. The humidifier 12 and dehumidifier 14 are substantially thermally isolated, except for heat transfer via the circulating carrier gas and combined feed liquid (*e.g.*, heat is not transferred between the humidifier 12 and the dehumidifier 14 via a shared heat-transfer wall in this HDH system 10).

Meanwhile, an initial feed solution (*e.g.*, with more than 1% by mass dissolved solute—for example, sea water with 3-4% by mass dissolved salt) is mixed with recirculated brine after the streams are passed through a pressure-retarded osmosis (PRO) unit 20 and combined to produce a combined feed liquid stream ($\dot{m}_r$). In other embodiments the initial feed solution can be flowback or produced water from production of oil and/or gas. In a particular example, the initial feed solution can be produced water with 10-25% dissolved solute by mass.

Next, heat is removed, *e.g.*, by a heat exchanger 22, from the combined feed liquid; and the combined feed liquid is then passed through a conduit 24 in the dehumidifier 14 to cool the humidified carrier gas therein and thereby produce an output flow of fresh water condensate ($\dot{m}_p$), wherein the fresh water concentrate can have no more than 1,000 mg per liter of solute dissolved therein. After exiting the dehumidifier 14 (in the outer loop 16) and supplied with heat (*e.g.*, from a heat exchanger or heater 26), the combined feed liquid is then directed into the humidifier 12, where it can be sprayed from a sprayer 28 to produce fine droplets from which water can be evaporated into the counter-current carrier gas.

Alternatively, the humidifier 12 can take another form, such as a bubble-column humidifier, as described in US 2014/0367871 A1. As shown, one or more intermediate exchange conduits 30 can transfer the feed liquid/brine and/or carrier gas between intermediate stages of the humidifier 12 and dehumidifier 14.

A concentrated brine stream $(\dot{m}_b)$ is discharged from the bottom of the humidifier 12. A first part of the concentrated brine stream is removed from the system; and a second part of the concentrated brine stream, referred to as the recirculated brine stream $(\dot{m}_{dc})$ with a mass fraction of salts (salinity), w, is pre-pressurized by a pump 32 and then fed through the osmosis chamber of a pressure-retarded-osmosis (PRO) unit 20, where it serves as the draw and where it is diluted and pressurized by the initial feed solution stream $(\dot{m}_f)$. The osmosis chamber 34 includes a semi-permeable membrane 36 that separates the draw (recirculated brine) stream from the initial feed solution stream and through which water passes from the initial feed solution stream to the draw stream. The semi-permeable membrane 36 can be formed of a polyamide and can be thinner than (due to an absence of high pressures), though otherwise similar to, membranes used in reverse-osmosis (RO) systems. The diluted draw stream $(\dot{m}_{dd})$ is then depressurized in a turbine 38 (coupled with an electrical generator) that produces power. The depressurized, diluted draw stream is then mixed with the concentrated feed liquid to form a combined feed liquid and fed to the humidification-dehumidification system 10. In an ideal case, both the concentrated feed liquid and the diluted draw are at the same salinity.

Pressure-retarded osmosis has been investigated in hybrid configurations with seawater desalination systems but found to be of limited use [see L. D. Banchik and J. H. Lienhard V, “Thermodynamic analysis of a reverse osmosis desalination system using forward osmosis for energy recovery," ASME 2012 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers, (2012) and W. Akram, M. H. Sharqawy, and J. H. Lienhard V, “Energy utilization of brine from an MSF desalination plant by pressure retarded osmosis," The International Desalination Association World Congress on Desalination and Water

Reuse 2013, Tianjin, China (2013)]. These approaches did not produce a significant amount of power, even at the physical (thermodynamic) limit.

The approach described herein, however, can produce a meaningful amount of power and substantially more power (particularly with highly saline solutions) than the above approaches. First, the amount of fresh water produced per unit feed (the recovery ratio) can be relatively low in single-pass HDH (compared with other systems), so large masses of concentrate are recirculated (in closed water HDH, or HDH-BR) to concentrate the produced water by a meaningful amount. Concentrating the produced water feed by a significant amount is critical in brine concentration applications, where the goal is reducing the volume of waste, rather than producing fresh water (as in, *e.g.*, drinking water desalination). PRO operates more effectively in this context--when large masses of concentrate are mixed with relatively small amounts of a more diluted stream. Second, large differences in salt concentration between the two streams fed through the PRO chamber produce more power when mixed in PRO; in particular, when a highly saline feed solution (*e.g.*, highly saline produced water with a dissolved salt concentration of 10-25% by weight) is used in a HDH-PRO system, as described herein, the PRO unit can produce a significant amount of power, as the inventors have recognized that the same salinity difference at a higher absolute salt concentration produces more power because of nonlinearities in the osmotic pressure vs. salinity curve.

Generally, pressure-retarded osmosis is most effective (*i.e.*, it produces the most power per unit of feed) when the draw salinity is high (*e.g.*, from 8% to 26%) both relative to that of the feed liquid (particularly with low-salinity, fresh-water feed liquid) and in absolute terms, where the slope of the osmotic pressure versus salinity curve is higher. Such high salinity can be achieved, *e.g.*, in a zero- or reduced-liquid discharge application, such as in an ecologically sensitive region where waste liquid is not readily discharged back into the environment. Furthermore, with pressure-retarded osmosis before the heat rejection step, the osmotic pressure of the recirculated brine stream will be higher than at room temperature, which increases the possible power output and can reduce the size of the heat exchanger required in the heat rejection step. In brine concentration by humidification-dehumidification, the absolute value of salinity is high; the difference between the salinity of the recirculated brine stream and the salinity of the initial feed solution is high; and the recirculated brine stream is warm. This combination means that the pressure-retarded osmosis system is operating over one of its most effective domains.

Process Analysis

Pressure-retarded osmosis produces the greatest amount of work 40 when mass ratios ($MR = \dot{m}_{dc} / \dot{m}_f$) are high ($\gtrsim$ 4). The value of the mass ratio, *MR*, is dictated by the recovery ratio in a single pass of the humidification-dehumidification system 10 ($SPR = \dot{m}_p / \dot{m}_r$) and by the recovery ratio of the entire system, *RR*. From a salt balance on the shaded pressure-retarded osmosis control volume in FIG. 2, the mass ratio, *MR,* can be expressed as follows:

$$MR = \frac{RR - SPR}{SPR}, \quad (1)$$

which is plotted in FIG. 3 for *SPR* = 0.05, 0.075, and 0.1. Thus, we see that the pressure-retarded osmosis system 20 performs best (with *MR* > 4) when the humidification-dehumidification system 10 is operating above 25–50% recovery, depending on the single-pass mass ratio. These values are typical recoveries for brine concentration, indicating that the hybridization is well conceived.

The maximum power is obtained from a pressure-retarded osmosis system 20 when the system size is large and the mass ratio, *MR*, is high. From L. D. Banchik, M. H. Sharqawy, and J. H. Lienhard V, "Limits of power production due to finite membrane area in pressure retarded osmosis," 468 Journal of Membrane Science 81-89 (2014), the maximum work ($\dot{W}$) per unit feed ($\dot{m}_f$) can be expressed as follows:

$$\frac{\dot{W}}{\dot{m}_f} = \frac{\eta \Delta\pi_{\max}}{\rho_{dd}} (\theta_d - 2\sqrt{\theta_d \theta_f} + \theta_f), \quad (2)$$

where

$$\pi_{\max} = \pi_{dc} - \pi_f, \quad (3)$$

$$\theta_d = \frac{\pi_{dc}}{\Delta\pi_{\max}}, \text{ and} \quad (4)$$

$$\theta_f = \frac{\pi_f}{\Delta\pi_{\max}}. \quad (5)$$

In the above equations, π denotes osmotic pressure; ρ_{dd} is the density of the dilute draw; and η is the combined efficiency of the turbine and generator.

As work is usually normalized per unit product in a desalination system and to benchmark this power production against work requirements for desalination systems, $\dot{W}/\dot{m}_p = \dot{W}/\dot{m}_f(1/RR)$ is plotted in FIG. 4. For a typical brine-concentration application, such as shale-gas-produced water with a feed salinity of 15%, and a 25°C brine stream, a maximum energy of 2.66 kWh/m^3 can be produced with the pressure-retarded osmosis hybridization described herein (this value of energy increases by about 8% per 10°C increase in brine-stream temperature). For a typical, small-scale installation of 1,000 m^3 of product water per day, this equates to about 110 kW, or about the output of a large residential diesel generator. The total electrical consumption of humidification-dehumidification is reported to be about 0.45 kWh/m^3 [*see* G. P. Narayan, M. St. John, S. M. Zubair, and J. H. Lienhard V, "Thermal design of the humidification-dehumidification desalination system: an experimental investigation," 58 International Journal of Heat and Mass Transfer 740-748 (2013)], indicating that even capturing 17% of the maximum power from the pressure-retarded osmosis unit 20 would be sufficient to power the humidification-dehumidification auxiliaries and make the system completely grid independent.

In describing embodiments of the invention, specific terminology is used for the sake of clarity. For the purpose of description, specific terms are intended to at least include technical and functional equivalents that operate in a similar manner to accomplish a similar result. Additionally, in some instances where a particular embodiment of the invention includes a plurality of system elements or method steps, those elements or steps may be replaced with a single element or step; likewise, a single element or step may be replaced with a plurality of elements or steps that serve the same purpose. Further, where parameters for various properties or other values are specified herein for embodiments of the invention, those parameters or values can be adjusted up or down by 1/100th, 1/50th, 1/20th, 1/10th, 1/5th, 1/3rd, 1/2, 2/3rd, 3/4th, 4/5th, 9/10th, 19/20th, 49/50th, 99/100th, *etc.* (or up by a factor of 1, 2, 3, 4, 5, 6, 8, 10, 20, 50, 100, *etc.*), or by rounded-off approximations thereof, unless otherwise specified. Moreover, while this invention has been shown and described with references to particular embodiments thereof, those skilled in the art will understand that various substitutions and alterations in form and details may be made therein without departing from the scope of the invention. Further still, other aspects, functions and advantages are also within the scope of the invention; and all embodiments of the invention need not necessarily achieve all of the advantages or possess all of the characteristics described above. Additionally, steps, elements and features discussed herein in connection with one embodiment can likewise be used in conjunction with other embodiments. The contents of references, including reference texts, journal articles, patents, patent applications, *etc.*, cited throughout the text are hereby incorporated by reference in their entirety; and appropriate components, steps, and characterizations from these references may or may not be included in embodiments of this invention. Still further, the components and steps identified in the Background section are integral to this disclosure and can be used in conjunction with or substituted for components and steps described elsewhere in the disclosure within the scope of the invention. In method claims, where stages are recited in a particular order—with or without sequenced prefacing characters added for ease of reference—the stages are not to be interpreted as being temporally limited to the order in which they are recited unless otherwise specified or implied by the terms and phrasing.

CLAIMS

What is claimed is:

1. A method for hybridized humidification-dehumidification and pressure-retarded osmosis, comprising:

directing a flow of a carrier gas through a humidifier;

directing the flow the carrier gas from the humidifier through a dehumidifier;

directing a flow of a combined feed liquid through the humidifier, where water vaporizes from the combined feed liquid into the carrier gas;

directing the flow of the combined feed liquid from the humidifier through the dehumidifier, wherein the combined feed liquid cools the carrier gas to condense water from the carrier gas;

extracting a concentrated brine stream from the humidifier, wherein the concentrated brine stream is a remnant of the combined feed liquid after water is vaporized from the combined feed liquid in the humidifier;

directing at least a portion of the concentrated brine stream through an osmosis chamber of a pressure-retarded osmosis unit on a first side of a membrane;

directing an initial feed solution through the osmosis chamber on a second side of the membrane in counterflow to the concentrated brine stream, wherein water from the initial feed solution flows through the membrane into the concentrated brine stream to dilute and increase the volumetric flow rate of the brine stream and to concentrate the initial feed solution;

extracting the diluted brine stream from the osmosis chamber and depressurizing the diluted brine stream to produce power; and

extracting the concentrated initial feed solution from the osmosis chamber and combining the depressurized, diluted brine stream with the concentrated initial feed solution to form the combined feed liquid.

2. The method of claim 1, wherein the combined feed liquid and the carrier gas are circulated with pumps, the method further comprising powering the pumps with the power produced by depressurizing the diluted brine stream.

3. The method of one of claim 1 or 2, further comprising powering at least one of a light, a computer for controlling operation of the humidifier and dehumidifier, and pumps that circulate the combined feed liquid, brine and the carrier gas with power produced by depressurizing the diluted brine stream.

4. The method of claim 1, wherein the initial feed solution comprises at least 1% by mass dissolved solute.

5. The method of claim 1, wherein the initial feed solution comprises at least 10% by mass dissolved solute.

6. The method of claim 1, wherein the initial feed solution comprises flowback or produced water from production of at least one of oil and gas.

7. The method of claim 1, further comprising heating the combined feed liquid as the combined feed liquid is passed from the dehumidifier to the humidifier.

8. The method of one of claim 1 or 7, further comprising extracting heat from the combined feed liquid before the combined feed liquid passes through the dehumidifier.

9. The method of claim 1, further comprising increasing the pressure of the concentrated brine stream before the concentrated brine stream is directed into the osmosis chamber.

10. A hybrid humidification-dehumidification and pressure-retarded osmosis system, comprising:

a humidifier;

a dehumidifier;

gas-flow conduits configured to circulate a carrier gas through the humidifier and through the dehumidifier;

liquid-flow conduits configured to circulate a combined feed liquid through the dehumidifier and through the humidifier;

an initial-feed-solution source comprising an initial feed solution; and

a pressure-retarded osmosis unit, including:

(a) an osmosis chamber;

(b) a semi-permeable membrane in the osmosis chamber, wherein the osmosis chamber is coupled with one of the liquid-flow conduits to feed concentrated brine stream from the humidifier through the osmosis chamber on a first side of the semi-permeable membrane and with the initial-feed-solution source to pass the initial feed solution from the initial-feed-solution source through the osmosis chamber on a second side of the semi-permeable membrane; and

(c) a turbine and generator coupled with an outlet from the second side of the semi-permeable membrane; and

a junction configured to combine flow of brine from the turbine with feed liquid from an outlet from the first side of the semi-permeable membrane, wherein one of the liquid-flow conduits provides fluid communication between the junction and the humidifier.

11. The hybrid humidification-dehumidification and pressure-retarded osmosis system of claim 10, further comprising pumps positioned and configured to pump fluids through the gas-flow conduits and through the liquid-flow conduits, wherein the pumps are configured to receive power from the turbine and generator.

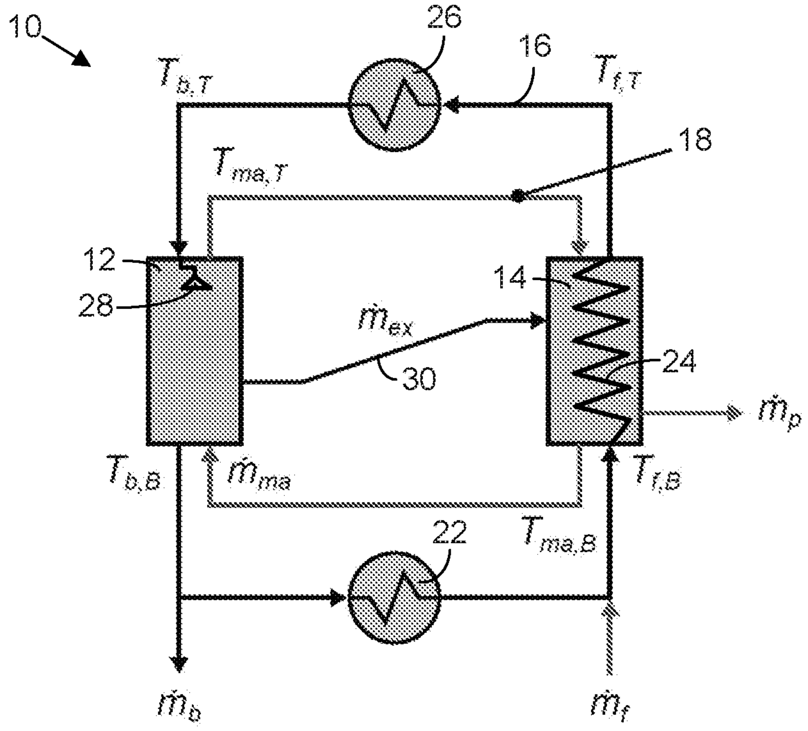
12. The hybrid humidification-dehumidification and pressure-retarded osmosis system of claim 11, wherein at least one of the pumps is positioned and

configured to pressurize the concentrated brine stream upstream from where the concentrated brine stream is fed into the osmosis chamber.

13. The hybrid humidification-dehumidification and pressure-retarded osmosis system of claim 10, wherein the initial feed solution comprises at least 1% by mass dissolved solute.

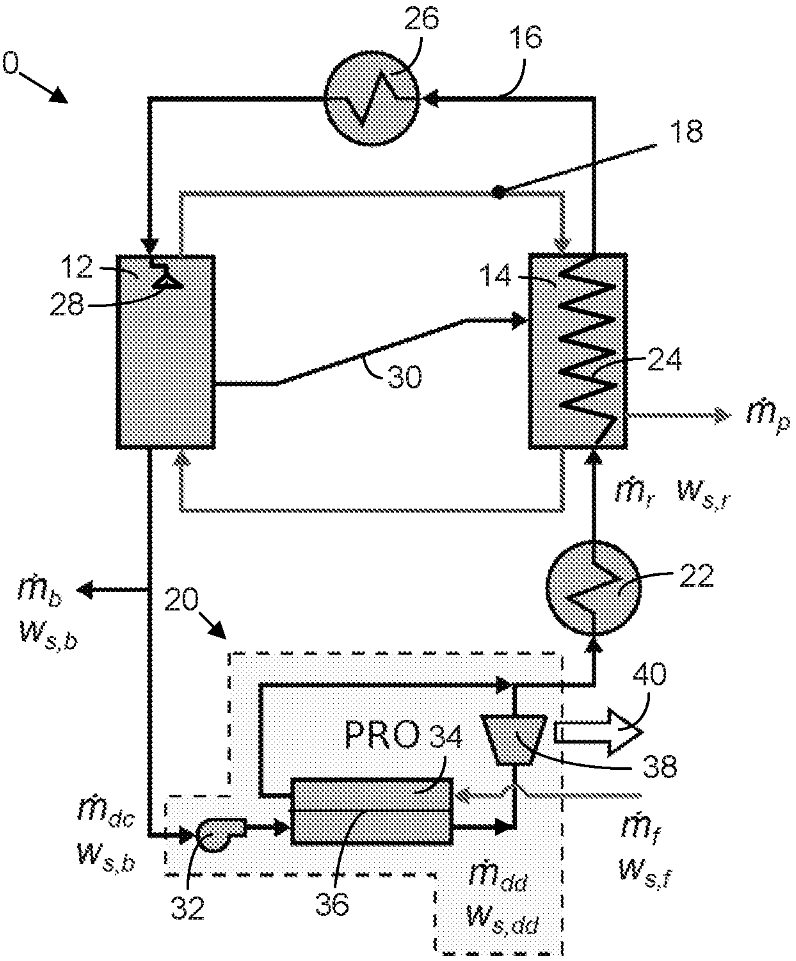
14. The hybrid humidification-dehumidification and pressure-retarded osmosis system of claim 10, wherein the initial feed solution comprises at least 10% by mass dissolved solute.

15. The hybrid humidification-dehumidification and pressure-retarded osmosis system of claim 10, wherein the initial feed solution comprises flowback or produced water from production of at least one of oil and gas.



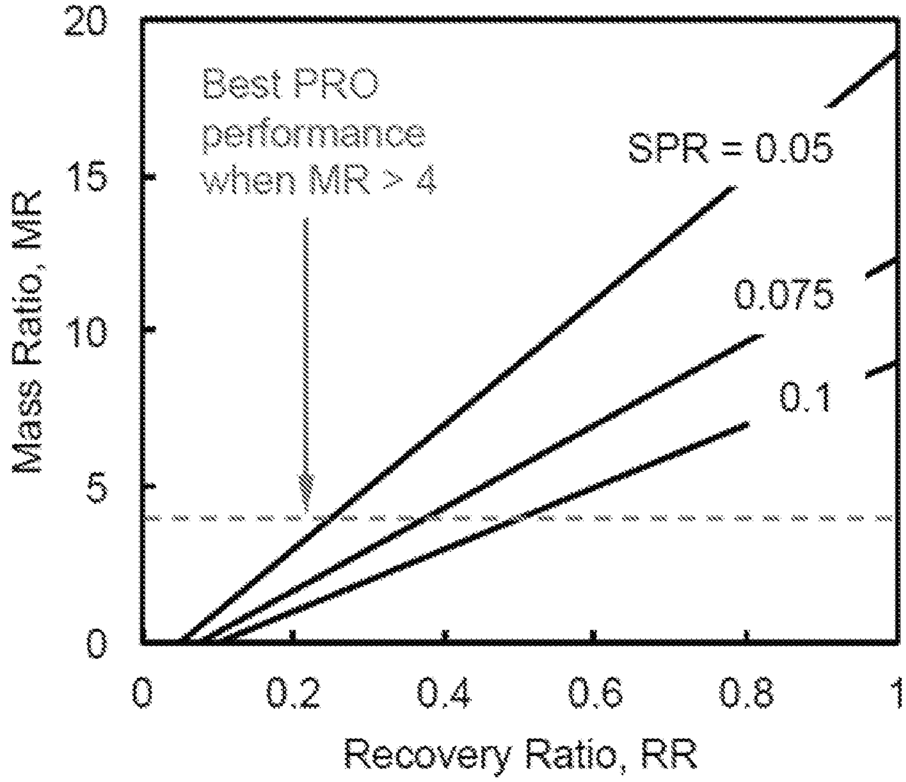
10
26
16
$T_{b,T}$
$T_{f,T}$
18
$T_{ma,T}$
12
14
28
$\dot{m}_{ex}$
24
30
$\dot{m}_p$
$T_{b,B}$
$\dot{m}_{ma}$
$T_{f,B}$
$T_{ma,B}$
22
$\dot{m}_b$
$\dot{m}_f$

FIG. 1



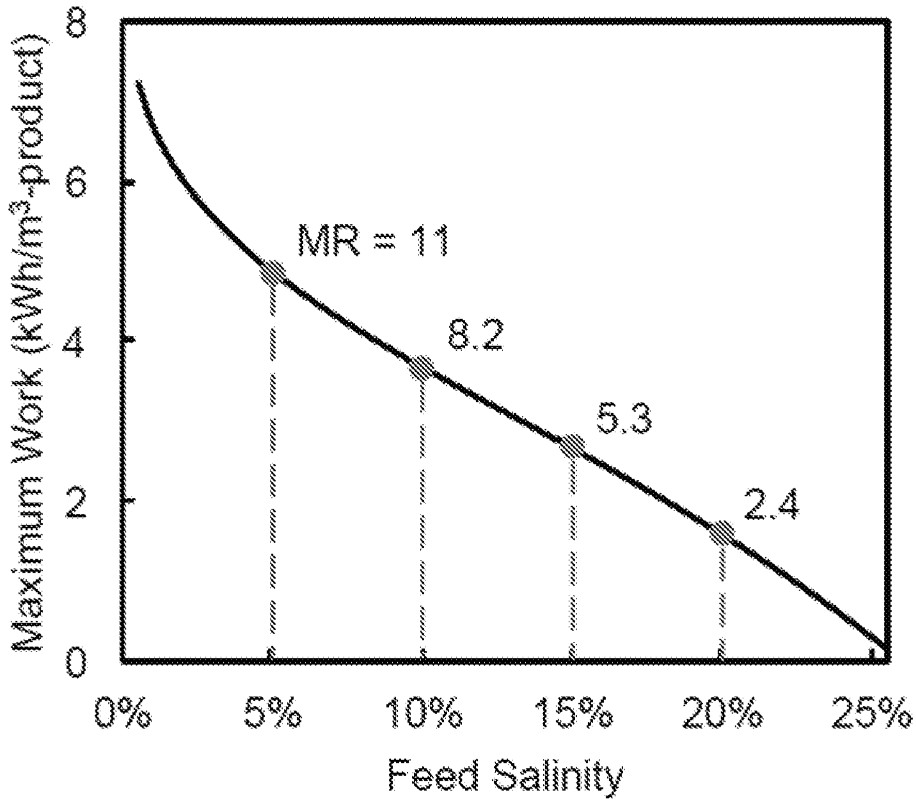
10
26
16
18
12
28
14
30
24
$\dot{m}_p$
$\dot{m}_r$ $w_{s,r}$
22
$\dot{m}_b$
$w_{s,b}$
20
40
PRO 34
38
$\dot{m}_{dc}$
$w_{s,b}$
$\dot{m}_f$
$w_{s,f}$
$\dot{m}_{dd}$
$w_{s,dd}$
32
36

FIG. 2



Best PRO
performance
when MR > 4
SPR = 0.05
0.075
0.1
Mass Ratio, MR
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
Recovery Ratio, RR

FIG. 3



MR = 11
8.2
5.3
2.4
Maximum Work (kWh/m3-product)
8
6
4
2
0
0%
5%
10%
15%
20%
25%
Feed Salinity

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 16/17262

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B01D 5/00, C02F 1/10, C02F 1/44, C02F 103/08, F03G 7/04, F24F 3/14, F28D 15/02 (2016.01)
CPC - B01D 5/00, C02F 1/10, C02F 1/44, C02F 2103/08, F03G 7/04, F24F 3/14, F24F 2003/1435, F28D 15/02
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8)- B01D 5/00, C02F 1/10, C02F 1/44, C02F 103/08, F03G 7/04, F24F 3/14, F28D 15/02 (2016.01);
CPC- B01D 5/00, C02F 1/10, C02F 1/44, C02F 2103/08, F03G 7/04, F24F 3/14, F24F 2003/1435, F28D 15/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC- 165/111, 165/225, 165/274, 165/281, 210/264, 210/652, 210/808, 261/22, 261/23.1, 261/150, 261/153, 261/157;
Patents and NPL (classification, keyword; search terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Pub West (US EP JP WO), Pat Base (AU BE BR CA CH CN DE DK EP ES FI FR GB IN JP KR SE TH TW US WO), Google Patent, Google Scholar, Free Patents Online; search terms: humidifier, dehumidifier, evaporate, condensate, desalinate, salinity, brine, brackish, pressure, retarder, vapor, vapour, osmosis, depressure, concentrate, dilute, liquid, fluid, gas

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2013/0199921 A1 (MCGOVERN) 08 August 2013 (08.08.2013), Fig. 1; para [0011], [0012], [0023]-[0026], [0031], [0033], [0035], [0037]-[0039], [0042]	1-9
Y	US 2011/0233137 A1 (CATH et al.) 29 September 2011 (29.09.2011), Fig. 2; para [0006], [0007], [0059], [0062], [0070], [0074], [0083]-[0088], [0143]	1-9
Y	US 2012/0091061 A1 (AL-JLIL et al.) 19 April 2012 (19.04.2012), para [0006], [0007], [0014], [0022], [0033], [0035], [0043]	1-9
Y	US 2011/0056822 A1 (ELSHARQAWY et al.) 10 March 2011 (10.03.2011), para [0012]-[0046]	1-9
Y	US 5,123,481 A (ALBERS et al.) 23 June 1992 (23.06.1992), col 3, ln 34 to col 32, ln 38	1-9

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 June 2016 (06.06.2016)	01 JUL 2016

Name and mailing address of the ISA/US
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450
Facsimile No. 571-273-8300

Authorized officer:
Lee W. Young
PCT Helpdesk: 571-272-4300
PCT OSP: 571-272-7774

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I: Claims 1-9, drawn to a method for hybridized humidification-dehumidification and pressure-retarded osmosis.

Group II: Claims 10-15, drawn to a hybrid humidification-dehumidification and pressure-retarded osmosis system.

The inventions listed as Groups I and II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

-- Please See Supplemental Box --

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-9

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continued from Box No. III, Observations where unity of invention is lacking,

Special Technical Features

Group II does not require a method for hybridized humidification-dehumidification and pressure-retarded osmosis, comprising:
directing a flow of a carrier gas through a humidifier; directing the flow the carrier gas from the humidifier through a dehumidifier;
directing a flow of a combined feed liquid through the humidifier, where water vaporizes from the combined feed liquid into the carrier gas;
directing the flow of the combined feed liquid from the humidifier through the dehumidifier, wherein the combined feed liquid cools the carrier gas to condense water from the carrier gas; extracting a concentrated brine stream from the humidifier, wherein the concentrated brine stream is a remnant of the combined feed liquid after water is vaporized from the combined feed liquid in the humidifier;
directing at least a portion of the concentrated brine stream through an osmosis chamber of a pressure-retarded osmosis unit on a first side of a membrane; directing an initial feed solution through the osmosis chamber on a second side of the membrane in counterflow to the concentrated brine stream, wherein water from the initial feed solution flows through the membrane into the concentrated brine stream to dilute and increase the volumetric flow rate of the brine stream and to concentrate the initial feed solution;
extracting the diluted brine stream from the osmosis chamber and depressurizing the diluted brine stream to produce power; and extracting the concentrated initial feed solution from the osmosis chamber and combining the depressurized, diluted brine stream with the concentrated initial feed solution to form the combined feed liquid, as required by Group I.

Group I does not require a hybrid humidification-dehumidification and pressure-retarded osmosis system, comprising:
a humidifier; a dehumidifier; gas-flow conduits configured to circulate a carrier gas through the humidifier and through the dehumidifier; liquid-flow conduits configured to circulate a combined feed liquid through the dehumidifier and through the humidifier; an initial-feed-solution source comprising an initial feed solution; and a pressure-retarded osmosis unit, including:
(a) an osmosis chamber;
(b) a semi-permeable membrane in the osmosis chamber, wherein the osmosis chamber is coupled with one of the liquid-flow conduits to feed concentrated brine stream from the humidifier through the osmosis chamber on a first side of the semipermeable membrane and with the initial-feed-solution source to pass the initial feed solution from the initial-feed-solution source through the osmosis chamber on a second side of the semipermeable membrane; and
(c) a turbine and generator coupled with an outlet from the second side of the semi-permeable membrane; and
a junction configured to combine flow of brine from the turbine with feed liquid from an outlet from the first side of the semi-permeable membrane, wherein one of the liquid-flow conduits provides fluid communication between the junction and the humidifier, as required by Group II.

Shared Common Features

The only feature shared by Groups I and II that would otherwise unify the groups is a hybrid humidification-dehumidification and pressure-retarded osmosis, comprising: a humidifier; a dehumidifier; a carrier gas; combined feed liquid from the humidifier through the dehumidifier; a concentrated brine stream feed for an osmosis chamber of a pressure-retarded osmosis unit on a first side of a membrane; and an initial feed solution through the osmosis chamber on a second side of the membrane. However, this shared technical feature does not represent a contribution over prior art, because the shared technical feature is anticipated by US 5,123,481 A to Albers, et al. (hereinafter 'Albers').

Albers discloses a hybrid humidification-dehumidification and pressure-retarded osmosis (col 20, ln 63 to col 21, ln 23; col 23, ln 60 to col 24, ln 7; col 47, ln 54 to col 48, ln 11, heat/mass transfer... humidification and dehumidification with powered from pressure-retarded osmosis.), comprising: a humidifier (Fig. 4A; col 20, ln 21-31, ambient air with humidity enters chamber, 34.); a dehumidifier (Fig. 4A; col 20, ln 45-62, dessicant in chamber, 36.); a carrier gas (col 19, ln 61 to col 20, ln 13); combined feed liquid from the humidifier through the dehumidifier (col 22, ln 23-34, reconcentrating alternative using air with humidity enough to dehydrate liquid dessicant.); a concentrated brine stream feed for an osmosis chamber of a pressure-retarded osmosis unit on a first side of a membrane (Fig. 15; col 24, ln 1-7; col 25, ln 54 to col 26, ln 11, PRO power generation with membrane... concentrate brine solution, 482, semi-permeble membrane, 486.); and
an initial feed solution through the osmosis chamber on a second side of the membrane (Fig. 14; col 24, ln 8-29, flushing stream, 495.).

As the technical features were known in the art at the time of the invention, this cannot be considered a special technical feature that would otherwise unify the groups.

Groups I and II therefore lack unity under PCT Rule 13 because they do not share a same or corresponding features.