

ELECTROCHEMICALLY REGENERATED LIQUID DESICCANT DEHUMIDIFICATION SYSTEM USING A SECONDARY HEAT PUMP

CROSS-REFERENCE TO RELATED APPLICATIONS

5 **[0001]** This application is a continuation-in-part of U.S. Patent Application No. 17/559,172, entitled “Electrochemically Regenerated Liquid Desiccant Dehumidification System Using a Secondary Heat Pump,” filed December 22, 2021, the disclosure of which is incorporated herein by reference in its entirety.

10 TECHNICAL FIELD

[0002] This disclosure relates generally to systems that utilize electrochemical regeneration of a liquid desiccant.

SUMMARY

15 **[0003]** Embodiments described herein are directed to a heat pump system using
an electrodialysis apparatus. In one embodiment, a system includes a liquid desiccant
regenerator configured to produce a first output stream from a first input stream. The first
output stream has a higher concentration of a liquid desiccant than the first input stream. The
regenerator also produces a second output stream from a second input stream. The second
20 output stream has a lower concentration of the liquid desiccant than the second input stream.
Regeneration of the liquid desiccant in the liquid desiccant regenerator decreases a
temperature of the liquid desiccant regenerator. The system includes an air contactor coupled
to the first output stream and exposing an input air stream to the first output stream. The first
output stream absorbs water from the input air stream to form at least one diluted output
25 desiccant stream. The at least one diluted output desiccant stream is circulated back into the
liquid desiccant regenerator. A heat pump of the system is thermally coupled to move the
heat from the first output stream to the liquid desiccant regenerator. The heat moved to the
liquid desiccant regenerator increases an efficiency of the liquid desiccant regenerator.

[0004] Other embodiments are directed to a system that includes a liquid desiccant regenerator configured to produce a first output stream from a first input stream. The first output stream has a higher concentration of a liquid desiccant than the first input stream. The regenerator also produces a second output stream from a second input stream. The second output stream has a lower concentration of the liquid desiccant than the second

input stream. The system includes an air contactor coupled to the first output stream and exposing an input air stream to the first output stream. The first output stream absorbs water from the input air stream to form at least one diluted output desiccant stream. The at least one diluted output desiccant stream is circulated back into the liquid desiccant regenerator.

5 The system includes a vapor compression heat pump having a refrigerant loop between a condenser and an evaporator. The system also includes a fluid loop between the evaporator and the air contactor, the fluid loop thermally coupled to move the heat from the air contactor to the evaporator.

[0005] In another embodiment, a method involves producing a first output stream
10 from a first input stream in a liquid desiccant regenerator, the first output stream having a higher concentration of a liquid desiccant than the first input stream. A second output stream is produced from a second input stream in the liquid desiccant regenerator, the second output stream having a lower concentration of the liquid desiccant than the second input stream. An input air stream is exposed to the first output stream in an air contactor. The first output
15 stream absorbs water from the input air stream to form at least one diluted output desiccant stream. The at least one diluted output desiccant stream is recirculated back into the liquid desiccant regenerator. Heat is moved from the first output stream to the liquid desiccant regenerator via a heat pump.

[0006] In some embodiments, a system includes a liquid desiccant regenerator
20 that is configured to produce a first output stream from a first input stream. The first output stream has a higher concentration of a liquid desiccant than the first input stream. The liquid desiccant regenerator is also configured to produce a second output stream from a second input stream. The second output stream has a lower concentration of the liquid desiccant than the second input stream. The system further includes an evaporator configured to be coupled
25 to and remove heat from an input air stream to produce a cooled input air stream. The system during includes an air contactor coupled to the first output stream and the cooled input air stream to expose the cooled input air stream to the first output stream such that the first output stream absorbs water from the cooled input air stream to form a diluted output desiccant stream and dehumidified output air stream. The diluted output desiccant stream is
30 circulated back into the liquid desiccant regenerator.

[0007] In some embodiments, a system includes a liquid desiccant regenerator configured to produce a first output stream from a first input stream in which the first output

stream has a higher concentration of a liquid desiccant than the first input stream. The regenerator is also configured to produce a second output stream from a second input stream in which the second output stream has a lower concentration of the liquid desiccant than the second input stream. The system further includes an air contactor configured to be coupled to the first output stream to expose an input air stream to the first output stream. The first output stream absorbs water from the input air stream to form a diluted output desiccant stream and a dehumidified air stream. The diluted output desiccant stream is circulated back into the liquid desiccant regenerator. The system further includes an evaporator configured to be coupled to and remove heat from the dehumidified air stream to produce a cooled dehumidified air stream.

[0008] In some embodiments, a system includes a liquid desiccant regenerator configured to produce a series of output streams with each output stream from the series of output streams being configured to possess a concentration of liquid desiccant. In some implementations, the concentration of liquid desiccant can be different across each output stream. The system further includes an evaporator configured to be coupled to and remove heat from an input air stream to produce a cooled input air stream. The system further includes a series of air contactors. Each air contactor is configured to be coupled to one or more of the series of output streams to form a diluted output desiccant stream and an input air stream to form a dehumidified output air stream. The diluted output desiccant stream is circulated back into the liquid desiccant regenerator. The first in the series of air contactors is coupled to the cooled input air stream, and each subsequent contactor is coupled to the air output by the contactor upstream of it (i.e., toward the evaporator), and the final air contactor in the series producing a dehumidified air stream.

[0009] The above summary is not intended to describe each disclosed embodiment or every implementation of the present disclosure. The figures and the detailed description below more particularly exemplify illustrative embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The discussion below refers to the following figures, wherein the same reference number may be used to identify the similar/same component in multiple figures. However, the use of a number to refer to a component in a given figure is not intended to

limit the component in another figure labeled with the same number. The figures are not necessarily to scale.

[0011] FIG. 1 is a diagram of a redox flow electrochemical regenerator stack and liquid desiccant system according to an example embodiment;

5 [0012] FIG. 2 is a graph showing power consumption under various conditions of a regenerator stack and liquid desiccant system according to an example embodiment;

[0013] FIG. 3 is a diagram of a redox flow electrochemical regenerator stack and system according to another example embodiment;

10 [0014] FIGS. 4A, 4B and 5 are diagrams showing secondary heat pumps integrated into a liquid desiccant regeneration system according to example embodiments;

[0015] FIGS. 6 and 7 are diagrams showing different arrangements of a liquid desiccant system in a cooling system according to example embodiments; and

[0016] FIG. 8 is a flow diagram of a method in accordance with certain embodiments.

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DETAILED DESCRIPTION

[0017] The present disclosure relates to electrochemically regenerated liquid desiccant dehumidification systems. A liquid desiccant system may be used in, among other things, heating, ventilation, and air-conditioning (HVAC). Air conditioning is an energy
20 intensive process and is responsible for nearly 10% of U.S. electricity consumption, with dehumidification accounting for more than half of the energy load in humid regions. The systems described herein provide an efficient, thermodynamic approach to dehumidification for air conditioning including a redox-assisted electrodialysis liquid desiccant regenerator that utilizes a heat pump.

25 [0018] Liquid desiccants (e.g., aqueous solutions of lithium chloride, LiCl and/or other salt such as NaCl, LiBr, and CaCl₂) will absorb moisture from air across an air-to-liquid interface (e.g., a membrane interface), which decreases concentration of the desiccant solute, resulting in a diluted output stream of liquid desiccant. In order to regenerate the liquid desiccation system in a loop, the diluted liquid desiccants can be efficiently re-concentrated
30 using a redox-assisted regenerator. This type of regenerator, referred to as a shuttle-promoted electrolyte removal (SUPER) cell, can increase or decrease concentrations of solutes in solutions through the use of ionic transport membranes and a redox shuttle.

[0019] In FIG. 1, a diagram shows a SUPER cell 100 according to an example embodiment. The cell 100 includes two electrodes 116, 118, at least three ion exchange membranes 110, 112, 114, and an energy supply 123. The first electrode 116 contacts a first solution of a first redox-active electrolyte material and configured to have a first reversible redox reaction with the first redox-active electrolyte material. The second electrode 118 contacts a second solution of a second redox-active electrolyte material and configured to have a second reversible redox reaction with the second redox-active electrolyte material. For purposes of simplicity, the first and second redox-active electrolyte solutions are shown in the FIG. 1 as a single redox shuttle solution 117 comprising the redox-active electrolyte materials.

[0020] Examples of a redox shuttle solution include 1,1'-bis((3-trimethylammonio)propyl)ferrocene ([BTMAP-Fc]²⁺) and 1,1'-bis((3-trimethylammonio)propyl)ferrocenium ([BTMAP-Fc]³⁺), or 1,1'-bis((3-dimethylethylammonio)propyl)ferrocene ([BDMEAP-Fc]²⁺) and 1,1'-bis((3-dimethylethylammonio)propyl)ferrocenium ([BDMEAP-Fc]³⁺), which are highly stable ferrocene derivatives that have very rapid electrochemical kinetics and negligible membrane permeability, or ferrocyanide/ferricyanide ([Fe(CN)₆]⁴⁻/[Fe(CN)₆]³⁻). Additional details for example redox shuttle solutions can be found in commonly-owned U.S. Patent Application 17/390,600, filed July 30, 2021 (Attorney docket number 20210171US01/0600.382US01), which is hereby incorporated by reference in its entirety.

[0021] The redox shuttle 117 is circulated between the two electrodes 116, 118 as shown by redox shuttle loop 124. When an electrical potential is applied to each electrode 116, 118 by energy supply 123, the redox shuttle is oxidized at a first electrode (e.g., 116) and reduced at the opposite electrode (e.g., 118). The energy supply 123 may be any variety of direct current (DC) energy supply such as a battery, photovoltaic panel, galvanic cell, potentiostat, AC/DC power converter, etc., and the energy supply may be contained within the electrochemical cell 100 or be external and coupled to the cell 100. Thus, as the shuttle 117 circulates between the electrodes, the portions of the shuttle 117 are continuously alternating between the redox states. In other words, the electrical potential engenders faradaic reactions happening at the two different electrodes 116, 118 and the redox material undergoing the faradaic reactions is circulated from one electrode to the other and back again.

[0022] In certain embodiments, each electrode 116, 118 may contact separate redox-active solutions instead of the same redox shuttle solution 117 being flowed in a loop. The separate redox-active solutions may have the same redox-active electrolyte material or different redox-active electrolyte materials. When different redox-active solutions are used
5 for the respective electrodes 116, 118, the energy supply may periodically reverse the potential supplied to the electrodes to restore the state of charge (e.g., the proportion of redox-active electrolyte material in each solution that is in the oxidized state compared to the reduced state) of each of the redox-active electrolyte material solutions.

[0023] Positioned between the electrodes 116, 118 are three ion exchange
10 membranes, which alternate in the type of ion exchanged. For example, among three membranes, a center membrane 110 may be a cation exchange membrane flanked by second 112 and third 114 anion exchange membranes, as is shown in FIG. 1. However, in other embodiments, the center, first membrane may be an anion exchange membrane and the second and third membranes may be cation exchange membranes. The membranes 110, 112,
15 114 define chambers, channels, or reservoirs, in the electrochemical cell 100. As may be seen, a first membrane 110 and a second membrane 112 define a first chamber 106, which in this example is configured as a desalinate chamber that decreases salt concentration in a fluid. The first membrane 110, in combination with a third membrane 114, also defines a second chamber 108, which in this example is configured as a salinate channel that increases salt
20 concentration in a fluid.

[0024] The membranes 110, 112, 114 are ion-selective as well as water-permeable, are insoluble in organic solvents, and are inert (e.g., do not chemically change) in the reaction mixture and/or products. In certain embodiments, the membranes are reinforced with a polymer mesh integrated into the membrane itself and in other embodiments, the
25 membranes are not reinforced. It will be understood that this can be extended to additional membranes, e.g., N membranes of alternating type that define respective N-1 channels or reservoirs.

[0025] A first stream 102 flows through the first chamber 106 of the electrochemical cell 100. The first stream 102 includes at least a solvent (water in this
30 example) and a salt (LiCl in this example) dissolved in the solvent at a first salt concentration (about 35% by weight in this example) when it enters the first chamber 106. A second stream 122 flows through the second chamber 108 of the electrochemical cell 100. The second

stream 122 has a second salt concentration (about 35% by weight) as it enters the first chamber. The second salt concentration is the same as the first salt concentration in this example, although could be different. During an operational mode of the electrochemical cell 100, an electrical potential is applied to the electrodes 116, 118 and the first and second streams 102, 122 are moved (e.g., pumped) through the first and second chambers 106, 108.

[0026] When an electrical potential is applied to the electrodes 116, 118, the redox shuttle 117 is oxidized at one electrode 116 and reduced at the other electrode 118, thereby driving salt ions 127 from the first stream 102 in the first chamber 106 into the second stream 122 in the second chamber 108. In particular, the redox shuttle 117 at the first electrode 116 accepts at least one ion 134 from the catalyst in the first chamber 106. The redox shuttle 117 at the second electrode 118 drives at least one ion 133 into the second stream 122 in the second chamber 108, and the charge is balanced by driving at least one ion 127, of opposite sign of charge to ions 133, 134, from the first stream 102 in the first channel 106 across the center membrane 110 into the second stream 122 in the second channel 108.

[0027] The result of the electrical potential being applied to the electrodes is that the first stream 102 has a reduced concentration of salt (e.g., below a 1% threshold concentration) during the operation mode when exiting the first chamber 106 and the second stream 122 increases in concentration of salt when exiting the second chamber 108. The outputs of the first and second chambers 106, 108 can be further processed by subsequent stages of a similar SUPER cell to achieve similar or increased levels of desalinization and salinization. Such a system may be used with various other salts, such as water-soluble ionic salts. Example cations that can be present in the salts include, but are not limited to, hydronium, lithium, sodium, potassium, magnesium, calcium, aluminum, zinc, and iron. Example anions that can be present in the salts include, but are not limited to, chloride, bromide, iodide, halide oxyanions, sulfur oxyanions, phosphorous oxyanions, and nitrogen oxyanions.

[0028] As noted above, the SUPER cell 100 can be used to regenerate a liquid desiccant stream that flows through a liquid-to-air heat and mass exchanger, including a direct contactor, packed bed air contactor, or liquid-to-air membrane energy exchanger (LAMEE) 130, which is shown in FIG. 1 coupled to the SUPER cell 100. For the purposes of this disclosure, instances of a LAMEE shown in any of the embodiments may be replaced

with and/or augmented with any type of direct contact or membrane liquid-to-air heat and mass exchanger.

[0029] As seen in FIG. 1, the second, concentrated stream 122 is used as an input 131 to the LAMEE 130. The LAMEE 130 receives an input air stream 142 with relatively high relative humidity (RH), and water vapor in the input air stream 142 is absorbed into the liquid desiccant. This results in the LAMEE 130 outputting an output air stream 144 with a relatively low RH. The water being absorbed in the liquid desiccant results in a diluted output stream 143 from the LAMEE 130, which can be fed back into the SUPER cell. In this case, the output of the first, diluted stream 102 can be discarded or used elsewhere.

[0030] The absorption of water into the liquid desiccant results in an increase in the temperature of air 142, 144 flowing through the LAMEE 130, which is a well-known thermodynamic phenomenon when water condenses from a gas to a liquid. This increase in temperature can be reduced or eliminated by heat absorbing/accepting element 136 (e.g., heat exchanger) that absorbs heat energy 135 from the LAMEE 130. Heat can also influence energy consumption of the SUPER cell 100. For example, running the SUPER at higher temperatures can make its operation more efficient, e.g., by lowering the electrical resistance of the membranes/electrodes/solutions and increasing the electrochemical kinetics. Therefore, a heat emitting/rejecting element 138 (e.g., heat exchanger) can supply heat 139 to the SUPER cell 100 and/or any of its internal flows. For instance, applying heat to specific components or fluid streams in the SUPER can be used to induce a temperature gradient inside the SUPER to encourage favorable phenomenon (like resistance) and discourage unfavorable phenomenon (like water osmosis). In a SUPER design with multiple stages, heat can be applied to specific stages to promote favorable performance. Inputting heat to SUPER cell 100 can also compensate for the endothermic effects due to regeneration of the liquid desiccant.

[0031] Specific subsets of components of the SUPER cell 100 can be heated via the heat rejecting element 138 using conventional heat transfer elements, such as heat conductive structures, vapor chamber heat pipes, convective transfer from heat sinks, etc. In one embodiment, heat from element 138 can be applied to one or more of the membranes 110, 112, 114 to lower electrical resistance. In another embodiment, heat from element 138 can be applied to one or more of the electrodes 116, 118 to lower electrical resistance. In another embodiment, the stream 143 input to the SUPER cell 100 may be heated before or

after entering the cell. For example, heating the concentrated stream 122 while keeping the dilute stream 102 relatively cooler can reduce water osmosis across the center membrane 110. In other embodiments, the redox shuttle loop 124 may be heated.

[0032] The desiccant flow rate through the LAMEE 130 can also affect
5 temperatures and system energy consumption. A high flow rate of liquid desiccant has low concentration change between the input stream 131 and the output stream 143. This may require more energy to reconcentrate the input stream 131 via the SUPER cell, as regeneration requires much more energy at higher concentrations. For example, the graph in FIG. 2 shows a marked increase in slope of the energy consumption curves for cell voltages
10 from 0.1 to 0.5 volts once LiCl desiccant concentration is higher than 25-30% by weight. One the other hand, a high desiccant flow rate but may require less rejection of heat 135 from the LAMEE 130. A low flow rate of liquid desiccant through the LAMEE 130 increases the concentration change between the input stream 131 and the output stream 143. This can reduce the energy needed to reconcentrate the input stream 131 via the SUPER cell 100,
15 although may increase the rejection of heat 135 from the LAMEE 130.

[0033] The heat absorbing element 136 and heat emitting element 138 may be thermally coupled to a same heat pump or two different heat pumps. Generally, a heat pump is a system that utilizes a heat transfer medium (e.g., gas, liquid, or solid) to move heat in a direction opposite that of spontaneous heat transfer. Well-known heat pump systems include
20 vapor-compression (VC) cycle machines used in refrigerators and air-conditioning. A working fluid (e.g., refrigerant such as R-134A, R-407C, etc.) is compressed and condensed in a condenser. The compression and condensation cause a rise in fluid temperature which results in heat transfer to the outside air (OA) or other heat sink. The cooled working fluid is sent from the condenser to an expansion valve where it evaporates into an evaporator. The
25 evaporation absorbs heat and the working fluid is sent back to the compressor to complete the cycle. This flow path of the working fluid is also referred to herein as a refrigerant loop.

[0034] Other types of heat pump systems include vapor absorption systems where a liquid refrigerant evaporates in a low partial pressure environment, absorbing heat from its surrounding. The vapor is then absorbed in another liquid, which is then heated to cause the
30 refrigerant to evaporate out again. One advantage to absorption systems is that they can be built using no moving parts, other than the refrigerant itself. Other heat pumps, such as ground source heat pumps, utilize a constant temperature source (e.g., the earth) transfer heat

to or from the ground using a working fluid, and may not need to rely on phase changes of the working fluid. Solids can be used as a heat pump media, such as in thermoelectric cooling devices.

[0035] The embodiments described herein improve the performance of
5 electrochemically regenerated liquid desiccant dehumidifiers by use of a secondary heat pump. Generally, as the term is used herein, a primary heat pump moves heat between a heating/cooling target (e.g., forced air in an HVAC system or a water stream) and a thermal sink (e.g., the ground or atmosphere). A secondary heat pump includes additional heat exchangers in the primary heat pump path to heat or cool other components in the system.
10 Many dehumidification systems use either a primary heat pump (as in the case of VC cycle air-conditioning) or a secondary heat pump (as in the case of a thermally regenerated desiccant wheel). The heat pump can be used to increase the relative humidity of air by cooling it, or to cool the air after dehumidification, compensating for heating caused by the dehumidification. In some embodiments, an electrochemically regenerated liquid desiccant
15 system directly couples with the heat rejection (hot side) of the secondary heat pump, the heat accepting (cold side) of the secondary heat pump, or both.

[0036] Before discussing the heat pump aspects in greater detail, it will be understood that a liquid desiccant system as shown in FIG. 1 may employ more than one SUPER cell in order to improve efficiency. For example, changing concentration levels of
20 the liquid desiccant solutions in smaller, discrete steps can minimize osmotic pressure differentials in each channel of the SUPER cells. Thus, in some embodiments, a SUPER liquid desiccant regenerator has two or more stages, each subsequent stage being configured to produce an output stream having a concentration of the liquid desiccant higher than the previous stage.

[0037] In FIG. 3, a diagram shows how a stack 301 of two SUPER cells 300, 302
25 can be coupled together into a two-stage regenerator to increase efficiency in a liquid desiccant regeneration system. A LAMEE 304 receives a concentrated stream 306 of liquid desiccant from the first SUPER cell 300. The concentration level of the stream 306 is about 30% here, although these are estimated values provided for the purposes of illustration and
30 not limitation. The LAMEE 304 causes water from an air flow (not shown) to be absorbed in the liquid desiccant, resulting in output streams 308, 309 having a lower concentration of desiccant, around 20% in this example. Note that the streams 308, 309 are shown exiting the

LAMEE 304 separately, however may be joined to a common fluid port within or outside of the LAMEE 304.

[0038] The output stream 308 is fed back into a salinization channel 300a of the first SUPER cell 300 via a fluid junction 310 (e.g., T-junction or manifold), where it is regenerated to the input concentration. The other output stream 309 is fed into a desalinization channel 300b of the first SUPER cell 300, where it is desalinized to around 10% concentration. This lower concentration solution is divided at fluid junction 312, which sends a first stream 314 through a desalinization channel 302b of the second SUPER cell 302, resulting in a discharge stream 315 of low concentration, e.g., <1%. A second stream 316 of the lower concentration solution from junction 312 is sent into a salinization channel 302a of the second SUPER cell 302, where it comes out as an increased concentration stream 318 and is rejoined with LAMEE exit stream 308 at junction 310.

[0039] In this example the SUPER cell 302 forms a first stage, and the SUPER cell 300 forms a second stage. The subsequent, second stage produces an output stream having a concentration (30% in this example) of the liquid desiccant higher than the corresponding output stream of previous, first stage output. The corresponding output of the first stage is 20% in this example. Pumps 320, 322 are shown driving the flows of liquid desiccant, although the number and location of pumps can vary from what is shown here. Generally, one pump may be used for each SUPER cell that is used in a different stage of processing. Other pumps (not shown) may be used to drive the redox shuttle in the SUPER cells 300, 302.

[0040] As with the arrangement shown in FIG. 1, the system shown in FIG. 3 includes at least one heat transfer element for accepting heat 324 from the LAMEE 304 and/or input heat 326 to the SUPER cells 300, 302 and/or fluids pumped through the cells 300, 302. Note that the heat 326 may be applied to a single stage of the SUPER cells 300, 302 (e.g., cell 300 or 302 but not both) where the application of heat will have the greatest impact on efficiency. This may include applying the heat 326 to just a subcomponent of the single one of the SUPER cells 300, 302. For systems with more than two stages (e.g., N-stages where $N > 2$), a subset of the two or more stages may be heated, where the subset ranges from one stage to N-1 stages. Any stages not in the subset are not directly heated by heat 326, although some indirect heating may occur due to circulation of liquid desiccant and the like. The input of heat 326 to the SUPER cells 300, 302 can be accomplished in several ways. A hot side of a

secondary heat pump can be brought into thermal contact with the SUPER electrochemical regenerator cells, such as through conductive heat transfer through the casing, electrodes, membranes, etc.

[0041] In FIG. 4A, a block diagram shows a liquid desiccant regeneration system with secondary heat pumping according to an example embodiment. A SUPER cell stack 400 includes three cells, each increasing or decreasing salinity within its channels by about 5% (compared to about 10% in the stack 301 shown in FIG. 3). The SUPER cell stack 400 regenerates solution for a dehumidifying LAMEE 401. As noted above, the electrochemical regeneration performed by the SUPER stack 400 with certain desiccants produces a cooling effect. A hot side of a secondary heat pump includes a heat exchanger 402 that rejects heat to liquid desiccant flowing through the SUPER stack 400. In this example, the secondary heat pump is coupled to a primary VC heat pump refrigerant loop, which includes an OA condenser 404, an expansion valve 405, an evaporator 406, and compressor 407. An air conditioning refrigerant, for example, can be used as a working fluid by both the primary and secondary heat pump. FIG. 4B also shows a block diagram of a liquid desiccant regeneration system with secondary heat pumping, but with the expansion valves routed in parallel to the evaporator and air contactor(s) (i.e., one or more air contactors), and the evaporator disposed upstream the air contactor to precool the air stream entering the air contactor(s), according to an example embodiment. Further, as shown in dotted lines in FIG. 4B, various components are optional, and so in other example embodiments, those components shown in dotted lines could be excluded from the system.

[0042] The hot side heat exchanger 402 of the secondary heat pump will offset some of the cooling effect in the SUPER stack 400. The SUPER stack 400 experiences reduced electrical and ionic resistance at higher temperatures leading to reduced losses at higher temperature. The hot side heat exchanger 402 also lowers the hot side temperature of the vapor compression loop before it reaches the condenser 404, which has direct thermodynamic benefits for the primary heat pump. The thermal contact between the SUPER stack 400 and the hot side heat exchanger 402 can be achieved via direct integration (e.g., heat conduction to solid components of the stack), indirect integration (e.g., via conduction and/or convective heat transfer to fluid pumped into the stack) or some combination thereof. This can be accomplished using direct contact to the refrigerant (which is pumped by the compressor 407) or with a third fluid loop (not shown).

[0043] It is anticipated that in some cases the SUPER cell stack 400 cannot absorb all the heat from the secondary heat pump. In other embodiments, the hot side of the heat pump can be coupled (directly or indirectly) with a secondary air contactor, such as humidifying LAMEE 408 which desorbs water from a liquid desiccant to an airflow (not shown) resulting in a lowering of temperature of the liquid desiccant. In other embodiments, the outlet fluid 410 of the SUPER cell stack, which has a very low concentration solution outlet stream, can be reused in the system by being fed into the humidifying LAMEE 408, which outputs a more concentrated liquid desiccant stream 411. Using the hot side of the heat pump, this outlet fluid 410 could be regenerated even if the ambient humidity levels were at 100%. This provides unique benefit to the regenerator that the SUPER cell stack 400 would no longer need a drain, in that the outlet fluid 410 would be reconcentrated by the humidifying LAMEE 408 and be fed back into the SUPER cell stack 400. In cases of sub-100% humidity, the heat pump would benefit from evaporative cooling lowering the temperature span of the secondary heat pump and increasing its efficiency.

[0044] In another embodiment, the dehumidifying LAMEE 401 is brought into thermal contact with the cold side of the heat pump, as indicated by heat exchangers 412 before the expansion valve 405 and the heat exchanger 414 after the expansion valve 405. The amount of cooling provided could be adjusted, e.g., by utilizing optional variable bypass valves 415, 416, which in this example, regulate the flow through heat exchanger 414. A similar valve arrangement could be used to regulate the flow through heat exchangers 402, 412 or any other component of the secondary heat pump. The valves could be linked to a system controller that monitors system temperatures and automatically adjusts the valves to maintain one or more desired operating points.

[0045] Cooling of the LAMEE input flow would allow the SUPER cell stack to operate at lower salt concentrations due to increased RH at lower temperatures of the LAMEE 401. Lowering salt concentrations would increase the efficiency of the SUPER cell stack 400. Additionally, the secondary heat pump can directly control outlet temperature in the LAMEE air contactor negating the need for a separate heat exchanger, and possibly reducing overall system costs. The illustrated evaporator 406 provides sensible cooling for the primary airflow, e.g., before or after passing through the LAMEE 401.

[0046] In FIG. 5, a block diagram shows a liquid desiccant regeneration system with secondary heat pumping according to another example embodiment. The primary and

secondary heat pump components work similar in this example, however a three-cell SUPER stack 500 feeds multiple stages of liquid desiccant to a four-stage dehumidification LAMEE 501. In this arrangement, cold side heat exchangers 512, 514 may have multiple independent heat exchange sections for each of the different SUPER-to-LAMEE desiccant flows. This system could use a humidifying LAMEE to absorb heat as shown in FIG. 5, as well as control valves to regulate the secondary heat pump.

[0047] In some desiccant technologies, the heat pump is used to accept the latent heat of condensation from the dehumidifier. This is shown in FIG. 5, where outside air plus return air 520 is input to the evaporator 406 before being passed through the dehumidifying LAMEE 501 and output as low RH cooled delivery air 521. The evaporator 406 may need to overcool the air sent to the LAMEE 501 to account for the latent heat of liquid dehumidification. The latent heat absorbed in this way is the rejected to the ambient at the condenser 404. If the liquid desiccant of the dehumidifying LAMEE 501 is kept close to the target temperature of the delivery air 521, then the air is conditioned on leaving the dehumidifier. This prevents overcooling and lets the conditioning process take place at a higher average conditioning temperature improving efficiency.

[0048] Alternatively, the evaporator can be placed downstream of the dehumidifier. This is shown in FIG. 4A, where outside air plus return air 420 is input to the dehumidifying LAMEE 401 before being passed through the evaporator 406 where it becomes low RH delivery air 421. This configuration eliminates water condensation on the evaporator 406, increasing its efficiency and lowering its air pressure drop, reducing the fan work of the system. Note that the airflow directions in FIGS. 4 and 5 are presented for purposes of illustration, and either embodiment (as well as other embodiments described herein) may use either airflow direction relative to a dehumidifier and an evaporator.

[0049] To operate at the highest possible evaporator temperature and minimize desiccant system size, a pre-evaporator cooling to the dehumidifier can be used. In FIG. 6, a block diagram shows a liquid desiccant regeneration system with pre-evaporator cooling according to an example embodiment. A SUPER regenerator stack 600 feeds a dehumidification LAMEE 601. A vapor compression heat pump includes an OA condenser 604, an expansion valve 605, an evaporator 606, a compressor 607, and refrigerant loop 608. To operate at the highest possible evaporator temperature and minimize desiccant system size, a pre-evaporator cooling element can extract heat from the dehumidification LAMEE

601. In FIG. 6, this pre-evaporator and cooling element is shown, for example, by a fluid loop 610 and pump 612. The fluid in the fluid loop could be the liquid desiccant, or a different fluid (e.g., water, ethylene glycol, etc.) may be used and transferred to the LAMEE 601 via a heat exchanger.

5 **[0050]** The evaporator 606 no longer needs to cool below the target outlet temperature but a significant amount of moisture may be removed on the evaporator 606 at no additional energy cost. The dehumidifier 601 can still be reduced in size due to condensing on the pre-evaporator. If the liquid desiccant regenerator 600 is a SUPER stack, then the dilute solution can be further diluted by the evaporator condensate, as shown in FIG. 10 7. In FIG. 7, and evaporator 706 and dehumidifier 701 form single air contactor that has a first section (the evaporator 706) which both cools and condenses to the delivery temperature. The second section (the dehumidifier) performs constant temperature dehumidification. The two sections are in thermal contact using any combination of heat pipes, two-phase flow, single phase flow, conduction, etc. A regenerator 700 regenerates the liquid desiccant. If 15 using a SUPER stack for the regenerator 700, then the dilute stream 704 from the regenerator is combined with condensate at the evaporator 706, resulting in a further diluted output stream 705. This stream 704 could be used to “clean” the evaporator 706 and adds a pressurized outflow from the evaporator 706. Note that certain components of a VC system (e.g., condenser, compressor) would be used with the evaporator 706, but are not shown in 20 this view. Features shown in FIGS. 6 and 7 (e.g., fluid loop 612 and dilute stream 704) can be added to previously described embodiments in FIGS. 1 and 3-5.

[0051] Note that in the embodiments disclosed above, a heat pump is shown in with an evaporator that absorbs heat and a condenser that outputs heat. In any of these embodiments, the evaporator can be replaced with a chilled solution heat exchanger and/or 25 the condenser can be replaced with a heated solution heat exchanger. The chilled and heated solutions may include water, water/glycol solution, saline solution, etc. The heat pump may still include a vapor compression system with an evaporator and condenser, but heat transfer is effected through the circulation of the solution through the system rather than direct contact with the evaporator and condenser.

30 **[0052]** In FIG. 8, a flow diagram shows a method according to an example embodiment. The method involves producing 800 a first output stream from a first input stream in a liquid desiccant regenerator, the first output stream having a higher concentration

of a liquid desiccant than first input stream. A second output stream is produced 801 from a second input stream. The second output stream has a lower concentration of the liquid desiccant than a second input stream. An input air stream is exposed 802 to the first output stream in an air contactor. The first output stream absorbs water from the input air stream to form at least one diluted output desiccant stream. The at least one diluted output desiccant stream is circulated 803 back into the liquid desiccant regenerator. Heat is moved 804 from the first output stream before entering the air contactor to the liquid desiccant regenerator via a heat pump.

[0053] In summary, systems and methods are described that can reduce energy consumption in electrochemically regenerated dehumidification and air conditioning systems, extend system performance, and enable co-located sensible heating and cooling with separate control. In one embodiment, a secondary heat pump is used to adjust the operating conditions of an electrochemically regenerated liquid desiccant system. An electrochemically regenerated liquid desiccant dehumidifier has at least one air contactor for dehumidifying air where a secondary heat pump system is utilized to control the water vapor absorption temperature, the regeneration temperature or a combination of both. The regeneration temperature can be controlled directly in the regenerator, in one or more air contactors used for humidification, or a combination of both.

[0054] Unless otherwise indicated, all numbers expressing feature sizes, amounts, and physical properties used in the specification and claims are to be understood as being modified in all instances by the term “about.” Accordingly, unless indicated to the contrary, the numerical parameters set forth in the foregoing specification and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by those skilled in the art utilizing the teachings disclosed herein. The use of numerical ranges by endpoints includes all numbers within that range (e.g., 1 to 5 includes 1, 1.5, 2, 2.75, 3, 3.80, 4, and 5) and any range within that range. All descriptions of solute concentrations by percentage are meant to describe percentage by weight unless otherwise indicated.

[0055] The foregoing description has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the embodiments to the precise form disclosed. Many modifications and variations are possible in light of the above teachings. Any or all features of the disclosed embodiments can be applied

individually or in any combination and are not meant to be limiting, but purely illustrative. It is intended that the scope of the invention be limited not with this detailed description, but rather, determined by the claims appended hereto.

CLAIMS

What is claimed is:

1. A system, comprising:
5 a liquid desiccant regenerator configured to produce:
a first output stream from a first input stream, the first output stream having a
higher concentration of a liquid desiccant than the first input stream; and
a second output stream from a second input stream, the second output stream
having a lower concentration of the liquid desiccant than the second input stream;
10 an evaporator configured to be coupled to and remove heat from an input air stream to
produce a cooled input air stream; and
an air contactor coupled to the first output stream and the cooled input air stream to
expose the cooled input air stream to the first output stream such that the first output stream
absorbs water from the cooled input air stream to form a diluted output desiccant stream and
15 dehumidified output air stream, wherein the diluted output desiccant stream is circulated back
into the liquid desiccant regenerator.
2. The system of claim 1, further comprising a heat pump configured to be thermally
coupled to move the heat from the first output stream to the liquid desiccant regenerator, the
20 heat moved to the liquid desiccant regenerator increasing an efficiency of the liquid desiccant
regenerator.
3. The system of claim 2, wherein the heat is moved from the first output stream before
entering the air contactor or as the first output stream enters the air contactor, the movement
25 of heat from the first output stream reducing a water vapor absorption temperature of the
liquid desiccant in the air contactor.
4. The system of claim 2, wherein the heat is applied to a subset of components of the
liquid desiccant regenerator to cause a temperature gradient inside the of the liquid desiccant
30 regenerator.

5. The system of claim 2, wherein the heat is applied to a one or more fluid streams inside the liquid desiccant regenerator.

6. The system of claim 2, wherein the air contactor is a first air contactor and the input air stream is a first input air stream, the system further comprising a second air contactor operable to desorb moisture from the second output stream into a second air stream, the desorbing of the moisture lowering a temperature of the second air contactor, the heat pump further thermally coupled to move part of the heat from the first output stream to the second air contactor.

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7. The system of claim 2, wherein the heat pump includes a vapor compression heat pump having a refrigerant loop between a condenser and the evaporator, the evaporator configured to cool at least one of the input air stream entering the air contactor or the dehumidified output air stream exiting the air contactor, the heat pump further including a first heat exchanger that thermally couples a hot side of the refrigerant loop to the liquid desiccant regenerator and a second heat exchanger that thermally couples a cold side of the refrigerant loop to the first output stream.

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8. The system of claim 7, wherein the heat exchanger and the evaporator and their respective expansion valves are disposed in parallel.

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9. The system of claim 7, wherein the heat exchanger and the evaporator and their respective expansion valves are disposed in series.

10. The system of claim 1, wherein the liquid desiccant regenerator includes two or more stages, each subsequent stage being configured to produce an output stream having a concentration of the liquid desiccant higher than a corresponding output of a previous stage, the first output stream corresponding to the output stream of the two or more stages having a highest concentration of the liquid desiccant.

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11. The system of claim 2, wherein a subset of the two or more stages are heated by the heat pump and any of the two or more stages that are not in the subset are not directly heated by the heat pump.

5 12. The system of claim 10, wherein the liquid desiccant regenerator is driven by an electric potential that engenders faradaic reactions happening at two different electrodes and a redox material undergoing the faradaic reactions is circulated from one electrode to the other and back again, and the resulting third liquid desiccant stream, having desorbed moisture and thus increased its desiccant concentration, are returned to the regenerator.

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13. A system, comprising:

a liquid desiccant regenerator configured to produce:

a first output stream from a first input stream, the first output stream having a higher concentration of a liquid desiccant than the first input stream; and

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a second output stream from a second input stream, the second output stream having a lower concentration of the liquid desiccant than the second input stream;

an air contactor coupled to the first output stream and exposing an input air stream to the first output stream, the first output stream absorbing water from the input air stream to form a diluted output desiccant stream and a dehumidified air stream, wherein the diluted
20 output desiccant stream is circulated back into the liquid desiccant regenerator; and

an evaporator configured to be coupled to and remove heat from the dehumidified air stream to produce a cooled dehumidified air stream.

14. The system of claim 13, further comprising a heat pump thermally coupled to move
25 the heat from the first output stream to the liquid desiccant regenerator, the heat moved to the liquid desiccant regenerator increasing an efficiency of the liquid desiccant regenerator.

15. The system of claim 14, wherein the heat is moved from the first output stream before entering the air contactor or as the first output stream enters the air contactor, the movement
30 of heat from the first output stream reducing a water vapor absorption temperature of the liquid desiccant in the air contactor.

16. The system of claim 14, wherein the heat is applied to a subset of components of the liquid desiccant regenerator to cause a temperature gradient inside the of the liquid desiccant regenerator.

5 17. The system of claim 14, wherein the heat is applied to a one or more fluid streams inside the liquid desiccant regenerator.

10 18. The system of claim 14, wherein the heat pump comprises a vapor compression heat pump having a refrigerant loop between a condenser and an evaporator, the evaporator used to cool at least one of the input air stream entering the air contactor or a dehumidified output stream exiting the air contactor, the heat pump further comprising a first heat exchanger that thermally couples a hot side of the refrigerant loop to the liquid desiccant regenerator and a second heat exchanger that thermally couples a cold side of the refrigerant loop to the first output stream.

15 19. The system of claim 14, wherein the heat pump comprises a vapor compression heat pump generating a chilled solution and a heated solution, the chilled solution being used to cool at least one of the input air stream entering the air contactor and a dehumidified output stream exiting the air contactor, and the heated solution being thermally coupled to the liquid
20 desiccant regenerator.

20. The system of claim 19, wherein at least part of the second output stream is combined with condensate at the evaporator resulting in a further diluted stream being output from the evaporator.

25 21. The system of claim 14, further comprising a second air contactor operable to desorb moisture from a second liquid desiccant stream into a second air stream, the desorbing of the moisture lowering a temperature of the second air contactor, the heat pump being further thermally coupled to move part of the heat from the first output stream to the second air
30 contactor.

22. The system of claim 13, wherein the regenerator comprises two or more stages, each subsequent stage being configured to produce an output stream having a concentration of the liquid desiccant higher than a corresponding output of a previous stage, the first output stream corresponding to the output stream of the two or more stages having a highest
5 concentration of the liquid desiccant.
23. The system of claim 22, wherein a subset of the two or more stages are heated by the heat pump and any of the two or more stages that are not in the subset are not directly heated by the heat pump.
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24. The system of claim 22, wherein the liquid desiccant regenerator is driven by an electric potential that engenders faradaic reactions happening at two different electrodes and a redox material undergoing the faradaic reactions is circulated from one electrode to the other and back again.
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25. A system, comprising:
a liquid desiccant regenerator configured to produce a series of output streams with each output stream from the series of output streams configured to possess a concentration of liquid desiccant;
20 an evaporator configured to be coupled to and remove heat from an input air stream to produce a cooled input air stream;
a series of air contactors with each air contactor configured to be coupled to one or more of the series of output streams to form a diluted output desiccant stream and an input air stream to form a dehumidified output air stream, wherein the diluted output desiccant stream is circulated back into the liquid desiccant regenerator; the first in the series of air contactors
25 is coupled to the cooled input air stream, each subsequent contactor is coupled to the air output by the contactor upstream of it, and the final air contactor in the series producing a dehumidified air stream.
- 30 26. The system of claim 25 where each of the output streams is at a different concentration.

27. The system of claim 26 where each of the output streams is coupled to one and only one of the air contactors from the series of air contactors

28. The system of claim 27 where the series of air contactors and the series of output
5 streams are ordered such that a first air contactor from the series of air contactors has the lowest concentration, and a final air contactor from the series of air contactors has the highest concentration, and the air contactors between the first and final are arranged in increasing concentration.

10 29. The system of claim 25, further comprising a heat pump thermally coupled to move the heat from the series of output streams to the liquid desiccant regenerator, the heat moved to the liquid desiccant regenerator increasing an efficiency of the liquid desiccant regenerator.

15 30. The system of claim 29, wherein the series of air contactors includes an air contactor operable to desorb moisture from the output liquid desiccant streams into a second air stream, the desorbing of the moisture lowering a temperature of that air contactor, the heat pump being further thermally coupled to move part of the heat from the series of output streams to that second air contactor and the resulting third liquid desiccant stream, having desorbed moisture and thus increased its desiccant concentration, are returned to the regenerator.

20 31. The system of claim 29, wherein the heat pump includes a vapor compression heat pump having a refrigent loop between a condenser and an evaporator, the evaporator used to cool at least one of the input air stream entering the air contactor or a dehumidified output air stream exiting the air contactor, the heat pump further including a first heat exchanger that
25 thermally couples a hot side of the refrigerant loop to the liquid desiccant regenerator and a series of second heat exchangers that thermally couple a cold side of the refrigerant loop to the series of output streams.

30 32. The system of claim 31, wherein the heat exchanger and the evaporator and their respective expansion valves are disposed in parallel.

33. The system of claim 31, wherein the heat exchanger and the evaporator and their respective expansion valves are disposed in series.

5 34. The system of claim 25, wherein the regenerator includes two or more stages, each subsequent stage being configured to produce an output stream having a concentration of the liquid desiccant higher than a corresponding output of a previous stage, the first output stream corresponding to the output stream of the two or more stages having a highest concentration of the liquid desiccant.

10 35. The system of claim 25, further comprising a second air contactor operable to desorb moisture from a second series of liquid desiccant streams into a second air stream, the desorbing of the moisture lowering a temperature of the second air contactor, the heat pump further thermally coupled to move part of the heat from the first output stream to the second air contactor, and the resulting third series of liquid desiccant streams, having desorbed
15 moisture and thus increased their desiccant concentration, are returned to the regenerator.

36. The system of claim 34, wherein the liquid desiccant regenerator is driven by an electric potential that engenders faradaic reactions happening at two different electrodes and a redox material undergoing the faradaic reactions is circulated from one electrode to the other
20 and back again.

37. A system, comprising:
a liquid desiccant regenerator configured to produce:
a first output stream from a first input stream, the first output stream having a
25 higher concentration of a liquid desiccant than the first input stream; and
a second output stream from a second input stream, the second output stream
having a lower concentration of the liquid desiccant than the second input stream;
an air contactor coupled to the first output stream and exposing an input air stream to
the first output stream, the first output stream absorbing water from the input air stream to
30 form at least one diluted output desiccant stream, wherein the at least one diluted output
desiccant stream is circulated back into the liquid desiccant regenerator;

a vapor compression heat pump having a refrigerant loop between a condenser and an evaporator; and

a fluid loop between the evaporator and the air contactor, the fluid loop thermally coupled to move the heat from the air contactor to the evaporator.

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38. The system of claim 37, wherein the fluid loop is driven by a pump.

39. A method comprising:

10 producing a first output stream from a first input stream in a liquid desiccant regenerator, the first output stream having a higher concentration of a liquid desiccant than the first input stream;

producing a second output stream from a second input stream in the liquid desiccant regenerator, the second output stream having a lower concentration of the liquid desiccant than the second input stream;

15 exposing an input air stream to the first output stream in an air contactor, the first output stream absorbing water from the input air stream to form at least one diluted output desiccant stream;

circulating the at least one diluted output desiccant stream back into the liquid desiccant regenerator; and

20 moving heat from the first output stream to the liquid desiccant regenerator via a heat pump.

40. The method of claim 39, wherein the heat is moved from the first output stream before entering the air contactor or as the first output stream enters the air contactor, wherein
25 moving the heat from the first output stream reduces a water vapor absorption temperature of the liquid desiccant in the air contactor.

41. The method of claim 39, wherein the heat pump comprises a vapor compression heat pump having a refrigerant loop between a condenser and an evaporator, the evaporator used
30 to cool at least one of the input air stream or a dehumidified output stream exiting the air contactor, the heat pump further comprising a first heat exchanger that thermally couples a

hot side of the refrigerant loop to the liquid desiccant regenerator and a second heat exchanger that thermally couples a cold side of the refrigerant loop to the first output stream.

42. The method of claim 41, further comprising combining at least part of the second
5 output stream with condensate at the evaporator resulting in a further diluted stream being output from the evaporator.

43. The method of claim 39, further comprising:
desorbing moisture from a second liquid desiccant stream into a second air stream at a
10 second air contactor, the desorbing of the moisture lowering a temperature of the second air contactor; and
moving part of the heat from the first output stream to the second air contactor via the heat pump.

15 44. The method of claim 39, wherein the regenerator comprises two or more stages, each subsequent stage being configured to produce an output stream having a concentration of the liquid desiccant higher than a corresponding output of a previous stage, the first output stream corresponding to the output stream of the two or more stages having a highest concentration of the liquid desiccant.

20 45. The method of claim 39, wherein the liquid desiccant regenerator is driven by an electric potential that engenders faradaic reactions happening at two different electrodes and a redox material undergoing the faradaic reactions is circulated from one electrode to the other and back again.