

LATENT ENERGY HARVESTING

CROSS REFERENCE TO RELATED APPLICATION

[001] This application claims the benefit of U.S. Provisional Application No. 63/287,609, filed on December 9, 2021, the entirety of which is incorporated by reference herein.

TECHNICAL FIELD

[002] This disclosure is generally related to energy systems, and more particularly, cooling, heating, ventilation, air-conditioning, and refrigeration systems.

BACKGROUND

[003] Conventional vapor compression refrigerant HVAC systems are used widely around the world and contribute to being the main power consumer in buildings. They operate by using cooling coils to lower the temperature and subsequently remove the humidity from the environment. The heat generated from the phase change occurring when the water vapor condenses produces approximately 60% of thermal energy that is needed to be overcome to allow for cooling to take place. However, this is not the most sustainable method when it comes to humid climates. In fact, at more humid locations, the contribution towards greenhouse gases and an inability to beneficially utilize latent energy dominates, and reduces the efficiency of legacy conventional cooling, heating, ventilation and air conditioning systems.

SUMMARY OF THE INVENTION

[004] In one embodiment, an evaporative cooling system, comprising: at least one direct evaporative cooling system, comprising: at least one fan or blower that induces an air stream; at least one evaporator installed in the air stream, wherein liquid water is supplied to the at least one evaporator, the at least one evaporator configured to directly evaporatively cool and humidify the air stream; and one or plural latent energy harvesting systems (LEHSs) installed alone or in combination, respectively, in the air stream, wherein when alone, the one LEHS is installed in either the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream or the air stream

upstream of the at least one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified, and wherein when in combination, the plural LEHSs are installed, respectively, in the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream, and in the air stream upstream of the at least one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified.

[005] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiment(s) described hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[006] Many aspects of the invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present systems and methods. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[007] Figure 1A is a schematic diagram that illustrates an embodiment of an example latent energy harvesting system (LEHS) that may be used in a variety of HVAC systems, in accordance with one embodiment.

[008] Figure 1B is a chart diagram that illustrates a basic trend on a psychrometric chart for when a latent energy harvesting system (LEHS) is introduced, and includes a process (1 to 2) for beneficial use in cooling, or for heating, or for combined cooling and heating purposes, in accordance with one embodiment.

[009] Figure 2 is a schematic diagram that illustrates the working principle behind a direct evaporative cooling (DEC) system in which the warm air comes in contact with water in the evaporator to produce cool air.

[010] Figure 3 is a chart diagram that illustrates a psychrometric chart for a DEC system showing the heat transfer from warm air to cool through the various stages.

[011] Figure 4 is a schematic diagram that illustrates when an LEHS is incorporated downstream of the heat exchanger in the DEC system, where the cool, dehumidified stream from the evaporator enters the LEHS, which in turn lowers the wet bulb temperature by replenishing the moisture, in accordance with one embodiment.

[012] Figure 5 is a chart diagram that illustrates the influence of an LEHS by showing the harvesting of water vapor (process 2-3) and the dehumidification of the air stream, in accordance with one embodiment.

[013] Figure 6 is a schematic diagram that illustrates an LEHS that is used upstream where warm, dehumidified air enters the evaporator allowing for heat transfer to occur, in accordance with one embodiment.

[014] Figure 7 is a chart diagram that illustrates how the trend behaves in the psychrometric chart after an LEHS is introduced upstream of the evaporator, in accordance with one embodiment.

[015] Figure 8 is a schematic diagram that illustrates two LEHSs upstream and downstream working simultaneously together and that demonstrates the versatility of how the LEHS is used for enthalpy change and moisture variations, in accordance with one embodiment.

[016] Figure 9 is a chart diagram that illustrates the influence when an LEHS is used upstream as well as downstream and the effect of it are demonstrated by the drastic enthalpy changes, in accordance with one embodiment.

[017] Figure 10 is a chart diagram that illustrates the direct evaporative cooling process in a psychrometric chart in the various stages of cooling and demonstrates the proportionality of how the latent heat is being harvested, in accordance with one embodiment.

[018] Figure 11 is a schematic diagram that illustrates that the LEHS can be placed in any airstream feeding the heat exchanger in the indirect evaporative cooling (IEC) system, in accordance with one embodiment.

[019] Figure 12 is a chart diagram that illustrates on a psychrometric chart the dehumidification trend by the LEHS in IEC systems, in accordance with one embodiment.

[020] Figure 13 is a schematic diagram that illustrates a regenerative-indirect cooling (R-IEC) system that is enabled with LEHS in any airstream, in accordance with one embodiment.

[021] Figure 14 is a chart diagram that illustrates the trend on a psychrometric chart of the LEHS dehumidification in the R-IEC equipment, in accordance with one embodiment.

[022] Figure 15 is a schematic diagram that illustrates the LEHS enhancing dew point indirect evaporative cooling (D-IEC) equipment having a two stage R-IEC system also enabled with the LEHS, in accordance with one embodiment.

[023] Figure 16 is a schematic diagram that illustrates the LEHS enhancing the D-IEC equipment have a two stage R-IEC system also enabled with the LEHS, in accordance with one embodiment.

[024] Figure 17 is a chart diagram that illustrates the trend on a psychrometric chart of the LEHS dehumidification in the R-IEC and D-IEC system, in accordance with one embodiment.

[025] Figure 18 is a schematic diagram that illustrates a Maisotsenko cycle (or M-cycle) with an LEHS which elaborates constant moisture in the primary airstreams, the M-cycle distinguished by the two dry primary channels and secondary air comes into contact from multiple passages in the dry channel, in accordance with one embodiment.

[026] Figure 19 is a chart diagram that illustrates the M-cycle on the psychrometric chart.

[027] Figure 20 is a chart diagram that illustrates on the psychrometric chart the M-cycle incorporating the LEHS dehumidification trend, in accordance with one embodiment.

[028] Figure 21 is a schematic diagram that illustrates an indirect, direct evaporative cooling (IDEC) system in which any configuration of the LEHS installation can be used in the inlet / outlets of both the primary and secondary airstreams, in accordance with one embodiment.

[029] Figure 22 is a schematic diagram that illustrates LEHS enhanced crossflow cooling that can be accomplished by mechanical or natural draft, in accordance with one embodiment.

[030] Figure 23 is a schematic diagram that illustrates LEHS enhanced counterflow cooling that can be accomplished by mechanical or natural draft, in accordance with one embodiment.

[031] Figure 24 is a schematic diagram that illustrates LEHS enhanced cocurrent cooling that can be accomplished by mechanical or natural draft, in accordance with one embodiment.

[032] Figure 25 is a schematic diagram that illustrates a dual season heating and cooling system operating in mild temperature conditions, in accordance with one embodiment.

[033] Figure 26 is a schematic diagram that illustrates a dual season heating and cooling system (intermediary mode) operating in both extremes, in accordance with one embodiment.

[034] Figure 27 is a schematic diagram that illustrates a dual season heating and cooling system operating in cold temperature conditions, in accordance with one embodiment.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[035] Disclosed herein are certain embodiments of HVAC systems that use one or more latent energy harvesting systems (LEHSs) to significantly enhance performance of each HVAC system. The (LEHS) is an assembly which comprises a heat exchanger coated with desiccant that removes the moisture from the humid airstream, having two chambers (adsorbing and desorbing), a vacuum pump to incorporate a partial vacuum and using the transfer of the heat of adsorption to be applied to the cooling of desorption to aid the desiccant to self-regenerate. The LEHS enables a spontaneous and simultaneous reaction in which the thermal energy from the water vapor is utilized to reactivate the desiccant. The LEHS may be used to minimize the cooling load in an entire HVAC system.

[036] In some embodiments of an LEHS-enhanced HVAC system, the one or more LEHSs are flexibly arranged to ensure the one or more LEHSs may be used enhance the performance of a vast number of applications and configurations, including a direct evaporative cooling (DEC) system, indirect evaporative cooling (IEC) system, regenerative-indirect evaporative cooling (R-IEC) system, dew point indirect evaporative cooling (D-IEC) system, Maisotsenko (M-cycle) IEC, Indirect- direct evaporative cooling (IDEC) system, and hybrid systems and cooling towers as described below.

[037] Digressing briefly, conventional direct evaporative cooling (DEC) systems are limited by the wet bulb temperature of the airstream that is utilized to derive evaporation, whereas conventional indirect evaporative cooling systems are limited to achieving near the dew point temperature of the airstream that is utilized to derive evaporation. Conventional evaporative cooling is less effective when the airstream supplied as the evaporation airstream is humid. Conventional direct evaporative cooling systems produce a cooled but humidified airstream. Conventional indirect evaporative cooling systems produce a humidified secondary airstream which moisture content is often undesirable. Conventional evaporative cooling systems consume considerable amounts of liquid water. Conventional evaporative cooling systems result in formation of a brine in the residual water that is not evaporated and deposition of dissolved solids on the surfaces of evaporator. Conventional evaporative cooling systems do

not provide for beneficial evaporative sourced heating from conversion of the latent energy within water vapor to sensible warming. Conventional evaporative cooling systems convert sensible heat to latent energy but do not make beneficial use of the latent energy that is derived, nor do conventional evaporative cooling systems make beneficial use of the latent energy within their initial sourced airstream (e.g., the humidity within ambient atmosphere air).

[038] There is a need for evaporative cooling that can achieve cooling below the wet bulb temperature, or below the dew point temperature of the sourced airstream utilized to derive evaporation. There is a need to derive effective evaporative cooling from a sourced evaporation airstream that is humid. There is a need to provide evaporative cooling without deriving a humidified airstream, be that airstream the product of direct evaporation or the secondary airstream of an indirect evaporative cooling system. There is a need for evaporative cooling systems that have higher water utilization efficiency, or which produce abundant, clean liquid water rather than consume liquid water, which produced liquid water can be used as a supply of evaporate or for other beneficial uses. There is a need for evaporative cooling systems which are not prone to produce brine by concentration of dissolved solids, and which are not subject to deposition of dissolved solids as scale onto the evaporator.

[039] With the following enhanced evaporative cooling and evaporative heating systems, also described below as LEHS-enhanced HVAC systems (or LEHS-enhanced cooling systems or the like), the effectiveness and efficiency of evaporation systems may be greatly enhanced with the selective use of one or more LEHSs, including providing the preconditioning of dehumidification of an airstream ahead of an evaporation process to directly depress the wet bulb temperature of the airstream. This dehumidified airstream may then be directed to a downstream evaporator before direct or indirect evaporative cooling is initiated, and the placement or installation of an LEHS downstream of the evaporators may be used to recover the water vapor evaporate for beneficial reuse of liquid water. The use of LEHS realizes the latent energy from water vapor for beneficial sensible heating, that is, to implement evaporation sourced heating.

[040] Unlike conventional direct evaporative cooling, which is limited by the wet bulb temperature of the airstream that is being utilized for evaporation, and unlike conventional indirect evaporative cooling, which is limited to achieving near the dew point temperature of the airstream used for evaporation, the LEHS-enhanced evaporative cooling systems provide for

cooling below the supply or ambient air dew point temperature by first dehumidifying and depressing the wet bulb temperature of the airstream that is used in the evaporation processes.

[041] Having summarized certain features of LEHS-enhanced HVAC systems of the present disclosure, reference will now be made in detail to the description of LEHS-enhanced HVAC systems as illustrated in the drawings. While LEHS-enhanced HVAC systems will be described in connection with these drawings, there is no intent to limit it to the embodiment or embodiments disclosed herein. For instance, though emphasis is placed on air conditioning systems for buildings, certain embodiments of LEHS-enhanced HVAC systems may be beneficially deployed in vehicles, such as integrated into the vehicle air conditioning system, and especially, electric vehicle applications, or for cooling and heating of industrial processes, or for heating domestic hot water and hydronic heating of spaces. Further, although the description identifies or describes specifics of one or more embodiments, such specifics are not necessarily part of every embodiment, nor are all of any various stated advantages necessarily associated with a single embodiment. On the contrary, the intent is to cover all alternatives, modifications and equivalents included within the spirit and scope of the disclosure as defined by the appended claims. Further, it should be appreciated in the context of the present disclosure that the claims are not necessarily limited to the particular embodiments set out in the description.

[042] Systems of enhanced evaporative air cooling; and of enhanced direct evaporative cooling of liquid water; and enhanced indirect cooling with enhanced direct evaporative cooling of liquid water; and of evaporation sourced heating

[043] Before beginning a discussion of the various HVAC applications with which performance is enhanced by one or more LEHSs, attention is directed to Figure 1A. In one embodiment, a latent energy harvesting system (LEHS) 10 is shown, the LEHS 10 comprising a heat exchange subsystem 12, an energy recovery subsystem 14, and a control system 16 (e.g., a controller). The LEHS 10 depicted in Figure 1A is representative of each of the various LEHSs shown and described throughout the description, though referenced in some instances using different reference numerals (e.g., different than reference numeral 10, such as reference numeral 404 in Figure 4 as an illustrative example). The heat exchange subsystem 12 comprises a loop that includes a transfer pump 18, one or more heat exchangers 20 (e.g., 20A, 20B), and plural (e.g., two shown, though additional quantities may be used in some embodiments) chambers 22 (e.g., 22A, 22B) that contain the heat exchangers 20. In one embodiment, the transfer pump 18

is a variable speed pump. Note that for purposes of facilitating an understanding of the LEHS 10, chamber 22A is referred to as an adsorbing chamber, whereas chamber 22B is referred to as a desorbing chamber, with the understanding that each chamber serves an adsorbing and desorbing function, and that the description that follows is intended to convey operations at a certain stage or instance or period of time. The routing of the heat of adsorption to a sealed, partial-vacuum chamber obviates the conventional need to introduce a significant amount of heat for regeneration (e.g., to release the water vapor).

[044] The energy recovery subsystem 14 comprises a condenser 24 coupled to a coolant source 26, a variable compression, variable speed vacuum pump 28 arranged at an input to the condenser 24, a check valve 30 arranged at an input to the vacuum pump 28, and a valve (e.g., 3-way valve) 32 arranged between the chambers 22 and fluidly coupled to the check valve 30. The energy recovery subsystem 14 further comprises a water pump 34 arranged at the output of the condenser 24. The energy recovery system 14 captures the beneficial heat energy from the output (e.g., for the phase transition from water vapor to liquid), which reduces the energy that would normally be consumed at the compressor (e.g., which in conventional compressor-based systems may be 90% of the total energy consumed by a compressor-based air conditioning system).

[045] The control system or controller 16 (hereinafter, referred to as a controller) receives input from plural coupled sensors 36 distributed throughout the LEHS 10, including at the chambers 22, exposed to the humid air and dry air flows, respectively, and at the condenser 24 as depicted in Figure 1A. The communications between the sensors 36 may be unidirectional or bi-directional, and achieved wirelessly and/or via wired connections. In one embodiment, the sensors 36 are configured as temperature and/or humidity sensors. Other types of sensors may also be used in the same and/or additional or other locations throughout the LEHS 10. The control system 16 may also provide for outputs that use control signals to trigger or actuate motive devices used throughout the LEHS 10, including providing control signals for opening and closing gates or doors 38 (hereinafter, referred to as doors for brevity) of the chambers 22.

[046] It should be appreciated that the LEHS 10 depicted in Figure 1A is one example embodiment and that some embodiments may include fewer components, additional components, or a different arrangement of components and/or different types of devices for achieving a similar function or purpose.

[047] Continuing with a further explanation of the components and operations, an embodiment of the LEHS 10 comprises plural (e.g., two) heat exchangers 20, each of the heat exchangers 20 further comprising a coating of an adsorbent material. The adsorbent material is formulated to adsorb and desorb certain gas molecules in an air stream. In one embodiment, the targeted gas for adsorption/desorption is water vapor. The adsorbent material is comprised of a metal organic framework (MOF), including for instance, MIL 100 Fe, which is engineered to adsorb water vapor from an air stream (e.g., humid air) in normal atmospheric conditions. The MOF also desorbs the water vapor when in a partial vacuum. The coated heat exchangers 20 are comprised of a plurality of metal surfaces, including aluminum, copper, or other thermally conductive material. Non-metal materials, including thermally conductive composites of graphene or metallized plastics, may alternatively comprise all or part of the heat exchangers 20 in some embodiments. The type of construction for each of the heat exchangers 20 may be a tube and fin configuration, microchannel configuration (with a stepped inlet manifold and outlet manifold providing for variable volume in step-wise, or in some embodiments, gradual, increments of volume change to deliver a balanced flow of coolant to each of the microchannels of the heat exchanger), rolled fin, or another structure with suitable surface area.

[048] The heat exchangers 20 have paths or channels for a cooling media. The cooling media comprises a fluid, including water, water/glycol, nanofluid, or refrigerant, which flows from an adsorbing heat exchanger that is adsorbing the water vapor from the air stream to a desorbing heat exchanger that is desorbing water vapor. In one embodiment, the fluid may be moved in a loop (e.g., conduit, including piping, tubing, hose, etc.) by the transfer pump 18. The fluid transfers the heat of adsorption collected by the adsorbing heat exchanger (e.g., 20A) to the desorbing heat exchanger (e.g., 20B). The LEHS 10 further comprises the plural (e.g., two) chambers 22 that each contain one of the coated heat exchangers 20. The heat exchangers 20 may be comprised of multiple heat exchangers arranged sequentially in the air stream and the cooling paths or channels may be connected in series or parallel or a combination of series and parallel connections. The multiple heat exchangers 20 may all be coated with the same adsorbent or one or more may be coated with a different adsorbent. The chambers 22 are configured so that the desorbing heat exchanger (e.g., 20B) may be sealed and placed in a partial vacuum to desorb the water vapor from the MOF coating of the heat exchanger 20B, and after it has fully surrendered the water vapor, opened (via a pair of doors 38B that open) to the flow of the air

stream to adsorb the water vapor from the air stream while the other chamber 22A is sealed in a partial vacuum and the water vapor desorbed. The sealing is achieved at least in part by the closing of the pair of doors 38 (e.g., 38A for chamber 22A, 38B for chamber 22B), each of the pair of doors 38 moved by a motive device (e.g., motor or an actuator) to a first position where it contacts a pliable material (e.g., compressible seal) such as a soft rubber ring or tube that is compressed between the door and the mouth of each end of a given chamber 22. The compression of the ring or tube is either by the negative pressure of the vacuum, by force of a motive device, or both. The motive device may comprise a gear motor, a solenoid, or a pneumatic or hydraulic or electric cylinder. The movement of the doors and the timing of the vacuum is controlled by the controller 16 in one embodiment. Note that a pair of doors 38 is described for each chamber, though in some embodiments, a different quantity of doors may be used for the assembly of chambers and/or for each chamber.

[049] The chambers 22 are connected by the valve 32 (e.g., three-way valve) to a vacuum line 126 leading to the vacuum pump 28. The three-way valve 32 is moved by a motive device (e.g., motor or solenoid). The three-way valve 32 switches the vacuum to the sealed desorbing chamber 22B and provides for evacuating of the water vapor from the adsorbent material. The three-way valve 32 may be arranged directly between the chambers 22 as shown in Figure 1A, or in some embodiments, it may be connected by pipes or hoses to ports through the wall of each chamber 22. The water vapor is drawn via conduit through the check valve 30 that keeps the desorbing chamber 22B under vacuum until the three-way valve 32 is switched over to connect to the adsorbing chamber 22A, which results in a release of the pressure on the chamber doors 38B and allows the doors 38B of the desorbing chamber 22B to open.

[050] The vacuum pump 28 is now connected via conduit to the adsorbing chamber 22A. The chamber doors 38A of the adsorbing chamber are closed (sealed), and the vacuum pump 28 moves the air out of the chamber 22A and the water vapor begins desorbing from the adsorbent material under the partial vacuum according to the alternating function of each chamber. The vacuum pump 28 is configured as a low torque, low-compression (e.g., approximately 1.6 – 1.8 compression ratio), high volume pump to move water vapor to the condenser 24 without the water vapor condensing within the pump 28. The vacuum pump 28 may comprise a rotary vane pump with a variable compression ratio, however other types of pumps may be used, including centrifugal, diaphragm, or peristaltic pumps. In some

embodiments, a series of two or more vacuum pumps that can be independently controlled may be implemented to function like a single variable compression pump. The vacuum pump 28 may comprise a cam ring, a rotor with moveable blades, a rotor shaft, and an adjustment mechanism, which in one embodiment comprises fasteners (e.g., screws, levers, etc.), to change the compression of the pump. In some embodiments, the adjustment mechanism may be configured to be used with a motive device, such as a push-rod actuated by an actuator, or in some embodiments, a threaded rod actuated by a motor. The vacuum pump 28 may also comprise a variable speed motor coupled thereto, which connects to one end of the rotor shaft. The adjustment mechanism allows the center of rotation to be adjusted to change the swept volume between the rotor and the cam ring to change the compression of the pump 28. The adjustment mechanism enables the vacuum pump 28 to be set for a certain range of performance for the LEHS 10.

[051] As explained above, a number of sensors 36, including temperature, humidity, and pressure sensors, are placed in the two chambers 22 and in the air stream before and after the heat exchangers 20, as well as before or, as shown in Figure 1A, after the vacuum pump 28. The sensors 36 are monitored by the controller 16. The controller 16 adjusts the timing of the chamber doors 38, the operation of all the pumps 18, 28, 34, and the three-way valve 32 based upon the conditions monitored by the sensors 36. For example, if the temperature of the desorbing chamber 22B falls below a programmed minimum temperature, then the controller 16 can increase the speed of the transfer pump 18 to move more heat from the adsorbing chamber 22A and slow the vacuum pump 28 to reduce the rate of desorption. Also the speed of transfer pump 18 is controlled to maintain the temperature of the adsorbing chamber 22A within a few degrees of the desorbing chamber 22B, preferably four to five degrees Celsius. In one embodiment, the speed of either pump (e.g., the vacuum pump 28 or the transfer pump 18) may be adjusted to keep the chambers isothermal. For instance, speeding up the vacuum pump increases the rate of desorption, which soaks up more heat, and speeding up the transfer pump moves more heat from the adsorbing chamber to the desorbing chamber. In some embodiments, either or both may be adjusted to keep the temperature of each chamber close together.

[052] The controller 16 for the LEHS 10 monitors a plurality of temperature, humidity, and pressure sensors 36 and actuates a motive device (e.g., motor or actuator) which in turn activates the adjustment mechanism (of the vacuum pump 28) to cause an increase in the

compression to raise the temperature of the water vapor, to prevent condensation within the vacuum pump 28, as well as maintain a target temperature in the condenser 24. Conversely, the controller 16 causes a decrease in the compression to lower the temperature of the water vapor. The condenser 24 ideally has a pressure that is between the pressure of the desorbing chamber (10-20 mbar) and the ambient pressure. In one embodiment, the pressure in the condenser 24 is 40-60 mbar. Operation according to this pressure range reduces the required compression ratio of the vacuum pump 28, which drastically reduces the power required to move the water vapor. The higher the pressure required for the vacuum pump 28 to move the water vapor towards ambient pressure, the larger the power required by the vacuum pump 28. Another factor to consider is that, the lower the pressure in condenser 24, the lower the saturation temperature. When the relative humidity is high (and hence a high rate of desorption) there is a risk associated with using too low of a compression ratio since the water may condense within vacuum pump 28, which reduces pump efficiency (e.g., increases the power requirement). Therefore, there is a balance to maintain between compression ratio, the amount of water being desorbed, and the temperature within the condenser 24. Once the water is in a liquid state, it is relatively non-compressible, and it is pumped to ambient pressure (for storage or other use) using the pump 34 that requires only a modest amount of power. Controlling the temperature of the condenser 24 enables the LEHS 10 to capture usable thermal energy by maintaining the proper temperature for a target application, such as hydronic heating or warming an air stream. In some embodiments, the condenser is designed to create its own partial pressure vacuum, thereby reducing energy consumption even further.

[053] The controller 16 may also vary the speed of the motor coupled to the vacuum pump 28, driving the vacuum pump 28 to match the desorption rate of the water vapor to the absorption rate of water vapor from the air stream by using measurements from the temperature and humidity sensors 36 to determine the required rate of desorption by the vacuum pump 28 to match the rate of water vapor being adsorbed from the air stream.

[054] In one embodiment, the controller 16 may comprise a computer device (e.g., an electronic control unit or ECU), a programmable logic controller (PLC), field programmable gate array (FPGA), application-specific integrated circuit (ASIC), among other devices, and in some embodiments, functionality of the latent energy harvesting system may be implemented using plural controllers (e.g., using a peer-to-peer or primary-secondary methodology). In one

embodiment, the controller 16 comprises one or more processors, input/output (I/O) interface(s), and memory, which may all be coupled to one or more data busses. The memory may include any one or a combination of volatile memory elements (e.g., random-access memory RAM, such as DRAM, and SRAM, etc.) and nonvolatile memory elements (e.g., ROM, Flash, hard drive, EPROM, EEPROM, CDROM, etc.). The memory may store a native operating system, one or more native applications, emulation systems, or emulated applications for any of a variety of operating systems and/or emulated hardware platforms, emulated operating systems, etc. The memory may comprise a non-transitory medium that may store software for implementing functionality of the LEHS 10 as described above.

[055] Execution of the software may be implemented by one or more processors of the controller 16 (or plural controllers) under the management and/or control of an operating system, though in some embodiments, an operating system may be omitted. Such processors may be embodied as a custom-made or commercially available processor, a central processing unit (CPU) or an auxiliary processor among several processors, a semiconductor based microprocessor (in the form of a microchip), a macroprocessor, one or more application specific integrated circuits (ASICs), a plurality of suitably configured digital logic gates, and/or other well-known electrical configurations comprising discrete elements both individually and in various combinations to coordinate the overall operation of the controller 16.

[056] When certain embodiments of the controller 16 are implemented at least in part as software (including firmware), it should be noted that the software can be stored on a variety of non-transitory computer-readable medium for use by, or in connection with, a variety of computer-related systems or methods. In the context of this document, a computer-readable medium may comprise an electronic, magnetic, optical, or other physical device or apparatus that may contain or store a computer program (e.g., executable code or instructions) for use by or in connection with a computer-related system or method. The software may be embedded in a variety of computer-readable mediums for use by, or in connection with, an instruction execution system, apparatus, or device, such as a computer-based system, processor-containing system, or other system that can fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions.

[057] When certain embodiment of the controller 16 are implemented at least in part as hardware, such functionality may be implemented with any or a combination of the following

technologies, which are all well-known in the art: a discrete logic circuit(s) having logic gates for implementing logic functions upon data signals, an application specific integrated circuit (ASIC) having appropriate combinational logic gates, a programmable gate array(s) (PGA), a field programmable gate array (FPGA), etc.

[058] The condenser 24 comprises a cold wall 178 where the water vapor can condense and fall into a sump 180. The cold wall 178 may be comprised of one or more walls with ridges or fins to provide the necessary surface area for condensation and heat transfer. The walls may be angular, cylindrical, or cone shaped. The cold wall 178 transfers the heat of condensation to a cooling media, such as a gaseous refrigerant or water that flows in a cavity or channels near the cold wall 178. The cooling media is warmed and flows away from the condenser 24 where the heat may be used in other processes. The liquid water collects in the sump 180 and may be moved by the water pump 34 to a storage tank (not shown) where it can be used for other processes. The condenser 24 is useful in capturing the latent heat energy from the water vapor and is preferably insulated from the environment to maximize the capture of the useful thermal energy. The insulation may be a foam or fiberglass layer wrapped around the condenser 24 or the condenser may be enclosed in a rigid housing and the space in between the housing and the condenser is a vacuum.

[059] In general, the LEHS 10 may be used to recover the latent energy of a gas, such as water vapor, in the atmosphere, and collect the condensate for reuse or storage. The adsorbent coating on the heat exchangers may alternatively comprise an adsorbent such as a MOF configured to adsorb carbon dioxide, sulfur dioxide, or other gases for reuse or removal from the atmosphere. However, water vapor is a larger fraction of the air flow than carbon, sulfur, or nitrogen oxides, and so is a much larger reservoir of latent energy in the atmosphere. An adsorbent comprising a MOF that is extremely hydrophilic in ambient conditions and then easily releases the water vapor in a partial vacuum is generally preferred to maximize the harvesting of latent energy in the atmosphere. Some examples of MOF include MIL-100(Fe), MOF 303, and MOF 801.

[060] As explained above, in some types of systems, a saturated adsorbent is desorbed (regenerated) by application of heat. The heat source is often an electric coil, which uses a significant amount of electrical energy since the coil must offset the heat taken by the water vapor leaving the adsorbent. For instance, the thermal energy released during adsorption is 630

to 690 watt hours per liter of water, depending upon temperature, properties of adsorbent, and relative humidity. An electric coil uses 630 watts of electric energy to desorb 1 liter of water, which results in a coefficient of performance (COP) of 1. In contrast, the LEHS 10 uses a vacuum to regenerate the adsorbent material, which uses approximately 40 watt hours per liter, providing a COP of 16 to desorb the water vapor. Variations in efficiency in vacuuming the water vapor and condensing the water for different applications may result in a COP range from 10 to 20. For example, the LEHS 10 that is able to condense the water vapor at a temperature below ambient is able to achieve a COP of 20 because the power consumed by the vacuum pump is lowered to 30 watt hours per liter.

[061] An example method of operation of the adsorbing and desorbing chambers may be described as follows, the method implemented using programming code that is executed by the controller 16 in conjunction with one or more motive devices and input from one or more sensors. The designation of chamber A and B is arbitrary, and is only meant to describe the sequence of adsorbing and then desorbing in one chamber while desorbing and then adsorbing in a second chamber. Temperature and humidity sensors may be placed in each chamber and the humidity level sensed is one possible method of triggering the cycle change for the chambers. An alternate method is to use the temperature and humidity of the incoming air stream based on preset parameters that determines the amount of time for each adsorb/desorb cycle. Another method is to use the temperature in each chamber to determine the trigger points for each cycle change for the chambers. In one embodiment, the method comprises closing the doors (e.g., the pair of doors) to chamber A, sealing chamber A, drawing a vacuum on chamber A, measuring humidity in chamber A, at a predefined relative humidity (e.g., 10%, though not limited to 10%), releasing the vacuum on chamber A, and opening doors to chamber A. The method further comprises closing doors (e.g., the pair of doors) to chamber B, sealing chamber B, drawing a vacuum on chamber B, measuring humidity in chamber B, at a predefined relative humidity (e.g., 10%), releasing the vacuum on chamber B, opening doors to chamber B, and repeating the method. Further information about an LEHS may be found in U.S. publication number, US 20210055010A1, also having serial number 16/993,699, entitled "Method and System for Dehumidification and Atmospheric Water Extraction with Minimal Energy Consumption", which is hereby incorporated by reference in its entirety.

[062] The process of dehumidification derived by an LEHS (e.g., LEHS 10) in an HVAC system can be illustrated by a psychrometric analysis as depicted in Figure 1B as the process (1 to 2). As is known, the psychrometric chart 100 includes information (e.g., at sea level) about dry bulb temperature (e.g., degrees F), wet bulb temperature (e.g., degrees F), specific volume (e.g., ft³/lb of dry air), humidity ratio (e.g., grains of moisture per pound of dry air), vapor pressure (e.g., inches of mercury), dew point (e.g., degrees F), relative humidity, enthalpy (e.g., BTU per pound of dry air), and saturation temperature (e.g., degrees F). The information of psychrometric, including terms, parameters, and units, are well-recognized in the industry, and hence explanation of the same is omitted for brevity. Figure 1B is a representation to show how implementing a LEHS in a conventional HVAC system impacts the psychrometric chart 100, where the dashed line from (1) to (2) represents dehumidification by the LEHS. Stage 1 is at 98°F dry bulb temperature, 83°F wet bulb, 55% relative humidity, and 47 BTU per pound enthalpy (typical ambient). The LEHS then dehumidifies the airstream to stage 2 at 101°F dry bulb temperature, 69.5°F wet bulb temperature, 20% relative humidity, and 33.5 BTU per pound enthalpy. This trend shows a process that has a very minimal change in the dry bulb temperature but a drastic difference in the enthalpy (13.5 BTU per pound change) and the wet bulb temperature. In other words, the trend shows the effect of conditioning of an airstream with an LEHS, essentially realizing a reduction of the wet-bulb temperature of the airstream with an insignificant amount of convection of sensible heat into the conditioned airstream, i.e. with little rise of the dry bulb temperature. Note that the depiction of the nearly vertical line downward on the psychrometric chart of the effect of the LEHS as to conditioning the air is indicative of a comparatively modest convection of sensible heat into the conditioned air stream, which heating is derived from a convection of a portion of the heat of adsorption of water vapor by the desiccant with the majority of the heat of adsorption being thermally transferred to cancel against the cooling associated with desorption on the alternative heat exchanger in the desorbing chamber.

[063] The air stream that is dehumidified by the LEHS incurs a depression of the wet bulb temperature. When the airstream entering a subsequent evaporation process is first dehumidified, a lower dry bulb temperature can be achieved compared to a higher wet bulb temperature of an air stream that was not dehumidified before using an evaporation process. Effectiveness is a measure of how closely the cooled “supply” of air temperature leaving the

evaporative cooler approaches the ambient wet bulb temperature of the air that is entering the cooling system. In comparison to conventional direct evaporative cooling systems, which typically have a cooling effectiveness of up to 75%, the cooling effectiveness of an LEHS enhanced evaporative cooling system may be greater than 100% of wet bulb temperature and may achieve cooling lower than the dew point temperature of the source air. Additionally, an LEHS may be used to dehumidify an airstream that has been humidified and cooled by an evaporation process. That humidified airstream is the product of direct evaporative cooling or the secondary airstream of an indirect evaporative cooling system, again depressing the wet bulb temperature of the evaporatively cooled and hence dehumidified airstream. The following description demonstrates applications where an LEHS may be beneficially deployed, including: upstream, and/or midstream, and/or downstream of an evaporator(s) with similar effect as is illustrated in the psychrometric chart 100 in Figure 1B as process (1 to 2) for beneficial use in cooling, or for heating, or for combined cooling and heating purposes.

[064] The LEHS is a very effective “upstream dehumidifying pre-conditioner” of an airstream that may be used for evaporation, as the LEHS depresses the wet bulb temperature of the airstream that induces evaporation. Similarly, an LEHS is a very effective “downstream dehumidifying post-conditioner” of an airstream that has been cooled and humidified by direct evaporation, or which airstream has been indirectly cooled and thus had its relative humidity increased.

[065] The water vapor and the associated latent energy that is in the water vapor that the LEHS “harvests” is condensed to liquid water in the condenser component of the LEHS, and this change of phase of the water vapor to liquid causes the conversion of latent energy to sensible heat. The water vapor that is harvested by the LEHS may originate from an ambient airstream, or it may be water vapor that is realized from evaporation by an evaporator (e.g., as a by-product of evaporative cooling). Hence, the LEHS functions as an enablement of enhanced evaporative cooling and enables what may simultaneously be called an “evaporation sourced heating” functionality: Every British Thermal Unit (BTU) of cooling availing a single BTU of sensible heating which systems of combined thermal cycle of evaporation, cooling and heating are contemplated embodiments of these systems.

[066] Dehumidification by an LEHS installed in the airstream that may be used in the evaporation process dramatically enhances the beneficial utilization of evaporative cooling when

the supply or ambient airstream is humid. Additionally, an evaporative cooling system water usage efficiency may be greatly improved by recuperation of the water vapor that is formed as evaporate from an evaporation process by processing the humidified airstream that exits the evaporator with an LEHS to harvest the infused water vapor and to condense to liquid water. Also, when water vapor is harvested from an ambient air stream (or a process drying air stream), abundant clean water may be produced for use in evaporative cooling systems. Evaporative cooling systems may become a water positive process (i.e., produce liquid water as a by-product of the cooling process), instead of a water consuming process. Harvesting water vapor from the supply airstream or the ambient atmosphere airstream and subsequently condensing the water vapor yields the heat of vaporization that is latent in the water vapor. When evaporation is caused to occur in an evaporative system, sensible heat is converted to latent energy stored within water vapor. Hence, when the evaporate (i.e., the water vapor) is harvested during LEHS induced dehumidification, and the water vapor is condensed and the latent energy of vaporization is converted to sensible heat, the equivalence of “evaporative heating” is achieved, while simultaneously deriving “evaporative cooling”, with the beneficial by-product(s) of the LEHS-enhanced evaporative cooling being either cooling, or heating, or both cooling and heating, and the production of liquid water. An LEHS is a system device that may effectively and efficiently harvest water vapor and which, when coupled with a condensing unit, derive liquid water and conversion of latent energy to sensible heat, wherein an evaporation process derives conversion from sensible heat to latent energy. Therein, the coupling of an LEHS with a direct and/or indirect evaporation cycle provides for exceptional effectiveness and efficiency of cooling and/or heating, and of liquid water usage efficiency, or even deriving liquid water production.

[067] The principle behind the workings of an example conventional direct evaporative cooling (DEC) system 200 and a simplified flow scheme are presented in Figure 2. The illustration shows that warm/hot air enters the wetted evaporator 202 through the inlet. The heat transfer is shown from the warm air to the water. Heat is transferred by the warm air stream that is comprised as sensible heat and becomes absorbed by the evaporated water vapor as latent heat. Corresponding to the value of latent heat of vaporization, a part (volume) of the water is evaporated, becoming infused as water vapor into the flowing airstream, increasing the moisture content in the airstream. The temperature of the outlet air decreases due to the sensible heat

transferred by the warm air, but the enthalpy of the outlet air remains the same with the enthalpy of the inlet air because of the latent heat infused into the air as moisture.

[068] The working process of the conventional direct evaporative cooling system is presented in the psychrometric chart 300 in Figure 3. Warm air enters (1) the inlet of the direct evaporative cooler 202, wherein sensible heat transfer is realized from the warm air to the water. Heat is transferred by the warm air stream as sensible heat and becomes absorbed by the evaporated water vapor as latent heat. Corresponding to the value of latent heat of vaporization, a part (volume) of the water is evaporated becoming infused as water vapor into the flowing airstream, increasing the moisture content of the airstream (1-2a). The temperature of the outlet air (2a) decreases due to the sensible heat transferred by the warm air, but the enthalpy of the outlet air remains the same with the enthalpy of the inlet air because of the latent heat infused into the air as moisture. At the limit, the airstream becomes saturated (2b) with moisture and the temperature is decreased to the wet bulb temperature at the inlet. The main advantage of conventional direct evaporative cooling is represented by the very simple construction of the equipment. The main disadvantages of the direct evaporative cooling are represented by: the increase of the air moisture content for which many applications will be undesirable, the limited effectiveness of the amount of sensible cooling that can be achieved being constrained to the wet bulb temperature at saturation, the consumption of a supply liquid water by conversion to an evaporate, and the inability to selectively make beneficial use of the latent energy within the evaporatively cooled and humid air. There is a need for a direct evaporative cooling system or systems that eliminate or mitigate one or more of these main disadvantages.

[069] The utilization of an LEHS enhances a direct evaporative cooling system that may completely or largely resolve the main disadvantages of direct evaporative cooling. A principle of the working of an example direct evaporative cooling (DEC) system augmented/enhanced with an LEHS, the system denoted as system 400, and a simplified flow scheme is presented in Figure 4. The warm/hot air enters an evaporator 402 (e.g., equipped with a pad or wettable surface that is sprayed with water, or alternatively, enters a misting of a stream of liquid water) at the wet bulb (WB) temperature of the inlet air. The heat transfer is realized from the warm air to the cooler water. Heat is transferred by the warm air stream as sensible heat and is absorbed by the water as latent heat. Corresponding to the value of latent heat, a portion (volume) of the water is evaporated, being infused as water vapor into the flowing air, increasing the moisture

content of the airstream. The temperature of the outlet air decreases due to the sensible heat transferred by the air, but the enthalpy of the outlet air remains the same with the enthalpy of inlet air because of the latent heat infused into the air as moisture. The cooled and humidified airstream then enters the adsorbing chamber of an LEHS 404, where water vapor is adsorbed into the desiccant coated on the heat exchanger, thereby decreasing the moisture content of the evaporatively cooled air stream, and the LEHS 404 lowers the wet bulb temperature but does not appreciably change the sensible temperature of the dehumidified airstream because of the near isothermal operation of the desiccant coated heat exchanger in the adsorbing chamber. The enthalpy of the cooled airstream is decreased due to the extraction of the latent energy that is derived with the removal of the water vapor from the cooled airstream. The water condensate derived in the condenser of the LEHS 404 can be air cooled and reutilized as a supply of liquid water for the evaporator, thereby realizing a high degree of water efficiency of the evaporative cooling system 400.

[070] The working process of the direct evaporatively cooled system 400 augmented with the installation of an LEHS in the evaporatively cooled air downstream of the evaporator 402 is presented in the psychrometric chart 500 in Figure 5. The dashed line represents dehumidification by the LEHS 404. The working process as depicted in (1-2) is of the evaporative cooling and humidification stage retaining constant enthalpy in (2-3) of the LEHS 404 harvesting the water vapor and dehumidifying the evaporatively cooled air stream, whereby there is a lowering of the wet bulb temperature and of the enthalpy of the cooled and dehumidified air stream. The latent energy is transferred from the air stream into the desiccant of the LEHS 404 and then (not depicted in the psychrometric chart 500) the heat is further transferred during the regeneration of desiccant by the vacuum pump of the LEHS 404 to the partial pressure condenser of the LEHS 404, wherein the latent energy is converted to sensible heat for selective use as beneficial evaporation sourced heating. The limit of the effective amount of sensible cooling that may be achieved is constrained to the wet bulb temperature at saturation (2a). The limit of the effective relative humidity that may be achieved approaches zero in theory (3a) and to (3b) if the evaporative cooling is taken to the limit of saturation as depicted by (2a). Most typically, the system is operated to provide for the targeted relative humidity of the climate-controlled zone (e.g., in occupied spaces, a relative humidity of 40 to 60% being customary). Lower relative humidity may be achieved, if desired. In effect, the

system embodiment 400 enables cooled air with lower relative humidity (e.g., as compared to a comparable direct evaporative cooling system (i.e., without beneficial augmentation of an LEHS)) and provides for higher efficiency of water by recycling all or a portion of the evaporate. The system 400 may selectively provide for beneficial use of evaporation sourced heating.

[071] A working principle of another embodiment of a direct evaporative cooling (DEC) system augmented with an LEHS installed upstream of the evaporator (collectively denoted as system 600) and a simplified flow scheme is shown in Figure 6. The warm/hot inlet air enters an adsorbing chamber of an LEHS 602, whereby the warm air is dehumidified by contact with the desiccant coating of the heat exchanger of the LEHS 602, and wherein the wet bulb temperature of the warm air is depressed, and the enthalpy of the warm air is reduced by the transfer of latent heat within the water vapor that is adsorbed from the warm air to the desiccant. The dehumidified and lowered enthalpy warm air enters an evaporator 604 and makes contact with a wetted surface, which is sprayed with water (or e.g., alternatively enters a misting of a stream of liquid water) with the dehumidified air at a lower wet bulb (WB) temperature, compared to the wet bulb temperature of the initial warm inlet air. Heat transfer is realized from the warm dehumidified air to the cooler water. Heat is transferred by the warm air stream as sensible heat and is absorbed as latent heat during the vaporization of the water. Corresponding to the value of sensible heat converted to latent heat, a portion (volume) of the water is evaporated, being infused as water vapor into the flowing air, increasing the moisture content of the airstream. The dry bulb (DB) temperature of the outlet air from the evaporator 604 decreases due to the sensible heat transferred by the air, but the enthalpy of the evaporatively cooled air remains the same with the enthalpy of dehumidified inlet air because of the latent heat infused into the air as moisture.

[072] The working process of the direct evaporative cooling system 600 augmented with the installation of an LEHS 602 upstream of the evaporator 604 is presented in the psychrometric chart 700 in Figure 7, where the dashed line represents dehumidification by the LEHS 602. The working process of the LEHS harvesting the water vapor and dehumidifying the warm air stream, whereby there is a lowering of the wet bulb temperature and of the enthalpy by dehumidification of the air stream, is depicted as (1-2), followed by (2-3) of the evaporative cooling and humidification stage retaining constant enthalpy. First, the latent energy is transferred from the air stream into the desiccant of the LEHS 602 (1-2) and then (not depicted in

the psychrometric chart 700) the water vapor with the latent energy is further transferred during the regeneration (in the LEHS 602) of desiccant by the vacuum pump to a condenser operating at partial pressure wherein, upon condensing, the latent energy is converted to sensible due to the phase change from vapor to liquid water and thereby realizing evaporation sourced heating. The evaporative cooling working process depicted as (2-3) is realized at constant enthalpy, as it can be observed on the psychrometric chart 700. At the limit, the cooling process may continue until the state of saturation depicted as (3a). The limit of the effective relative humidity that may be achieved approaches zero in theory. If the relative humidity was to approach zero, then the dry bulb temperature may be lowered towards (2a) and at the limit, the direct evaporative cooling process may continue until the state of saturation depicted as (4a). In the depicted system 600 (e.g., of an LEHS enhanced direct evaporative cooling system), the system 600 may produce a much lower wet bulb (WB) and dry bulb (DB) temperature and much lower absolute moisture content in the air, and an enhanced efficiency of water usage, than a conventional direct evaporative cooling system (i.e., without a beneficial LEHS augmentation). This embodiment of an evaporative cooling system 600 beneficially augmented by an LEHS 602 upstream of the evaporator 604 may realize a cooler WB temperature than the previously-described LEHS augmented embodiment wherein the LEHS 404 is installed downstream of the direct evaporator 402 (e.g., system 400 of Figure 4), especially in humid environments, but the system 600 may produce supply air with higher relative humidity than the system 400 with the LEHS 404 that is installed downstream of the direct evaporator 402. This embodiment of an LEHS enhanced direct evaporative cooling system 600 provides for selective beneficial use of evaporation sourced heating.

[073] A principle of the working of an embodiment of a direct evaporative cooling (DEC) system 800 augmented with a first LEHS 802 installed upstream of a direct evaporator 804 and a second LEHS 806 installed downstream of the direct evaporator 804, and a simplified flow scheme are presented in Figure 8. The warm/hot inlet air enters an adsorbing chamber of the LEHS 802, whereby the hot air wet bulb temperature is depressed and the air is dehumidified by contact with the desiccant coating of the heat exchanger of the LEHS 802. The enthalpy of the warm air is reduced by the transfer of latent heat within the water vapor that is adsorbed from the warm air to the desiccant. The dehumidified and lowered enthalpy hot air enters the evaporator 804, where a surface is sprayed with water (or e.g., alternatively enters a misting of a stream of

liquid water) with the dehumidified air at a lower wet bulb (WB) temperature compared to the wet bulb temperature of the initial hot inlet air. Heat transfer is realized from the warm dehumidified air to the cooler water. Heat is transferred by the warm air stream as sensible heat and is absorbed as latent heat as the water evaporates. Corresponding to the value of sensible heat converted to latent heat, a part (volume) of the water is evaporated, being infused as water vapor into the flowing air, increasing the moisture content of the airstream. The dry bulb (DB) temperature of the outlet air of the upstream LEHS 802 decreases while passing through the evaporator 804 due to the sensible heat transferred by the air, but the enthalpy of the evaporatively cooled air remains the same with the enthalpy of dehumidified inlet air because of the latent heat infused into the air as moisture. The cooled and humidified airstream then exits the evaporator 804 and enters the adsorbing chamber of the downstream LEHS 806, within which water vapor is adsorbed into the desiccant coated onto the heat exchanger, thereby decreasing the moisture content and the wet bulb temperature of the evaporatively cooled air stream but not appreciably changing the sensible temperature of the dehumidified airstream. The enthalpy of the cooled airstream is decreased due to the extraction of the latent energy that is derived with the removal of the water vapor from the evaporatively cooled airstream.

[074] The water condensate derived in the condenser of each or any of the LEHSs may be air cooled (or otherwise cooled) and reutilized as a supply of liquid water for the evaporator thereby realizing a high degree of water efficiency of the evaporative cooling system. In moderately humid and humid environments, this embodiment can produce an abundance of liquid water as a by-product of evaporative cooling, deriving more water than is evaporated because the system is first harvesting water from the incoming warm air stream to first dehumidify the warm air stream to realize a lowered wet bulb temperature for more effective evaporation, and cooling and dehumidifying the evaporatively cooled but humid air stream to a desirable lower relative humidity cool air stream.

[075] The working process of the system 800 comprising the DEC equipment augmented with the installation of a first LEHS 802 upstream of the evaporator 804 and a second LEHS 806 downstream of the evaporator 804 is presented in the psychrometric chart 900 in Figure 9, where the dashed line represents dehumidification by the LEHSs. The working process of the first LEHS 802 harvesting the water vapor and dehumidifying the warm air stream is depicted as (1-2), whereby there is a lowering of the wet bulb temperature and of the enthalpy by

dehumidification of the air stream followed as depicted by (2-3) of the evaporative cooling and humidification stage retaining constant enthalpy. First, the latent energy is transferred from the air stream into the desiccant of the LEHS 802 and then (not depicted in the psychrometric chart 900) further transferred during the regeneration of desiccant by the vacuum pump to the partial pressure condenser of the LEHS 802, wherein the latent energy is converted to sensible deriving evaporation sourced heating. The evaporative cooling working process depicted as (2-3) is realized at constant enthalpy as it can be observed on the psychrometric chart 900. At the limit, the evaporative cooling process may continue until the state of saturation depicted as (3a). The working process of the second LEHS downstream 806 of the evaporator 804 is depicted as (3-4) with harvesting the water vapor and dehumidifying the evaporatively cooled air stream, whereby there is a lowering of the wet bulb temperature and of the enthalpy of the direct evaporatively cooled, yet dehumidified air stream. The latent energy being transferred from the air stream into the desiccant of the LEHS 806 and then (not depicted in the psychrometric chart 900) is the heat further transferred during the regeneration of desiccant by the vacuum pump to the partial pressure condenser of the LEHS 806, wherein the latent energy is converted to sensible thereby deriving evaporative sourced heating, the limit of the effective amount of sensible cooling that can be achieved being constrained to the WB temperature at saturation (3a). The limit of the effective relative humidity that may be achieved approaches zero in theory (depicted as 2a or 4a), but most typically the second in series LEHS 806 may be operated to provide for the targeted relative humidity of the climate-controlled zone as depicted at (4), (e.g., in occupied spaces, a relative humidity of 40 to 60% being customary). Lower relative humidity may reasonably be achieved, if desired. If the direct evaporative cooling is realized to the limit and saturation occurs (depicted as 3a), then if dehumidification by the downstream LEHS 806 is in turn taken to the limit of zero humidity, a state of temperature and humidity depicted as (4b) may be realized. If dehumidification by the upstream LEHS 802 is taken to the limit of zero humidity as depicted by (2a) and if evaporative cooling is in turn taken to the limit of saturation as depicted by (3b), then a state of temperature and humidity depicted as (4c) may be realized. Compared to conventional direct evaporative cooling (i.e., without beneficial LEHS augmentation), this embodiment provides for the following performance/benefits: achieving greater effectiveness of cooling (i.e., a lower wet bulb (WB) temperature), being capable of achieving below the dew point of the warm entering air stream; achieving a lower relative humidity of the cooler air,

achieving greatly enhanced efficiency of water use, including the production of liquid water as a by-product; and achieving evaporative sourced heating, which may be used for beneficial purposes, such as heating domestic hot water, or process heating.

[076] To achieve yet cooler temperatures of an airstream, direct evaporative cooling systems incorporating an LEHS after each stage of direct evaporative cooling may be performed in two or more stages in series (e.g., as reflected by the psychrometric chart 1000 of Figure 10). In one embodiment, a system comprising stages in series of direct evaporative cooling for highly humid or moderately humid environments may have an LEHS installed upstream of the airstream of the first direct evaporator such that it lowers the wet bulb temperature of the airstream used in the first stage of direct evaporative cooling to realize a greater cooling effect of the first evaporator. A second LEHS is installed downstream of the first evaporator to dehumidify the cooled airstream before passing the cooled and dehumidified airstream to a second in series direct evaporator, and then repeating such stages until the airstream is cooled to near freezing or towards the limit to freezing, which may be useful for low temperature refrigeration applications and low temperature processes. For arid environments with low relative humidity, one embodiment may dispense with utilizing an LEHS in the airflow upstream of the first evaporator in an embodiment using stages in series of LEHS enhanced direct evaporative cooling. Wherein two or more LEHS can be used with a first LEHS positioned such as to dehumidify an airstream upstream of an evaporator and a second LEHS positioned downstream of an evaporator, an alternative system architecture would involve split ducting so as to utilize one LEHS to perform the dual purposes of 1) dehumidifying the airstream first upstream of the evaporator and 2) dehumidifying the evaporatively cooled airstream that is downstream of the evaporator. The dual purposing can be accomplished by utilizing parallel ducting of the airstream to direct parallel flow of streams of air across the adsorbent coated heat exchangers of the LEHS wherein one parallel air duct channels the airstream that is to be dehumidified upstream of the evaporator and a second parallel air duct acts as a return loop air duct that channels the evaporatively cooled airstream that exits the evaporator i.e., the downstream airstream, back through the set of adsorbent coated heat exchangers of the LEHS. The parallel ducting of the upstream air flow and the downstream return loop mitigates against mixing of the airstream that is dehumidified upstream of the evaporator from the airstream that is dehumidified downstream of the evaporator. The use of a single LEHS to provide dual

dehumidification purposes requires that the LEHS be sized proportionally to allow for separately handling both the volumes of air that first flow upstream and secondly downstream of the evaporator. Utilizing a single LEHS for dual dehumidification purposes alleviates redundancy of LEHS devices, essentially opting to use one larger LEHS instead of two smaller LEHS. The parallel ducting provides for a LEHS to be in essence simultaneously upstream and downstream of an evaporator simply by incorporating a separate return loop of the air that is downstream of the evaporator and flowing the returned air separately by parallel, non-mixing, flow through the adsorbent coated heat exchangers of the LEHS.

[077] A working process of LEHS enhanced, direct evaporative cooling performed in many stages may be presented in the psychrometric chart 1000 of Figure 10, where the dashed line represents dehumidification by the LEHS. The beneficial dehumidification and wet bulb depression effects of the stages of series of LEHS are depicted as (1-2), (3-4), (5-6), (7-8), and (9-10). The stages of direct evaporative cooling effects are depicted as (2-3), (4-5), (6-7), and (8-9). The latent heat harvested for evaporative sourced heating by the condenser of the LEHS is proportional to the effects of the stages of series of LEHS.

[078] **General background regarding conventional systems of indirect evaporative coolers (IECs)**

[079] Indirect evaporative coolers (IECs) are a second type of evaporative cooling systems, their primary intended purpose to decrease air temperature without changing its water vapor content by employing a heat exchanger. A basic IEC unit comprises: a fan or a blower, a primary airstream (also referred to as a supply airstream), a secondary airstream, an evaporator installed within the secondary airstream, a thermally conductive heat exchanger that transfers heat between the primary airstream and an evaporatively cooled secondary airstream, and liquid water, which is supplied by a water distribution system. IEC systems are generally divided into: wet-bulb temperature IEC systems (WBT-IEC) and sub wet-bulb temperature IEC systems (Sub WBT-IEC). With WBT indirect evaporative coolers, the typical primary component is a wet surface, air-to-air heat exchanger in which two individual air streams flow throughout two adjacent channels consisting of a wetted air channel and a dry air channel. Those having ordinary skill in the art would readily recognize conventional indirect cooling system architectures comprising a wetted and dry channel of airstreams. The primary (supply) air is cooled via sensible heat transfer to the secondary airstream with the aid of water evaporation in

the wetted air channel, where the water vapor along with latent heat of the vaporized water is carried within the secondary airstream. The cooled primary airstream leaves the IEC unit with a temperature close to WBT of the inlet air but not below it. The wetted air channel absorbs heat from the dry air channel and cools the primary air by sensible heat transfer through the heat exchanger from the dry air passage (process 1-2), while the wet air stream involves water vaporization and resultant latent heat transfer between the working air and water film (process 1-3). As a result, the primary airstream (state 1) is cooled at constant moisture content toward the WBT of the inlet air (state 2), whereas the secondary airstream is gradually saturated and its temperature is decreased (state 2), and then heated again along the 100% saturation line until it is customarily discharged/rejected to the ambient atmosphere (state 3) because while the secondary airstream may be cooled, it is caused to be humidified to typically undesirable high levels or relative humidity. Favorably, the WBT-IEC systems cool the primary air without any additional moisture to the supplied air, but the WB effectiveness of the systems is lower than that of the DEC systems due to the indirect nature of the cooling of the primary airstream instead of the direct action on the airstream. Additionally, the WBT-IEC systems consume a supply of liquid water for deriving evaporate.

[080] There is need for indirect evaporative cooling systems which will avail higher WB effectiveness or achieve temperatures below WB and even achieve temperatures below the dew point of the initial primary airstream inlet temperature. Additionally, there is need to have higher efficiency of water usage and a need to be able to enhance the relative humidity property of the secondary airstream by dehumidification of the secondary airstream to provide for beneficial use purposes of the secondary airstream.

[081] **Indirect evaporative cooling (IEC) systems enhanced by LEHS**

[082] A working principle scheme of an LEHS enhanced, indirect evaporative cooling IEC system 1100 is presented in Figure 11. Note that Figure 11 (and like-arranged figures, such as Figure 13) shows two different perspectives of the same system 1100 (e.g., side-by-side), such as, for instance, a front-view and side-view. The warm, humid primary air (or product) (1) enters LEHS 1 where the primary airstream is dehumidified (1-2) before it enters a dry channel of an indirect evaporatively cooled heat exchanger 1102. The warm primary (or product) air (2) flows inside the dry channels (2-3) and transfers heat through the heat exchange surface to the wet channels. At the outlet of the dry channel of the evaporator, the primary (or product) air (3) has a

lower temperature as compared to the primary airstream at inlet (2), due to the transferred sensible heat. The secondary (working) airstream (5) enters LEHS 3, where the secondary airstream is dehumidified and the wet bulb temperature is depressed (5-6) before the secondary (working) airstream (6) flows inside the wet channels together with the disbursed water. Note that the primary and secondary air streams are typically induced by splitting a single air stream (e.g., derived from the same single fan or blower, though in some embodiments, induced by separate fans or blowers). The behavior of the air and water in the wet channel is similar to the direct evaporative cooling (DEC) processes (6-7). The water temperature becomes near the WB temperature of the secondary air. The heat transferred through the surface between the dry and wet channels is absorbed by the water as latent heat and a corresponding portion (volume) of the water is evaporated, being infused into the secondary air, increasing the moisture content of this air (7). The cooled and humidified secondary airstream is then routed through LEHS 4 to dehumidify the secondary airstream and depress its wet bulb temperature (7-8), to make a beneficial cooled and dehumidified product airstream for use as comfort supply air (8) from a secondary airstream, and to recuperate water evaporate for reuse as a supply of liquid water to enhance the water usage efficiency of the indirect evaporative cooling system. This system 1100 may become liquid water positive instead of liquid water consuming. Additionally, the latent energy harvested by LEHS 1 and LEHS 2 and LEHS 3 within the water vapor from the ambient supply airstreams (1-2) and (3-4) and (5-6), respectively, and the latent energy harvested with the evaporate water vapor by the LEHS 4 from the secondary airstream is caused to be recouped when the latent energy is converted from latent to sensible heat upon condensing with the condensers of the LEHSs for potential beneficial use, thereby inducing evaporation-induced heating, or in the alternative, the heat is rejected to the ambient environment.

[083] A working process of the primary air (2-3) is realized at constant moisture content, and the working process of the secondary air (6-6a) is realized at constant enthalpy, as can be observed on the psychrometric chart 1200 of Figure 12, where the dashed line represents dehumidification by the LEHSs. At the limit, the cooling process of the primary air could continue until the WB temperature of the secondary air at the inlet (6) of Figure 11, of the secondary air channel. If the secondary air is raised to the water vapor saturation state, proceeding after this stage forward, the heat from the primary air is split as latent heat absorbed

by the water and as sensible heat absorbed by the secondary air. Thus, the temperature of the secondary air at the outlet (6a) may be one of the following:

- a. Lower than the WB temperature of the secondary air at the inlet (no saturation, depicted as 6a);
- b. Equal with the WB temperature of the secondary air at the inlet (saturation is reached at the outlet, depicted as 6b);
- c. Higher than the WB temperature of the secondary air at the inlet (saturation before the outlet, depicted as 7).

[084] The main advantage of conventional IEC is that primary air is cooled without modifying its moisture content. The main disadvantage of conventional IEC is that the cooling process of the primary air is limited by the wet bulb (WB) temperature of the secondary air at the inlet. Because of this limitation, this type of equipment and/or process is also named a wet bulb IEC. An additional disadvantage is that the cooling of the secondary airstream requires a supplied source of water and consumes liquid water by conversion to evaporate (water vapor) and produces brine due to the concentration of dissolved solids within the liquid water. Also the secondary airstream of the indirect evaporative system is caused to have high humidity, which diminishes its value for use in cooling a climate-controlled zone, such as indoor cooling, thus the secondary airstream is typically exhausted out to the ambient environment. Additionally, the latent heat in the water vapor of the secondary airstream is not selectively utilized for beneficial purposes, as it is routinely rejected to the ambient environment as a high relative humidity exhaust airstream.

[085] There is a need for an indirect evaporative cooling (IEC) system that can mitigate or eliminate some or all of the main disadvantages of the IEC.

[086] An IEC evaporative cooling (IEC) system 1100, referring again to Figure 11, may be beneficially enhanced by augmentation with one or more LEHSs to derive cooling of the primary/supply air to below the wet bulb (WB) temperature of the secondary air at the inlet to the LEHS 3 located upstream of the evaporator of the secondary airstream, thereby shifting the wet bulb (WB) temperature potential to a much lower WB temperature (5-6), and if desired, to further derive cooling of the primary (supply) air to below the dew point of the secondary air at the inlet. An IEC system 1100 with beneficial augmentation with LEHSs 1-4 can operate with much higher water efficiency due to the ability to recoup the evaporate from the exhaust of the

secondary airstream, thereby requiring and consuming much less supply of liquid water and/or by producing liquid water as a byproduct from harvested water vapor from the source of the secondary airstream. The installation of an LEHS 4 in the secondary airstream downstream of the evaporator enables a dehumidification of the cooled secondary airstream (7-8) for beneficial use in aiding the cooling of a climate-controlled zone to derive another beneficially cooled supply airstream (8). The inclusion of an LEHS to dehumidify the primary (supply) air may be implemented upstream of the evaporator and/or downstream of the evaporator. If the LEHS for dehumidification of the primary (supply) airstream is implemented upstream of evaporator (1-2), as depicted by LEHS 1, the potential for deriving saturation and dewing of the cooled primary airstream may be mitigated. This mitigation is of particular importance and value if the primary airstream is intended to be cooled below the dew point temperature of the primary airstream at its inlet (1). If the LEHS for dehumidification of the primary (supply) airstream is implemented downstream of the indirect evaporator (3-4), as depicted by LEHS 2, the primary airstream may be further dehumidified and its wet bulb temperature depressed (4).

[087] **Exemplary embodiments of an IEC beneficially augmented with LEHS(s)**

[088] **Regenerative indirect evaporative cooling (R-IEC)**

[089] The concept of regenerative indirect evaporative cooling (R-IEC) was motivated by a desire to decrease the primary air temperature at the outlet to be below the wet-bulb (WB) temperature of the secondary air at the inlet. The regenerative process consists of extracting a part (volume) of the cooled primary air at its outlet and using it as secondary air. Since the secondary air is previously evaporatively cooled, the corresponding WB temperature is sensibly lower than the WB temperature of regular (outside) secondary air and the limit at which the primary air can be cooled is considerably lower.

[090] A working principle schematic of a preferred embodiment of an LEHS-enhanced R-IEC system 1300 is presented in Figure 13, wherein an LEHS 1 is implemented in the primary airstream upstream of the indirect evaporator 1302. A LEHS 2 is implemented in the secondary airstream downstream of the evaporator 1302 to recuperate the water vapor and to derive a dehumidified secondary airstream product. A LEHS 3 is implemented in the residual primary airstream downstream of the evaporator 1302 to further dehumidify the indirectly cooled airstream. Any selective combination of implementations of an LEHS in a primary and/or a secondary airstream is contemplated to be within the scope of an LEHS-enhanced R-IEC system

1300 with either the utilization of one, two, or three LEHSs being readily configured for specific beneficial application purposes.

[091] The warm primary air (1) flows through LEHS 1, where the primary air is dehumidified and its wet bulb temperature is depressed, and then exits the LEHS 1 and the primary air (2) flows to enter inside the dry channels and transfers heat through the evaporatively cooled heat exchange surface to the wet channels. At the outlet of the dry channel, the primary air (3) has a lower temperature than at the inlet to the dry channel (2). A part of the outlet primary air (5) is used as secondary air, being introduced in the wet channels. The working process inside the wet channels is similar to the one described previously in the basic IEC with the difference being, in regenerative IEC, the secondary airstream is cooler. Because the primary airstream (2 to 3) is cooled by passing through the indirect evaporative cooler 1302, its relative humidity is raised from its warmer and lower relative humidity condition at the inlet of the indirect evaporative cooler 1302. Hence, it may be beneficial to have the cooled and raised relative humidity primary airstream passed through (4 to 8) an LEHS 2 to lower its relative humidity to a desired level. Additionally, the secondary airstream that exits the wet channel of the indirect evaporative cooler (6) may be passed through (6 to 7) an LEHS 3 to lower the relative humidity of the secondary airstream for beneficial utilization of a dehumidified secondary airstream (7). The heat of vaporization that is latent in the water vapor that is harvested by the LEHSs and converted to sensible heat at the condenser of the LEHSs may be selectively, beneficially used for heating, thereby inducing evaporation sourced heating or, in the alternative, the heat can be rejected to the ambient environment. Note that as to the heat transfer schemes disclosed herein, any combination of the LEHSs may be used beneficially, or rejected (i.e., all or some or none may be chosen to transfer heat for beneficial purposes or to reject to the ambient environment).

[092] An exemplary corresponding working process of the LEHS-enhanced R-IEC system 1400 is presented in the psychrometric chart 1400 of Figure 14, where the dashed line represents dehumidification by the LEHSs. Referring to Figure 14 (with reference to the LEHSs of Figure 13), the primary airstream is dehumidified by the LEHS 1 and its wet bulb temperature is depressed as illustrated by the arrow from 1 to 2. Then, the primary airstream is indirectly evaporatively cooled as illustrated by the arrow from 2 to 3, while the secondary airstream is cooled and humidified, but once saturation is achieved, the secondary airstream then sensibly

warms to the limit at 4 because of heat transfer from the primary airstream as illustrated from 3 to 4. The secondary airstream then flows into an LEHS 3 and is dehumidified, and the secondary airstream wet bulb temperature is depressed, as illustrated by the arrow from 4 to 3. The end point relative humidity of the dehumidified secondary airstream may be higher than the level denoted as 3 or it may be lower than 3. The level at 3 is chosen for simplicity of illustration.

[093] Dew point indirect evaporative cooling (D-IEC)

[094] The concept of the dew point indirect evaporative cooling (D-IEC) was motivated to decrease the primary air temperature to be nearer to the limit of the dew point (DP) temperature of the primary air at the inlet. An LEHS-enhanced, D-IEC comprises multiple stages of the previously discussed LEHS-enhanced R-IEC system 1300 (Figure 13). A working principle of an LEHS-enhanced D-IEC system 1500 with two stages of LEHS-enhanced R-IEC is presented in Figure 15 (system 1500A) and 16 (1500B). The corresponding working process is presented in the psychrometric chart 1700 of Figure 17, where the description of the system 1500 and chart 1700 should be readily understood to one having ordinary skill in the art based on the above description of the individual LEHS-enhanced R-IEC system 1300 and corresponding psychrometric chart 1400, and hence omitted here for brevity.

[095] Maisotsenko (M-cycle) indirect evaporative cooling (M-IEC)

[096] A type of indirect evaporative cooling system, developed by Dr. Valeriy Maisotsenko, provides an alternative possibility for cooling the primary air to near the dew-point temperature of the inlet air. Named after its inventor, the system was named M-IEC or the M-cycle. The M-IEC has two types of dry channels, one for the primary air and one for the secondary air. The main characteristic of the system is that secondary air has multiple passages from its dry channels into the wet channels. The primary air is simply flowing into the dedicated dry channels.

[097] A working process schematic is depicted in Figure 18 of an LEHS-enhanced M-IEC system 1800, wherein the cooling of the primary airstream (1-3) is realized at constant moisture. The working process of the secondary airstream (e.g., secondary airstream pathways 2a-5a, 2b-5b, 2c-5c, 2d-5d) and the corresponding isothermal humidification processes inside the system 1800 are represented on the psychrometric chart 2000 by the corresponding states in Figure 20, where the dashed line represents dehumidification by the LEHSs, and the solid line represents evaporation in the wet channel.

[098] Digressing briefly, for conventional M-IEC systems, at the limit of heat transfer from the primary airstream to the secondary airstream, the final dew point temperature of the primary air at the outlet can arrive near the dew point temperature of the inlet primary air. This type of system is also called a dry bulb IEC. The main advantage of an M-IEC system is that primary air is cooled without modifying the moisture content almost near the dew-point temperature. The main disadvantage of conventional M-IEC systems is the more complex construction and flow scheme inside the equipment and, similar to all conventional evaporative cooling systems, another disadvantage is that the system requires consumption of a non-self generated supply of clean liquid water and has inherently lower water usage efficiency compared to an LEHS-enhanced evaporative cooling system. The heat of vaporization that is latent in the water vapor that is harvested by the LEHSs and converted to sensible heat at the condenser of the LEHSs may be selectively and beneficially used for heating, and thereby induce evaporation sourced heating or, in the alternative, the heat may be rejected to the ambient environment.

[099] The conventional Maisotsenko Cycle (M-cycle) works by cooling both the working air and the supplied air in several stages. Each stage contributes to cooling by lowering the wet bulb temperature as depicted in the psychrometric chart 1900 of Figure 19 as (2-5), (2a – 5a), (2b-5b), (2c-5c), and (2d-5d). The cumulative result is a lower supply air temperature (closer towards dew point) than is possible with conventional evaporative cooling technologies. The key difference between this M-cycle process and other indirect processes is that the working air that is accumulating moisture is exhausted at each stage, enabling more cooling to take place and with no increase in humidity to the final supply air stream. Referring to the LEHS-enhanced M-IEC system 1800 in Figure 18, an LEHS 1 situated upstream of an M-Cycle evaporative cooling system 1802 may enable a lower starting wet bulb temperature of the airstream entering an M-cycle; and an LEHS 3 situated downstream of the M-cycle evaporative cooling system 1802 may dehumidify the exhaust of the secondary airstreams to yield an additionally cooled, but targeted, moderate or low humidity airstream as a beneficial product air and to recuperate the evaporate for reuse as a liquid water source to enhance the water efficiency and/or for recovery of the sensible heat converted to latent energy during evaporation for beneficial evaporative heating purposes. Also, an LEHS 2 may be situated downstream of the primary airstream to dehumidify the cooled (non-moisture added) primary airstream to a desired lower relative humidity.

[100] **Indirect, direct evaporative cooling (IDEC) systems enhanced by LEHS**

[101] In addition to the above-discussed LEHS-enhanced embodiments of direct and indirect evaporative air-cooling systems, further embodiments of a LEHS enhanced two-stage indirect, direct evaporative cooling system are contemplated, and comprise a first stage of any of the LEHS enhanced embodiments of the above-described indirect evaporative air-cooling systems, coupled with a second stage in series with the first stage, of any of the LEHS-enhanced embodiments of the direct evaporative air-cooling systems also discussed above. Building on the advantages of LEHS enhancements for the performance of both direct and indirect evaporative air cooling as discussed above, LEHS-enhanced, two-stage indirect, direct evaporative air-cooling systems are highly beneficial as to cooling effectiveness and water consumption compared to any prior art, conventional two-stage indirect, direct evaporative air cooling systems and as to simultaneously deriving evaporative sourced heating. An example embodiment of an LEHS-enhanced indirect, direct evaporative cooling system 2100 is depicted in Figure 21. Note that IDEC systems are merely combinations of the aforementioned indirect systems with a second stage of direct evaporative cooling and are known to those having ordinary skill in the art. Any combination of the installations of an LEHS in the inlet or outlets of primary or secondary airstreams may be utilized as an LEHS enhanced embodiment of a conventional indirect, direct evaporative cooling system.

[102] In effect, direct evaporative cooling systems and the M-Cycle evaporative cooling systems represent the lower and upper bounds of a conventional evaporative cooling spectrum, respectively. Selective LEHS integrations into systems along this spectrum enables dramatically enhanced evaporative cooling effectiveness and/or provides for simultaneous beneficial evaporative heating effectiveness and/or enhanced water usage efficiency or even to provide for liquid water production compared to all conventional evaporative cooling systems

[103] **Hybrid systems of airstream cooling**

[104] Certain embodiments of enhanced hybrid airstream cooling systems combine two or more stages in series of a first stage LEHS-enhanced liquid water evaporation cooling system followed downstream in the airstream by an installation of a second stage of cooling by conventional refrigerant vapor compression evaporative cooling. As is known, a conventional vapor compression system [also known as DX systems] typically comprises at least a refrigerant, a compressor, a refrigerant expansion device, an evaporator and a condenser, which scheme is

attributed to be first invented by Willis Carrier in 1902 and which there have been many moderate enhancements of efficiency and nuances of design over the last 120 years. A first such enhanced hybrid air cooling system embodiment comprises a first stage direct evaporative cooling system with an LEHS installed in the airstream downstream of the liquid water evaporator(s) to dehumidify the directly evaporatively cooled and humidified airstream, and installed further downstream in the airstream is a cooling evaporator coil of a refrigerant vapor compression system and, optionally, with an LEHS installed yet further downstream to dehumidify the airstream cooled by the evaporator coil of a refrigerant vapor compression system.

[105] A second enhanced hybrid air cooling system embodiment comprises a first cooling stage, direct evaporative cooling system with an LEHS installed upstream in the airstream ahead of the liquid water evaporator(s) to dehumidify and depress the wet-bulb temperature of the airstream before entry of the airstream into the liquid water evaporators, and an LEHS installed in the airstream downstream of the liquid water evaporator(s) to dehumidify the directly evaporatively cooled and humidified airstream; followed downstream in the airstream by a second cooling stage in series comprising a cooling evaporator coil of a refrigerant vapor compression system, and optionally with an LEHS installed yet further downstream to dehumidify the airstream cooled by the evaporator coil of a refrigerant vapor compression system.

[106] A third enhanced hybrid air cooling system embodiment comprises a first cooling stage comprising an LEHS-enhanced indirect evaporative cooling system within a primary airstream and/or the LEHS dehumidified secondary evaporatively cooled airstream, followed downstream of the airstream by a second air cooling stage in series, comprising a cooling evaporator coil of a refrigerant vapor compression system, and optionally with an LEHS installed yet further downstream to dehumidify the airstream cooled by the evaporator coil of a refrigerant vapor compression system.

[107] A fourth enhanced hybrid air cooling system embodiment comprises a first cooling stage comprising an LEHS-enhanced indirect, direct evaporative air cooling system in which cooled airstreams are dehumidified by an LEHS before passing to a second cooling stage in series comprising a cooling evaporator coil of a refrigerant vapor compression system and

optionally with an LEHS installed yet further downstream to dehumidify the airstream cooled by the evaporator coil of a refrigerant vapor compression system.

[108] Additional embodiments of hybrid liquid water evaporative air cooling systems coupled with refrigerant vapor compression systems may be inclusive of two or more stages in series of the first through fourth hybrid air cooling systems described immediately above.

[109] A fifth category of enhanced hybrid cooling system embodiments comprises a system wherein liquid water produced by condensing of the water vapor harvested by an LEHS is used to evaporatively cool the condenser of the refrigerant vapor compression system to enhance the efficiency, effectiveness and capacity of cooling by the traditional refrigerant vapor compression system.

[110] **Liquid water-cooling towers systems enhanced by LEHS**

[111] Conventional evaporative liquid water-cooling towers are heat rejection devices. Utilization of evaporative sourced heating derived from the water vapor condenser of an LEHS-enhanced cooling tower may selectively become heat recuperation devices. Evaporative liquid water-cooling towers are system architectures of direct evaporative cooling of liquid water for beneficial purposes. The cooled liquid water may also be used to indirectly cool other warm substances with the use of the higher thermal conductivity of liquid compared to air cooling (dry cooling) and substances that are commonly indirectly liquid water cooled via heat transfer through heat exchangers from warm fluids or vapors. Also, the cooled liquid water is commonly used to indirectly cool airstreams by flow through a liquid water-cooled heat exchanger installed in an air handler.

[112] Much like direct and indirect air-cooling systems that have been described above, installation of one or more LEHSs may be used to greatly enhance the efficiency and effectiveness of cooling towers and to greatly enhance the water usage efficiency, or even to derive net liquid water positive operation of cooling towers by harvesting water vapor from the ambient atmosphere. Since an LEHS may derive clean, non-mineralized water condensate from having harvested water vapor from airstreams, the cooling tower may be operated with little concentration of dissolved solids and formation of brine and with much less need for disposal flushing to bleed off or blowdown, and thus minimal replacement of such brine. Also, with an LEHS supplying clean liquid water as the source of evaporate, the contamination and scaling of deposited minerals on the cooling tower surfaces is minimized.

[113] Most liquid water-cooling towers are capacity rated based on operating at a wet bulb temperature of 78° F/25.55°C. The operating capacity of the water-cooling towers and/or of closed loop water cooling towers may be greatly enhanced if the wet bulb temperature of their operating inlet airstream is depressed by the utilization of one or more LEHSs. Alternatively, the range of the cooling tower may be enhanced while maintaining the capacity. The cooling tower thermal efficiency may be greatly enhanced with the installation of an LEHS compared to the same cooling tower system without the installation of an LEHS.

[114] The wet bulb temperature of the entering airstream of a cooling tower may be depressed by dehumidification conditioning of at least a portion (volume) of the entering airstream with an LEHS, which may provide for direct evaporative cooling of the warm water to below the wet bulb temperature of the airstream upstream of the LEHS and may also provide for direct evaporative cooling below the dew point temperature of the airstream upstream of the LEHS. The range of a cooling tower refers to the temperature difference between the hot water entering the cooling tower and the cold water exiting the cooling tower, whereas the approach of a cooling tower refers to the difference between the cold cooling tower water and the wet bulb temperature of the airstream entering the cooling tower. The utilization of an LEHS to lower the wet bulb temperature of the ambient airstream upstream of the inlet to the cooling tower provides for greater direct evaporation cooling effectiveness, thereby providing for cooler cold water and enhancing the range of the cooling tower and narrowing the approach of the cooling tower, compared to a cooling tower without beneficial augmentation by an LEHS of the inlet airstream. An enhanced embodiment of a cooling tower system that provides for greater range and/or a superior approach is superior to a cooling tower without such an LEHS enhancing embodiment.

[115] An LEHS may be installed in the warm moist exhaust airstream of a cooling tower and may provide for recuperating at least a portion of the water vapor evaporate for reuse as a liquid water supply once the water vapor has been condensed by the condenser of the LEHS. Also, the latent energy that resides in the water vapor that the LEHS harvests from the source inlet airstream (e.g., the ambient atmosphere) and/or the water vapor evaporate within the exhaust airstream derived within the cooling tower may be converted to sensible heat for beneficial purposes by condensing and releasing of the heat of vaporization. The approach of an LEHS-enhanced cooling tower may be enhanced compared to the same cooling tower which does not have its inlet airstream dehumidified. Also, an LEHS-enhanced cooling tower provides

for selective recuperation of the heat of vaporization instead of the customary rejection of the thermal energy to the ambient environment, and thus provides for selective evaporative sourced heating.

[116] The effectiveness of cooling of the liquid water-cooling towers may be further enhanced by augmenting the operation of the cooling tower by first evaporatively cooling the airstream that enters into the cooling tower by use of LEHS-enhanced evaporative air-cooling systems discussed above, wherein the cooled airstream is dehumidified by an LEHS before entry to the cooling tower.

[117] Architectures of common cooling tower systems may be enhanced by one or more LEHSs. Certain embodiments of LEHS-enhanced cooling towers are shown in Figures 22-24, and include an LEHS enhanced cross flow systems 2200 (Figure 22), counterflow systems 2300 (Figure 23), and cocurrent flow systems 2400 (Figure 24). Based on the description above pertaining to how the LEHSs may be deployed in cooling tower systems and the resultant benefits, and further based on the general knowledge of common cooling tower systems, one having ordinary skill in the art should understand operations of these systems, and hence description of the same is omitted for brevity. The airflow inducement may be derived by natural draft, or mechanical draft, in which mechanical draft may be induced at the discharge or at the intake of the airstream. Alternatively, the cooling tower system may be a mechanical draft assisted, natural draft tower type.

[118] LEHS enhanced dual season combined evaporative cooling and atmospheric latent energy sourced heating systems and evaporative sourced heating systems

[119] Figure 25 depicts a schematic of the working principle of a dual season (hot/warm and cool/cold climate) cooling and heating system 2500 configured as to when the system operating is in a cooling mode and simultaneously functioning as an atmospheric latent energy sourced heating and evaporative sourced heating system. Air stream diverters 2502 (e.g., 2502a, 2502b, 2502c) are positioned so as to allow the inlet air to pass from the LEHS 1 through an evaporator 2504 and then through LEHS 2, and then pass into a climate-controlled zone providing targeted setpoint, evaporatively cooled and dehumidified supply air to the indoor space.

[120] Figure 26 depicts a schematic of the working principle of a dual season (hot/warm and cool/cold climate) cooling and heating system 2600 when operating in a heating mode

during mild temperature conditions (e.g., when the inlet airstream is warmer than about 45°F). The system 2600 is of the same or similar construction as the system 2500 of Figure 25, yet operating according to a different mode. An evaporator 2604 is selectively discontinued as to its use to mitigate against causing freezing of the liquid water within the evaporator 2604. Operating in this mode provides for simultaneously functioning as an atmospheric latent energy sourced heating and evaporative sourced heating system, wherein the evaporator 2604 is harvesting the sensible energy of the inlet airstream and converting the sensible heat to latent heat. The harvested atmospheric latent heat is converted to sensible heat within the condensing unit of the LEHS 1. A first airstream diverter 2602a is opened to direct the dehumidified airstream through the evaporator 2604 to harvest the sensible heat from the airstream by conversion to latent energy within water vapor. The resultant humidified airstream is directed by a second diverter 2602b to cause the humidified airstream to pass through the LEHS 2, wherein the water vapor and associated latent energy derived by the evaporator 2604 is harvested by the LEHS 2, the latent energy being converted to sensible heat within the condensing unit of the LEHS 2. A third airstream diverter 2602c is closed to cause the cooled and dehumidified airstream to be passed back out to the ambient environment, since in this instance, the indoor climate-controlled zone is in need of warming, not cooling. In the alternative, the cooled and dehumidified airstream may be routed to a place or space in need of cooling for example, a separate cooled storage facility.

[121] Figure 27 depicts a schematic of the same type of system operating in a cold climate atmospheric latent energy sourced heating mode. In other words, Figure 27 depicts a schematic of the working principle of a dual season (hot /warm and cool/cold climate) cooling and heating system 2700, which is of the same or similar structure as systems 2500 and 2600, yet operating according to a different mode. This mode is utilized when the temperature of the inlet airstream is low enough to induce freezing within an evaporator 2704 and the use of the evaporator is discontinued. Ambient outdoor sourced air is allowed to flow into LEHS 1, wherein water vapor is harvested from the air and the latent energy is converted to sensible heat within the condensing unit of LEHS 1. A first airstream diverter 2702a is closed, thus disallowing the dehumidified atmospheric airstream that exits LEHS 1 from flowing to the evaporator 2704, and instead, the cold dry air is caused to be returned to the ambient environment. A second airstream diverter 2702b is positioned to allow ambient atmospheric air

to be passed into and through the LEHS 2 (and to not have an airstream flow from the evaporator 2704), thereby allowing the LEHS 2 to have a source of air from which ambient water vapor and associated latent energy is harvested. The LEHS 2 converts the latent energy to sensible heat within the condensing unit of LEHS 2. A third airstream diverter 2702c is positioned to cause the cold, dehumidified airstream that exits LEHS 2 to flow back out to the ambient environment, and not into the indoor climate-controlled zone. When operating in this configuration, both LEHS are deployed as active ambient environment latent energy air source heat pumps.

[122] In this description, references to “one embodiment”, “an embodiment”, or “embodiments” mean that the feature or features being referred to are included in at least one embodiment of the technology. Separate references to “one embodiment”, “an embodiment”, or “embodiments” in this description do not necessarily refer to the same embodiment and are also not mutually exclusive unless so stated and/or except as will be readily apparent to those skilled in the art from the description. For example, a feature, structure, act, etc. described in one embodiment may also be included in other embodiments, but is not necessarily included. Thus, the present technology can include a variety of combinations and/or integrations of the embodiments described herein. Although the systems and methods have been described with reference to the example embodiments illustrated in the attached drawing figures, it is noted that equivalents may be employed and substitutions made herein without departing from the scope of the disclosure as protected by the following claims.

Claims

At least the following is claimed:

1. An evaporative cooling system, comprising:
at least one direct evaporative cooling system, comprising:
at least one fan or blower that induces an air stream;
at least one evaporator installed in the air stream, wherein liquid water is supplied to the at least one evaporator, the at least one evaporator configured to directly evaporatively cool and humidify the air stream; and
one or plural latent energy harvesting systems (LEHSs) installed alone or in combination, respectively, in the air stream,
wherein when alone, the one LEHS is installed in either the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream or the air stream upstream of the at least one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified, and
wherein when in combination, the plural LEHSs are installed, respectively, in the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream, and in the air stream upstream of the at least one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified.
2. The evaporative cooling system of claim 1, further comprising one or more additional direct evaporative cooling systems arranged in series with the at least one direct evaporative cooling system, the one or more additional direct evaporative cooling systems configured according to the at least one direct evaporative cooling system.
3. A hybrid system, comprising: primary, supply air stream cooling and conditioning stages in series comprising a first upstream stage system of the evaporative cooling system of any one

of claims 1 through 2, followed downstream in the air stream by a vapor compression cooling system.

4. An evaporative cooling method, comprising:
for at least one direct evaporative cooling system:
inducing an air stream;
directly evaporatively, using at least one evaporator, cooling and humidifying the air stream; and
dehumidifying the directly evaporatively cooled and humidified air stream or dehumidifying the air stream to be directly evaporatively cooled and humidified using a latent energy harvesting system (LEHS) installed in either the air stream downstream of the at least one evaporator or the air stream upstream of the at least one evaporator, respectively, or
dehumidifying the directly evaporatively cooled and humidified air stream and dehumidifying the air stream to be directly evaporatively cooled and humidified using plural latent energy harvesting systems (LEHSs), with one of the plural LEHSs installed in the air stream downstream of the at least one evaporator and another of the plural LEHSs installed in the air stream upstream of the at least one evaporator.
5. The evaporative cooling method of claim 4, further comprising, using one or more additional direct evaporative cooling systems arranged in series with the at least one direct evaporative cooling system, the one or more additional direct evaporative cooling systems operating according to the at least one direct evaporative cooling system.
6. An indirect evaporator cooling system, comprising:
at least one fan or blower that induce a primary, supply air stream and a secondary air stream;
an evaporator installed in the secondary air stream, wherein liquid water is supplied to the evaporator installed in the secondary air stream;
a thermally conductive heat exchanger that transfers heat from a primary, supply air stream to an evaporatively cooled secondary air stream; and

one or plural latent energy harvesting systems (LEHSs) installed alone or in combination, respectively, in the secondary air stream,

wherein when alone, the one LEHS is installed downstream of the evaporator of the secondary airstream or upstream of the evaporator of the secondary airstream, and

wherein when in combination, the plural LEHSs are installed, respectively, downstream of the evaporator of the secondary airstream, and upstream of the evaporator of the secondary airstream.

7. The system of claim 6, wherein the indirect evaporative cooling system is of a regenerative indirect evaporative cooling type.

8. The system of claim 6, wherein the indirect evaporative cooling system is of a dew point indirect evaporative cooling type.

9. The system of claim 6, wherein the indirect evaporative cooling system is of a Maisotsenko Cycle type.

10. The system of any one of claims 6 - 9, wherein an additional LEHS, configured according to the each of the one or plural LEHSs, is installed in the primary, supply air stream upstream or downstream of the thermally conductive heat exchanger to dehumidify the indirectly cooled primary, supply air stream, or wherein plural additional LEHSs, each configured according to the each of the one or plural LEHSs, are installed respectively in the primary, supply air stream upstream and downstream of the thermally conductive heat exchanger to dehumidify the indirectly cooled primary, supply air stream.

11. A two-stage indirect, direct evaporative cooling system, comprising:
- a first stage comprising an indirect evaporative cooling system of a primary, supply air stream, the indirect evaporative cooling system comprising:
 - at least one fan or blower that induce a primary, supply air stream and a secondary air stream;
 - an evaporator installed in the secondary air stream, wherein liquid water is supplied to the evaporator installed in the secondary air stream;
 - a thermally conductive heat exchanger that transfers heat from a primary, supply air stream to an evaporatively cooled secondary air stream; and
 - one or plural latent energy harvesting systems (LEHSs) installed alone or in combination, respectively, in the secondary air stream,
 - wherein when alone, the one LEHS is installed downstream of the evaporator of the secondary airstream or upstream of the evaporator of the secondary airstream, and
 - wherein when in combination, the plural LEHSs are installed, respectively, downstream of the evaporator of the secondary airstream, and upstream of the evaporator of the secondary airstream; and
 - a second stage in series with the first stage, the second stage comprising a direct evaporative cooling system of the said primary, supply air stream, the direct evaporative cooling system comprising:
 - at least one direct evaporative cooling system, comprising:
 - at least one fan or blower that induces an air stream;
 - at least one evaporator installed in the air stream, wherein liquid water is supplied to the at least one evaporator, the at least one evaporator configured to directly evaporatively cool and humidify the air stream; and
 - one or plural LEHSs installed alone or in combination, respectively, in the air stream,
 - wherein when alone, the one LEHS is installed in either the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream or the air stream upstream of the at least

one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified, and

wherein when in combination, the plural LEHSs are installed, respectively, in the air stream downstream of the at least one evaporator and configured to dehumidify the directly evaporatively cooled and humidified air stream, and in the air stream upstream of the at least one evaporator and configured to dehumidify the air stream to be directly evaporatively cooled and humidified.

12. The two-stage indirect, direct evaporative cooling system of claim 11, wherein the indirect evaporative cooling system is of a regenerative indirect evaporative cooling type.

13. The two-stage indirect, direct evaporative cooling system of claim 11, wherein the indirect evaporative cooling system is of a dew point indirect evaporative cooling type.

14. The two-stage indirect, direct evaporative cooling system of claim 11, wherein the indirect evaporative cooling system is of a Maisotsenko Cycle type.

15. The two-stage indirect, direct evaporative cooling system of any one of claims 11 - 14, wherein an additional LEHS, configured according to the each of the one or plural LEHSs, is installed in the primary, supply air stream upstream or downstream of the thermally conductive heat exchanger to dehumidify the indirectly cooled primary, supply air stream, or wherein plural additional LEHSs, each configured according to the each of the one or plural LEHSs, are installed respectively in the primary, supply air stream upstream and downstream of the thermally conductive heat exchanger to dehumidify the indirectly cooled primary, supply air stream.

16. A hybrid system, comprising: a primary, supply air stream cooling and conditioning stages in series comprising a first upstream stage system of claim 15, followed downstream in the cooled primary, supply air stream by a vapor compression cooling system.

17. The two-stage indirect, direct evaporative cooling system of claim 15, wherein an additional LEHS, configured according to the each of the one or plural LEHSs, is installed in the airstream downstream of the direct evaporative cooling system to dehumidify the indirectly and directly cooled primary, supply air stream.
18. A hybrid system, comprising: a primary, supply air stream cooling and conditioning stages in series comprising a first upstream stage system of claim 17, followed downstream in the cooled primary, supply air stream by a vapor compression cooling system.
19. A hybrid system, comprising: a primary, supply air stream cooling and conditioning stages in series comprising a first upstream stage system of any one of claims 11 - 14, followed downstream in the cooled primary, supply air stream by a vapor compression cooling system.
20. The two-stage indirect, direct evaporative cooling system of claim 11, wherein the evaporative cooling system further comprises one or more additional direct evaporative cooling systems arranged in series with the at least one direct evaporative cooling system, the one or more additional direct evaporative cooling systems configured according to the at least one direct evaporative cooling system.
21. An induced air, evaporative wetted surface air cooler or condenser system, comprising a closed, warm process fluid or a process vapor heat exchange loop, at least one fan and/or blower, liquid water, a liquid water stream cocurrent disbursing mechanism, an induced cocurrent flow of an airstream and a water stream traveling in a downward direction across and in contact with the closed process fluid or process vapor heat exchange loop, a sump that gathers warmed liquid water that has made contact with and had heat transferred from the closed heat exchange loop, a pump that flows liquid water to the liquid water stream cocurrent disbursing mechanism, a latent energy harvesting system (LEHS) configured according to the LEHS, that is installed in the airstream upstream of the induced cocurrent flow of an airstream and water stream to dehumidify at least a portion of the induced cocurrent flow of an air stream, and a pump that flows liquid

water from the partial pressure condenser of the LEHS for cocurrent disbursement with the cocurrent flow of the airstream.

22. The system of claim 21, further comprising an additional LEHS that recuperates at least a portion of the exhausted water vapor that derives from the cocurrent evaporative cooling of the closed process fluid or process vapor heat exchange loop.

23. An evaporative cooling tower system, comprising:

- a latent energy harvesting system (LEHS) that is installed in the airstream upstream of the induction of an air draft into the evaporative cooling tower to dehumidify at least a portion of the air stream induced as an air draft into the evaporative cooling tower;

- a mechanical draft mechanism and/or natural draft mechanism configured to induce an air draft;

- the cooling tower;

- a liquid water stream inducing mechanism; and

- a sump to gather cooled liquid water.

24. The system of claim 23, further comprising a latent energy harvesting system (LEHS) configured to harvest at least a portion of the exhausted water vapor in an airstream that derives from evaporation of liquid water induced in a cooling tower.

25. The system of any one of claim 23, wherein the airstream of the air-to-water flow into the cooling tower is one of crossflow or counterflow.

26. The system of claim 23, wherein the mechanical draft mechanism and/or natural draft mechanism comprises a draw through mechanical draft tower type with a fan at the discharge (at the top) which pulls air up through the tower.

27. The system of claim 23, wherein the mechanical draft mechanism and/or natural draft mechanism comprises a forced draft mechanical draft tower with a fan or blower that pushes air at the air intake through the tower.

28. The system of claim 23, wherein the mechanical draft mechanism and/or natural draft mechanism comprises a mechanical fan/blower assisted, natural draft tower type.
29. An evaporative cooling tower system comprising:
a LEHS enabled direct or indirect evaporatively cooled air system of claims 1 through 20 that depresses the wet bulb temperature of an air stream, which lowered wet bulb temperature airstream is induced to flow downstream into an evaporative cooling tower system of claims 21 through 28.
30. The system of claims 1 through 29 wherein parallel ducting of return air is incorporated so as to provide the use of a LEHS to be capable of dehumidifying an airstream that is upstream of an evaporator and an airstream that is downstream of an evaporator.