

HEAT TRANSFER APPARATUS AND METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/600,452 filed November 17, 2023, U.S. Provisional Application No. 63/565,875, filed March 15, 2024, and U.S. Provisional Application No. 63/679,310, filed August 5, 2024, which are all incorporated herein by reference in their entireties.

TECHNICAL FIELD

[0002] This disclosure relates to systems for removing heat from a process fluid and, more specifically, relates to packaged cooling systems such as cooling towers.

BACKGROUND

[0003] Industrial cooling systems are used to remove heat from process fluid in various industrial processes, such as manufacturing processes, HVAC systems for buildings, and heat transfer systems for computer datacenters. One common approach for some industrial cooling systems is to have a heat exchanger, such as an air handler, in a building that transfers heat to a first process fluid (e.g., water or a water-glycol mixture) and a chiller in the building that removes heat from the first process fluid. The chiller transfers heat from the first process fluid to a second process fluid, which is routed to a heat rejection apparatus, such as cooling tower outside of the building. The cooling tower removes heat from the second process fluid and returns cooled second process fluid to the chiller. Chillers used in industrial cooling systems are typically quite large, with power ratings in the range of 100-300 horsepower being common.

[0004] An issue with operating an industrial cooling system year-round is that the cooling system is typically designed with sufficient maximum capacity to provide the required cooling even during the hottest days of the year. Providing sufficient maximum capacity for the hottest days of the year in traditional cooling systems involves utilizing higher-capacity system components, such as more powerful chillers, fan motors, pumps, etc. than are required for the rest of the year. The higher-capacity system components consume more energy and/or water than would lower-capacity components, but are used to provide sufficient maximum capacity for the cooling system.

[0005] Ice thermal storage systems are sometimes used with industrial cooling systems to provide extra cooling capacity at peak energy usage, such as in the afternoon of a sunny and humid summer day. Ice thermal storage systems have a thermal storage tank that is

charged, e.g., ice in the tank is frozen, and discharged as needed to supplement the chiller and cooling tower of the cooling system. For example, the ice thermal storage system may operate to freeze water in the tank overnight when electricity may be less expensive from the local utility. The ice thermal storage system is discharged, e.g., the ice in the tank is melted by process fluid traveling through a coil in the ice tank, in the afternoon of the sunny and humid summer day to provide increased cooling capacity for the cooling system.

[0006] An issue with some cooling systems that utilize ice thermal storage is that the cooling system still relies on a large, e.g., 200+ horsepower, chiller in the building to chill water provided to the heat exchanger in the building. While providing sufficient maximum capacity, these large chillers often consume large amounts of energy even when the cooling capacity required is low. Another issue with some ice thermal storage cooling systems is that the one or more ice tanks may take up an entire room, or even a separate building, in order to provide adequate cooling capacity for a large-scale industrial cooling system. The size and complexity of large-scale ice thermal storage tanks may be impractical for some facilities. Further, ice thermal storage systems utilize glycol as a process fluid which is more expensive than water, increases pumping power required to circulate the process fluid, and reduces heat transfer performance.

SUMMARY

[0007] In one aspect of the present disclosure, a heat transfer apparatus is provided for an industrial process that requires process fluid at a process fluid set temperature. The heat transfer apparatus includes an air inlet, an air outlet, and a process fluid heat exchange circuit to receive process fluid from the industrial process at a temperature different than the process fluid set temperature and provide process fluid to the industrial process at the process fluid set temperature. The process fluid heat exchange circuit includes a heat exchanger, an airflow generator operable to cause air to travel from the air inlet to the air outlet and contact the heat exchanger, and a thermal energy storage.

[0008] The process fluid heat exchange circuit has a first mode wherein the process fluid bypasses the thermal energy storage and the heat exchanger transfers heat between the process fluid and the air. The process fluid may bypass the thermal energy storage by, for example, being routed around the thermal energy storage or being routed to the thermal energy storage when the thermal energy storage has limited heat exchange capability. As a further example, the process fluid may bypass the thermal energy storage when the process fluid is directed through the thermal energy storage but the phase change material has been

drained from the thermal energy storage such that the process fluid leaves the thermal energy storage at substantially the same temperature as it entered the thermal energy storage. The process fluid heat exchange circuit has a second mode wherein the thermal energy storage transfers heat between the process fluid and the thermal energy storage and the heat exchanger transfers heat between the process fluid and the air. The heat transfer apparatus further comprises a controller operatively connected to the process fluid heat exchange circuit.

[0009] The controller is configured to operate the process fluid heat exchange circuit in the second mode based at least in part upon a parameter of the air and a determination of the process fluid heat exchange circuit in the first mode being unable to provide the process fluid at the process fluid set temperature. In this manner, the heat transfer apparatus may utilize the thermal energy storage to trim or partially satisfy the heat transfer load required to provide the process fluid at the process fluid set temperature. By selectively utilizing the thermal energy storage at peak heat transfer loads, such as on the hottest days of the year, the heat exchanger can be sized to have smaller capacity than if the heat exchanger were to satisfy the peak heat transfer load by itself, which facilitates the use of less water and/or energy by the heat exchanger during off-peak heat transfer load situations.

[0010] The present disclosure also provides a method for operating a heat transfer apparatus associated with an industrial process that requires process fluid at a process fluid set temperature. The heat transfer apparatus includes a process fluid heat exchange circuit for the process fluid that includes a heat exchanger, a fan to cause movement of air relative to the heat exchanger, and a thermal energy storage. The process fluid heat exchange circuit has a first mode wherein the process fluid bypasses the thermal energy storage and the heat exchanger transfers heat between the process fluid and the air. The process fluid heat exchange circuit has a second mode wherein the thermal energy storage transfers heat between the process fluid and the thermal energy storage and the heat exchanger transfers heat between the process fluid and the air. The method includes operating the process fluid heat exchange circuit in the second mode based at least in part upon a parameter of the air and a determination of the process fluid heat exchange circuit in the first mode being unable to provide the process fluid to the industrial process at the process fluid set temperature.

[0011] In one aspect of the present disclosure, a heat transfer apparatus is provided that includes a process fluid heat exchange circuit including a heat exchanger, an airflow generator operable to cause air to contact the heat exchanger, a thermal energy storage, and a mechanical cooler. The process fluid heat exchange circuit has a plurality of modes

including a first mode wherein the heat exchanger is operable to transfer heat between a process fluid and the air and a second mode wherein the heat exchanger is operable to transfer heat between the process fluid and the air and the mechanical cooler is operable to remove heat from the process fluid. The plurality of modes further includes a third mode wherein the heat exchanger is operable to transfer heat between the process fluid and the air and the thermal energy storage is operable to remove heat from the process fluid and a fourth mode wherein the heat exchanger is operable to transfer heat between the process fluid and the air, the mechanical cooler is operable to remove heat from the process fluid, and the thermal energy storage is operable to remove heat from the process fluid. The heat transfer apparatus further includes a controller configured to operate the process fluid heat exchange circuit in one of the plurality of modes based at least in part upon a determination of a thermal duty of the heat transfer apparatus. In this manner, the controller may operate the process fluid heat exchange circuit in various configurations based at least in part upon the thermal duty which provides flexibility in tuning the heat transfer apparatus to efficiently remove heat from the process fluid.

[0012] In another aspect of the present disclosure, a heat transfer apparatus is provided including an air inlet, an air outlet, and a process fluid cooling system for cooling a process fluid. The process fluid cooling system includes a fan assembly to cause air to travel from the air inlet to the air outlet, a dehumidifier having a dehumidification mode wherein the dehumidifier removes water from the air and a bypass mode wherein the dehumidifier removes less water from the air than when the dehumidifier is in the dehumidification mode, and an adiabatic precooler having a precooler mode wherein the adiabatic precooler lowers the dry bulb temperature of the air and a standby mode wherein the adiabatic precooler lowers the dry bulb temperature of the air less than when the adiabatic precooler is in the precooler mode. The heat transfer apparatus further includes a heat exchanger that receives the process fluid and is downstream of the dehumidifier and the adiabatic precooler. The process fluid cooling system has a first mode wherein the dehumidifier is in the dehumidification mode and the adiabatic precooler is in the precooler mode, a second mode wherein the dehumidifier is in the bypass mode and the adiabatic precooler is in the precooler mode, and a third mode wherein the dehumidifier is in the bypass mode and the adiabatic precooler is in the standby mode. In this manner, the dehumidifier and the adiabatic precooler may be selectively operated to satisfy an operating criterion for the heat transfer apparatus such as providing a process fluid at a process fluid set temperature, satisfying a heat transfer load, minimizing energy consumption, and/or minimizing water

consumption. Further, the heat transfer apparatus may include a water recovery system to recover water removed from the air by the dehumidifier. The recovered water may be utilized by the heat transfer apparatus as make-up water for the adiabatic precoolers as one example.

[0013] The present disclosure also provides a heat transfer apparatus having a heat exchanger for cooling a process fluid, the heat exchanger comprising a liquid distribution system, and a fan operable to cause air to move relative to the heat exchanger. The heat exchanger has a wet mode wherein the liquid distribution system distributes liquid; a dry mode wherein the liquid distribution system distributes less liquid than in the wet mode. The heat transfer apparatus further includes a thermal energy storage having a heat transfer mode wherein the thermal energy storage removes heat from the process fluid and a bypass mode wherein the thermal energy storage removes less heat from the process fluid than when the thermal energy storage is in the heat transfer mode. The heat transfer apparatus further includes a controller configured to receive either a request to minimize water consumption or a request to minimize energy consumption and determine a thermal duty for the heat transfer apparatus from a plurality of thermal duties including a lower thermal duty, an intermediate thermal duty, and a higher thermal duty. In response to receiving the request to minimize water consumption, the controller is configured to operate the heat exchanger in the dry mode and the thermal energy storage in the bypass mode based at least in part upon the thermal duty being the lower thermal duty; operate the heat exchanger in the dry mode and the thermal energy storage in the heat transfer mode based at least in part upon the thermal duty being the intermediate thermal duty; and operate the heat exchanger in the wet mode and the thermal energy storage in the heat transfer mode based at least in part upon the thermal duty being the higher thermal duty. In response to receiving the request to minimize energy consumption, the controller is configured to operate the heat exchanger in the wet mode and the thermal energy storage in the bypass mode based at least in part upon the thermal duty being the lower thermal duty; and operate the heat exchanger in the wet mode and the thermal energy storage in the heat transfer mode based at least in part upon the thermal duty being the higher thermal duty. The controller may thereby operate components of the heat transfer apparatus in different modes depending on the thermal duty and the request to minimize water or energy consumption, which permits accurate and efficient operation of the heat transfer apparatus to provide a requested process fluid set temperature, for example.

[0014] In accordance with another aspect of the present disclosure, a heat transfer apparatus is provided for an industrial process that requires process fluid at a process fluid set temperature. The heat transfer apparatus includes a process fluid heat exchange circuit to receive a process fluid at a temperature different than the process fluid set temperature and provide the process fluid at the process fluid set temperature. The process fluid heat exchange circuit includes a mechanical cooler having a hot side heat exchanger and a cold side heat exchanger and a hybrid cooler to receive process fluid from the hot side heat exchanger of the mechanical cooler and provide cooled process fluid to the cold side heat exchanger of the mechanical cooler. Because the hybrid cooler can provide cooler process fluid to the cold side heat exchanger of the mechanical cooler than a dry cooler or an adiabatic cooler, the work load required for the cold side heat exchanger of the mechanical cooler to provide the process fluid at the process fluid set temperature is lower which enables the use of a lower-capacity mechanical cooler and associated energy savings.

[0015] The hybrid cooler includes a direct heat exchanger and an indirect heat exchanger. The hybrid cooler has a dry mode wherein the indirect heat exchanger transfers heat from the process fluid to air and a hybrid mode wherein the indirect heat exchanger and the direct heat exchanger transfer heat from the process fluid to the air. The process fluid heat exchange circuit has a plurality of modes including a first mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the dry mode; a second mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the dry mode; a third mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the hybrid mode; and a fourth mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the hybrid mode.

[0016] The process fluid may bypass one or more components (e.g., mechanical cooler, direct heat exchanger, indirect heat exchanger) of the heat transfer apparatus by, for example, being routed around the component or being routed to the component when the component has limited heat exchange capability. For example, the process fluid heat exchange circuit can bypass the mechanical cooler by directing the process fluid through the hot and cold side heat exchangers of the mechanical cooler while the mechanical cooler is not operating such that the process fluid leaves the mechanical cooler at substantially the same temperature as it entered the mechanical cooler.

[0017] The heat transfer apparatus further comprises a controller operatively connected to the process fluid heat exchange circuit, the controller configured to operate the process fluid heat exchange circuit in one of the plurality of modes based at least in part upon a

determination of a thermal duty of the heat transfer apparatus. The controller may thereby operate components of the heat transfer apparatus in different modes depending on the associated thermal duty, which permits accurate and efficient operation of the heat transfer apparatus to provide a requested process fluid set temperature, for example.

[0018] The present disclosure also provides a heat transfer apparatus for an industrial process that requires process fluid at a process fluid set temperature. The heat transfer apparatus includes a process fluid heat exchange circuit comprising a mechanical cooler having a hot side heat exchanger and a cold side heat exchanger and a fluid cooler to receive the process fluid from the hot side heat exchanger and provide cooled process fluid to the cold side heat exchanger. The fluid cooler has a wet mode wherein the fluid cooler utilizes a liquid to facilitate heat transfer from the process fluid to air and a dry mode wherein the fluid cooler utilizes less liquid to facilitate heat transfer from the process fluid to the air than in the wet mode. The process fluid heat exchange circuit is operable in a plurality of modes including a first mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the dry mode thereof removes heat from the process fluid; a second mode wherein the mechanical cooler and the fluid cooler in the dry mode thereof remove heat from the process fluid; a third mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the wet mode thereof removes heat from the process fluid; and a fourth mode wherein the mechanical cooler and the fluid cooler in the wet mode thereof remove heat from the process fluid. The heat transfer apparatus further includes a controller operatively connected to the process fluid heat exchange circuit and configured to change the process fluid heat exchange circuit between the operating modes based at least in part upon a determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature. In this manner, the controller may operate one or more components of the heat transfer apparatus to satisfy the process fluid set temperature while turning off or reducing energy and/or water consumption of one or more other components.

[0019] In one embodiment, the determination of the whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature is based at least in part upon a temperature of the process fluid supplied by the process fluid heat exchange circuit, the process fluid set temperature, and a control range parameter. The controller may thereby make an accurate decision to change operating modes that takes into account the cooling capacity of the process fluid heat exchange circuit in the current operating mode and hysteresis of the process fluid heat exchange circuit.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0020] FIG. 1 is a schematic representation of a heat transfer apparatus according to a first approach;
- [0021] FIG. 2 is a more detailed schematic representation of the heat transfer apparatus of FIG. 1;
- [0022] FIG. 3 is a schematic representation of a heat transfer apparatus that is a first example of the heat exchanger of FIG. 1;
- [0023] FIGS. 4A and 4B are a chart showing the status of different components of the heat transfer apparatus of FIG. 3 during different operating modes while the heat transfer apparatus minimizes water consumption and discharges a phase change material;
- [0024] FIGS. 5A and 5B are a chart showing the status of components of the heat transfer apparatus of FIG. 3 during different operating modes while the heat transfer apparatus minimizes energy consumption and discharges the phase change material;
- [0025] FIGS. 6A and 6B are a chart showing the status of components of the heat transfer apparatus of FIG. 3 during different operating modes while the heat transfer apparatus minimizes water consumption and charges the phase change material;
- [0026] FIGS. 7A and 7B are a chart showing the status of components of the heat transfer apparatus of FIG. 3 showing the status of the components during different operating modes and while the heat transfer apparatus minimizes energy consumption and charges the phase change material;
- [0027] FIG. 8 is a schematic representation of a second example of the heat transfer apparatus of FIG. 1;
- [0028] FIGS. 9A and 9B are a chart showing the status of components of the heat transfer apparatus of FIG. 8 during different operating modes while the heat transfer apparatus minimizes water consumption and discharges a phase change material;
- [0029] FIGS. 10A and 10B are a chart showing the status of components of the heat transfer apparatus of FIG. 8 during different operating modes while the heat transfer apparatus minimizes energy consumption and discharges the phase change material;
- [0030] FIGS. 11A and 11B are a chart showing the status of components of the heat transfer apparatus of FIG. 8 during different operating modes while the heat transfer apparatus minimizes water consumption and charges the phase change material;
- [0031] FIGS. 12A and 12B are a chart showing the status of components of the heat transfer apparatus of FIG. 8 during different operating modes while the heat transfer apparatus

minimizes energy consumption and charges the phase change material;

[0032] FIG. 13 is a schematic representation of a third example of the heat transfer apparatus of FIG. 1, the heat transfer apparatus having a secondary closed-loop pump to facilitate charging of the phase change material;

[0033] FIGS. 14-19F are schematic representation of the heat transfer apparatus of FIG. 13 during different operating modes;

[0034] FIGS. 20A and 20B are a chart showing the status of components of the heat transfer apparatus of FIG. 13 during different operating modes while the heat transfer apparatus minimizes water consumption and discharges the phase change material;

[0035] FIGS. 21A and 21B are a chart showing the status of components of the heat transfer apparatus of FIG. 13 during different operating modes while the heat transfer apparatus minimizes energy consumption and discharges the phase change material;

[0036] FIGS. 22A and 22B are a chart showing the status of components of the heat transfer apparatus of FIG. 13 during different operating modes while the heat transfer apparatus minimizes energy consumption and charges the phase change material;

[0037] FIGS. 23A and 23B are a chart showing the status of components of the heat transfer apparatus of FIG. 13 during different operating modes while the heat transfer apparatus minimizes energy consumption and charges the phase change material;

[0038] FIGS. 23C-23F are a chart showing the status of components of the heat transfer apparatus of FIG. 13 during different operating modes that are selected according to state machine diagrams of FIGS. 85, 89, 92, 95;

[0039] FIG. 24 is a fourth example of the heat transfer apparatus of FIG. 1, the heat transfer apparatus having a direct heat exchanger and an indirect heat exchanger for removing heat from a process fluid;

[0040] FIG. 25 is a fifth example of the heat transfer apparatus of FIG. 1, the heat transfer apparatus having a direct heat exchanger to remove heat from a process fluid;

[0041] FIG. 26 is a schematic representation of a heat transfer apparatus according to a second approach;

[0042] FIG. 27 is a more detailed schematic representation of the heat transfer apparatus of FIG. 26;

[0043] FIG. 28 is a schematic representation of a first example of the heat transfer apparatus of FIG. 26;

[0044] FIGS. 29-32 are schematic representations of the heat transfer apparatus of FIG. 28 during different operating modes;

- [0045] FIG. 33 is a chart showing the status of components of the heat transfer apparatus of FIG. 28 during different operating modes while the heat transfer apparatus minimizes water consumption and discharges a phase change material;
- [0046] FIG. 34 is a chart showing the status of components of the heat transfer apparatus of FIG. 28 during different operating modes while the heat transfer apparatus minimizes energy consumption and discharges the phase change material;
- [0047] FIG. 35 is a chart showing the status of components of the heat transfer apparatus of FIG. 28 during different operating modes while the heat transfer apparatus minimizing water consumption and charges the phase change material;
- [0048] FIG. 36 is a chart showing the status of components of the heat transfer apparatus of FIG. 28 during different operating modes while the heat transfer apparatus minimizes energy consumption and charges the phase change material;
- [0049] FIG. 37 is a schematic representation of a second example of the heat transfer apparatus of FIG. 26;
- [0050] FIG. 38 is a chart showing the status of components of the heat transfer apparatus of FIG. 37 during different operating modes while the heat transfer apparatus minimizes water consumption and discharges the phase change material;
- [0051] FIG. 39 is a chart showing the status of components of the heat transfer apparatus of FIG. 37 during different operating modes while the heat transfer apparatus minimizes energy consumption and discharges the phase change material;
- [0052] FIG. 40 is a chart showing the status of components of the heat transfer apparatus of FIG. 37 during different operating modes while the heat transfer apparatus minimizes water consumption and charges the phase change material;
- [0053] FIG. 41 is a chart showing the status of components of the heat transfer apparatus of FIG. 37 during an adiabatic cooling mode, while minimizing energy consumption, and charging the phase change material;
- [0054] FIG. 42 is a schematic representation of a third example of the heat transfer apparatus of FIG. 26;
- [0055] FIG. 43 is a schematic representation of a fourth example of the heat transfer apparatus of FIG. 26;
- [0056] FIG. 44 is a schematic representation of a heat transfer apparatus according to a third approach;
- [0057] FIG. 45 is a schematic representation of a first example of the heat transfer apparatus of FIG. 44;

- [0058] FIGS. 46-49 are schematic views of a portion of the heat transfer apparatus of FIG. 45 showing different operating modes;
- [0059] FIG. 50 is a chart showing the status of components of the heat transfer apparatus of FIG. 45 during different operating modes, while minimizing energy consumption;
- [0060] FIG. 51 is a chart showing the status of components of the heat transfer apparatus of FIG. 45 while the heat transfer apparatus minimizes water consumption;
- [0061] FIG. 52 is a chart showing the status of components of the heat transfer apparatus of FIG. 45 during different operating modes and while the heat transfer apparatus generates water;
- [0062] FIG. 53 is a schematic view of a second example of the heat transfer apparatus of FIG. 44;
- [0063] FIG. 54 is a chart showing the status of components of the heat transfer apparatus of FIG. 53 during different operating modes and while the heat transfer apparatus minimizes energy consumption;
- [0064] FIG. 55 is a chart showing the status of components of the heat transfer apparatus of FIG. 53 during different operating modes and while the heat transfer apparatus minimizes water consumption;
- [0065] FIG. 56 is a chart showing the status of components of the heat transfer apparatus of FIG. 53 during different operating modes and while the heat transfer apparatus generates water;
- [0066] FIG. 57 is a schematic representation of a third example of the heat transfer apparatus of FIG. 44;
- [0067] FIG. 58 is a schematic representation of a fourth example of the heat transfer apparatus of FIG. 44;
- [0068] FIG. 59 is a schematic representation of a heat transfer apparatus in a chiller on mode;
- [0069] FIG. 60 is a schematic representation of the heat transfer apparatus of FIG. 59 showing the heat transfer apparatus in a chiller off mode;
- [0070] FIG. 61 is a schematic representation of a heat transfer apparatus having a condenser coil of a chiller downstream of a finned coil as air is directed through the heat transfer apparatus;
- [0071] FIGS. 62 and 63 are schematic representation of a heat transfer apparatus when the heat transfer apparatus is in a chiller on mode and a chiller off mode;
- [0072] FIGS. 64-67 are schematic representation of a heat transfer apparatus showing

different modes of the heat transfer apparatus;

[0073] FIG. 68 is a schematic representation of a heat transfer apparatus having an evaporator of a chiller in an outer structure of the heat transfer apparatus;

[0074] FIG. 69 is a perspective view of the heat transfer apparatus of FIG. 68 showing the heat transfer apparatus having a thermal energy storage side-by-side the evaporator;

[0075] FIGS. 70-73 are schematic representations of a heat transfer apparatus during different operating modes thereof;

[0076] FIGS. 74 and 75 are schematic representations of a heat transfer apparatus having a phase change material with an elevated storage temperature during different operating modes of the heat transfer apparatus;

[0077] FIG. 76 is a schematic view of a heat transfer apparatus having a phase change material tank bypass;

[0078] FIG. 77 is a perspective view of a heat transfer apparatus having two stacked air/process fluid heat exchangers and a phase change material tank;

[0079] FIG. 78 is a schematic view of a heat transfer apparatus having a housing and a phase change material tank in the housing;

[0080] FIG. 79 is a schematic view of a heat transfer apparatus having a membrane mass exchanger that dehumidifies air before the air reaches a heat exchanger of the heat transfer apparatus;

[0081] FIG. 80 is a schematic view of a heat transfer apparatus having a membrane mass exchanger upstream of an adiabatic cooling pad and a finned coil to dehumidify the air and improve the efficiency of heat transfer between the finned coil and the air flow;

[0082] FIG. 81 is a schematic view of a vacuum membrane mass exchanger having sheet membranes interposed between air passageways and permeate passageways;

[0083] FIG. 82 is a schematic view of a heat transfer apparatus having a dehumidifier that uses liquid desiccant to dehumidify air before the air reaches an indirect heat exchanger of the heat transfer apparatus;

[0084] FIG. 83 is a schematic view of a heat transfer apparatus having a shape memory alloy cooler;

[0085] FIG. 84 is a graph showing temperature versus entropy for a shape memory alloy material of the shape memory alloy cooler;

[0086] FIG. 85 is a state machine diagram of a method for operating the heat transfer apparatus of FIG. 13 to minimize water consumption when there is a cooling load;

[0087] FIG. 86 is a block diagram of parameters utilized in the method of FIG. 85;

- [0088] FIG. 87 is a table showing control logic used in the state machine diagram of FIG. 85 to select an initial operating mode of the heat transfer apparatus;
- [0089] FIGS. 88A, 88B, 88C are a table showing control logic used in the state machine diagram of FIG. 85 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode of the heat transfer apparatus;
- [0090] FIG. 89 is a state machine diagram of a method for operating the heat transfer apparatus of FIG. 13 to minimize water consumption when there is no cooling load;
- [0091] FIG. 90 is a table showing control logic utilized in the method of FIG. 89 to select an initial operating mode of the heat transfer apparatus of FIG. 13;
- [0092] FIG. 91 is a table showing logic utilized in the method of FIG. 89 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode;
- [0093] FIG. 92 is a state machine diagram of a method for controlling the heat transfer apparatus of FIG. 13 to minimize energy consumption when there is a cooling load;
- [0094] FIG. 93 is a table showing control logic utilized in the method of FIG. 92 to select an initial operating mode of the heat transfer apparatus;
- [0095] FIGS. 94A, 94B, 94C are a table showing control logic used in the state machine diagram of FIG. 92 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode;
- [0096] FIG. 95 is a state machine diagram of a method for operating the heat transfer apparatus of FIG. 13 to minimize energy consumption when there is no cooling load;
- [0097] FIG. 96 is a table showing control logic utilized in the method of FIG. 95 to select an initial operating mode of the heat transfer apparatus;
- [0098] FIG. 97 is a table showing control logic utilized in the method of FIG. 95 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode;
- [0099] FIGS. 98A-98H is a flow diagram of another method for selecting operating modes for the heat transfer apparatus of FIG. 13;
- [00100] FIG. 99 is a schematic view of a heat transfer system for cooling process fluid from a building, the heat transfer system having heat transfer apparatuses in a row connected to process fluid supply and return conduits;
- [00101] FIG. 100 is a schematic view of a heat transfer system having two rows of heat transfer apparatuses connected to process fluid supply and return conduits of a building;

- [00102] FIG. 101 is a schematic view of a heat transfer system for cooling process fluid from a building, the heat transfer system having heat transfer apparatuses that each include a fluid cooler and a structure containing a chiller and a pump;
- [00103] FIG. 102 is a schematic view of a heat transfer apparatus having a chiller and a fluid cooler including an adiabatic precooler and a fluid cooling coil;
- [00104] FIG. 103 is a schematic representation of a first example of the heat transfer apparatus of FIG. 102, FIG. 103 showing the heat transfer apparatus in a first operating mode wherein a fluid cooler cools process fluid from a cooling load;
- [00105] FIG. 104 is a schematic view of the heat transfer apparatus of FIG. 103 showing the heat transfer apparatus in a second operating mode wherein the fluid cooler and a chiller operate to cool process fluid from the cooling load;
- [00106] FIG. 105 is a schematic view of a second embodiment of the heat transfer apparatus of FIG. 102, FIG. 105 showing the heat transfer apparatus in a first operating mode wherein a fluid cooler cools process fluid from a cooling load;
- [00107] FIG. 106 is a schematic view of the heat transfer apparatus of FIG. 105 showing the heat transfer apparatus in a second operating mode wherein the fluid cooler and a chiller provide cooling for the cooling load;
- [00108] FIG. 107 is a schematic view of a third embodiment of the heat transfer apparatus of FIG. 102, FIG. 107 showing the heat transfer apparatus in a first operating mode wherein a fluid cooler cools process fluid from a cooling load;
- [00109] FIG. 108 is a schematic view of the heat transfer apparatus of FIG. 106 showing the heat transfer apparatus in a second operating mode wherein the fluid cooler and a chiller provide cooling for the cooling load;
- [00110] FIG. 109 is a schematic view of a fourth embodiment of the heat transfer apparatus of FIG. 102, FIG. 109 showing the heat transfer apparatus in a first operating mode wherein a fluid cooler cools process fluid from a cooling load;
- [00111] FIG. 110 is schematic view of the heat transfer apparatus of FIG. 109 showing the heat transfer apparatus in a second operating mode wherein the fluid cooler and a chiller provide cooling for the cooling load;
- [00112] FIG. 111 is a state machine diagram of a method for operating a heat transfer apparatus to minimize water consumption;
- [00113] FIG. 112 is a block diagram of parameters utilized in the method of FIG. 111;
- [00114] FIG. 113 is a table showing control logic used in the method of FIG. 111 to select an initial operating mode of the heat transfer apparatus;

- [00115] FIG. 114 is a table showing control logic used in the method of FIG. 111 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode of the heat transfer apparatus;
- [00116] FIG. 115 is a state machine diagram of a method of operating a heat transfer apparatus to minimize water consumption;
- [00117] FIG. 116 is a state machine diagram of a method of operating a heat transfer apparatus to minimize energy consumption;
- [00118] FIG. 117 is a table showing control logic used in the method of FIG. 116 to select an initial operating mode of the heat transfer apparatus;
- [00119] FIG. 118 is a table showing control logic used in the method of FIG. 116 to change from a current operating mode of the heat transfer apparatus to a subsequent operating mode of the heat transfer apparatus;
- [00120] FIG. 119 is a state machine diagram of a method for operating a heat transfer apparatus to minimize energy consumption;
- [00121] FIG. 120 is a state machine diagram of a method for operating a heat transfer apparatus to minimize water consumption wherein an initial operating mode is determined;
- [00122] FIG. 121 is a state machine diagram of a method for operating a heat transfer apparatus to minimize water consumption wherein an initial operating mode is not determined;
- [00123] FIG. 122 is a schematic view of a heat transfer system for cooling process fluid from a building, the heat transfer system having different types of central chiller plant modules;
- [00124] FIG. 123 is a schematic view of a heat transfer apparatus having a hybrid cooler and a chiller;
- [00125] FIG. 124 is a schematic view of a heat transfer apparatus having a hybrid cooler, a chiller, and a thermal energy storage;
- [00126] FIG. 125 is a schematic view of a first embodiment of the heat transfer apparatus of FIG. 123, FIG. 125 showing the heat transfer apparatus in a free cooling mode wherein the dry cooling coil rejects heat from the process fluid;
- [00127] FIG. 126 is a schematic view of the heat transfer apparatus of FIG. 125 showing the heat transfer apparatus in a free cooling mode wherein a heat exchanger and a direct heat exchanger operate to reject heat from the process fluid;
- [00128] FIG. 127 is a schematic view of the heat transfer apparatus of FIG. 125 showing the heat transfer apparatus in a free cooling mode with the dry cooling coil, the heat exchanger, and the direct heat exchanger operating to reject heat from the process fluid;

- [00129] FIG. 128 is a schematic view of the heat transfer apparatus of FIG. 125 showing the heat transfer apparatus operating in a mode wherein the dry cooling coil and the chiller are operated to reject heat from the process fluid;
- [00130] FIG. 129 is a schematic view of the heat transfer apparatus of FIG. 125 showing the heat transfer apparatus in a mode wherein the heat exchanger, direct heat exchanger, and the chiller operate to reject heat from the process fluid;
- [00131] FIG. 130 is a schematic view of the heat transfer apparatus of FIG. 125 showing the dry cooling coil, heat exchanger, direct heat exchanger, and the chiller operating to reject heat from the process fluid;
- [00132] FIG. 131 is a schematic view of a second embodiment of the heat transfer apparatus of FIG. 123 in an operating mode, the heat transfer apparatus of FIG. 131 having a hybrid cooler with a heat exchanger and direct heat exchanger system in parallel with a dry cooling coil;
- [00133] FIGS. 132-136 are schematic views of the heat transfer apparatus of FIG. 131 in different operating modes;
- [00134] FIG. 137 is a schematic view of a third example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 137 having a hybrid cooler with an adiabatic precooler upstream of a dry cooling coil;
- [00135] FIG. 138 is a fourth example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 138 having a direct heat exchanger and a dry cooling coil in parallel with adiabatic precooling for the dry cooling coil;
- [00136] FIG. 139 is a schematic view of a fifth example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 139 having a hybrid cooler with a dry cooling coil, an indirect heat exchanger, and a direct heat exchanger;
- [00137] FIGS. 140, 141, 142 are schematic views of the hybrid cooler of FIG. 139 showing the hybrid cooler in an energy saver mode, an adiabatic mode, and a water saver mode;
- [00138] FIG. 143 is a schematic view of a sixth example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 143 having a dry cooling coil and a direct heat exchanger;
- [00139] FIG. 144 is a schematic view of a seventh example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 144 having a water loop that includes a hybrid cooler having a dry cooling coil and a direct heat exchanger;

- [00140] FIG. 145 is a schematic view of an eighth example of the heat transfer apparatus of FIG. 123, the heat transfer apparatus of FIG. 145 having a water loop that includes a hybrid cooler having a direct heat exchanger and a dry cooling coil in parallel;
- [00141] FIG. 146 is a schematic view of a heat transfer apparatus including distributed components;
- [00142] FIG. 147 is a state machine diagram of a method of operating a heat transfer apparatus to minimize water consumption;
- [00143] FIG. 148 is a state machine diagram of a method of operating a heat transfer apparatus to minimize water consumption;
- [00144] FIG. 149 is a state machine diagram of a method of operating a heat transfer apparatus to minimize energy consumption;
- [00145] FIG. 150 is a state machine diagram of a method of operating a heat transfer apparatus to minimize energy consumption;
- [00146] FIGS. 151, 152, 153, 154 are schematic views of heat transfer apparatuses having heat exchangers to separate a chilled water loop of the cooling load from a glycol loop of the heat transfer apparatus; and
- [00147] FIGS. 155-159 are schematic views of heat transfer apparatuses having bypasses for fluid coolers that permits modulation of the process fluid flow to the fluid coolers.

DETAILED DESCRIPTION

- [00148] With reference to FIG. 1, a heat transfer apparatus 10 according to a first approach is provided. The heat transfer apparatus 10 has an outer structure such as a housing 12, one or more air inlets 14 and one or more air outlets 16. The heat transfer apparatus 10 has a heat exchanger 19 for transferring heat between the process fluid and the air moving from the air inlets 14 to the air outlet 16. The heat exchanger 19 may utilize various air/process fluid flow configurations, such as cross-flow, counter flow, parallel flow, or a combination thereof. The heat transfer apparatus 10 further includes a thermal energy storage (TES) such as a phase change material (PCM) tank 26 and a mechanical cooler, such as a heat pump or chiller 28, for providing additional heat transfer for the process fluid. The PCM in the PCM tank 26 may have a fixed or variable freezing temperature. The heat exchanger 19 includes an adiabatic precooler 20 having a precooling pad 22 and an indirect heat exchanger such as a fluid cooling coil 24. The heat transfer apparatus 10 has an air flow generator such as one or more fans 30 that are operable to cause air flow from the air inlets 14, across the precooling pads 22 and fluid cooling coils 24, and out from the air outlet 16. The one or more fans 30 may be fixed or variable speed fans. The PCM tank 26 and chiller 28 provide

trim cooling as needed to satisfy a cooling load requirement while permitting the fan 30, adiabatic precooler 20, and indirect heat exchanger 23 to be sized for less than peak cooling loads which reduces water consumption and/or energy consumption for off-peak cooling loads. The heat transfer apparatus 10 may thereby satisfy a peak cooling load or requested process fluid set temperature for an industrial process at a particular geographic location even on the hottest days of the year. Further, the heat transfer apparatus 10 is operable to either minimize water consumption or energy consumption while satisfying cooling loads throughout the year.

[00149] Regarding FIG. 2, a more detailed schematic representation of the heat transfer apparatus 10 is provided. The heat transfer apparatus 10 includes a process fluid inlet 34 to receive process fluid, such as a water or water/glycol mixture, from an industrial process such as a computer datacenter. In one embodiment, multiple heat transfer apparatuses 10 may be arranged in parallel such that the process fluid inlet 34 receives process fluid from an upstream heat transfer apparatus 10. The process fluid received at process fluid inlet 34 may be a liquid, a gas, or a liquid/gas mixture. The heat transfer apparatus 10 has a process fluid outlet 36 for returning process fluid to the industrial process, or to a downstream heat transfer apparatus. The heat transfer apparatus 10 may be operated to cool or heat the process fluid received at the process fluid inlet 34 as desired for a particular embodiment.

[00150] The heat transfer apparatus 10 has a controller 40 with a memory 42 that is a non-transitory computer readable medium for storing instructions to operate the heat transfer apparatus 10. The controller 40 has a processor 44 to perform the instructions stored in the memory 42 and control the heat transfer apparatus 10. The processor 44 may include, for example, one or more microprocessors and/or one or more application specific integrated circuits (ASIC). The memory 42 may include, for example, a magnetically readable storage medium (e.g. a magnetic hard drive), electrical charge-based storage medium (e.g. EEPROM, RAM), and/or a solid-state storage medium (e.g., a flash drive). The controller 40 further includes a communication circuitry 46 for communicating with a remote device, such as a HVAC system controller of a building. The communication circuitry 46 may include, for example, a WiFi network interface, an ethernet interface, and/or a cellular (e.g., 3G, 4G, 4G LTE, 5G) network interface. The communication circuitry 46 receives a process fluid variable, such as at least one of temperature, pressure, and flow rate, that the remote device has requested the heat apparatus 10 to provide. The processor 44 stores the process fluid variable in a memory 42 and operates the heat transfer apparatus 10 to provide process fluid at the process fluid outlet 36 that satisfies the process fluid variable. The

communication circuitry 46 may receive other data from the remote device as well as transmit data to the remote device, such as air temperature and/or pressure; process fluid temperature, flow rate, and/or pressure; and/or component status data. The controller 40 may control two or more heat transfer apparatuses 10. The controller 40 may be on-board the heat transfer apparatus 10, remote from the heat transfer apparatus such as HVAC system controller of a building, or may be a cloud-based computing system that controls the heat transfer apparatus 10 via the internet, as some examples.

[00151] The adiabatic precooler 20 includes an evaporative liquid distribution system 50 configured to distribute evaporative liquid, such as water, onto the precooling pad 22. The evaporative liquid distribution system 50 includes a sump 52 to collect evaporative liquid from the precooling pad 22 and a pump 54 to pump evaporative liquid from the sump 52 to a liquid distributor, such as a spray nozzle, of the evaporative liquid distribution system 50 to distribute evaporative liquid onto the precooling pad 22. The evaporative liquid distribution system 50 further includes a makeup valve 56 to permit water to be added to the sump 52 to compensate for evaporation of evaporative liquid, a liquid level sensor 58 to detect the level of the evaporative liquid in the sump 52, a drain valve 60 for draining the sump 52, and a conductivity sensor 62 for monitoring one or more variables of the evaporative liquid in the sump 54.

[00152] The chiller 28 may take different forms, such as a refrigerant-based chiller, a solid state chiller (e.g., electrocaloric, magnetocaloric, thermoelastic), or a gas-based chiller (reverse Brayton cycle) as some examples. In the embodiment of FIG. 2, the chiller 28 is refrigerant-based chiller and includes a condenser 64, an evaporator 66, a compressor 68, and an expansion valve 70.

[00153] The heat transfer apparatus 10 has a process fluid distribution system 80 for routing or directing the flow of process fluid between the components of the heat transfer apparatus 10. The process fluid distribution system 80 may include one or more bypass pump(s) 82, throttling valve(s) 84, and bypass valve(s) 86. A given valve may function either as a bypass valve or a throttling valve depending on the mode of the heat transfer apparatus 10, as discussed in greater detail below.

[00154] The PCM tank 26 includes a phase change material 90, such as ice or another phase change material having a melting temperature above 32°F and a heat exchanger 92 for exchanging heat between the phase change material 90 and the process fluid. The phase change material 90 may include ice, paraffin waxes, non-paraffin organics, hydrated salts, or metallics as some examples. The PCM tank 26 further includes a drain valve 94 for emptying

the PCM tank 26, a flow valve 96 to fill the PCM tank 26, an air pressure sensor 98 for detecting air pressure in the PCM tank 26, an air release valve 100 to release air pressure from the PCM tank 26 when the air pressure exceeds a predetermined threshold, and a PCM charge sensor 102. An example of the PCM charge sensor 102 is a liquid level sensor for PCM having different solid and liquid densities. Another example of the PCM charge sensor 102 is one or more temperature probes at different locations on the PCM tank 26. The PCM tank 26 further includes a humidity control system 104 for detecting humidity within the PCM tank 26. The humidity control system 104 may include a relative humidity sensor 106 and a humidity control device 108 such as a dehumidifier.

[00155] The PCM tank 26 has an air distribution system 101 for blowing air into the PCM tank 26 to agitate the liquid PCM and promote faster and more even melting and/or freezing of the PCM. The air distribution system 101 directs air into the PCM at the bottom of the PCM tank 26 and the air agitates the PCM as the air rises in the PCM tank 26. To provide this functionality, the air distribution system 101 may include an air pump, check valve, relative humidity sensor, and a humidity control device such as a vent as shown in FIG. 2.

[00156] The heat transfer apparatus 10 of the first approach may take various forms. With reference to FIG. 3, a heat transfer apparatus 110 is provided that is a first example of the heat transfer apparatus 10. The heat transfer apparatus 110 includes a process fluid heat exchange circuit 111 operable to receive a process fluid from a cooling load 136, cool the process fluid to achieve a requested process fluid variable such as a process fluid set temperature, and direct the cooled process fluid back to the cooling load 136. The heat transfer apparatus 110 has a controller 113 for operating the components of the process fluid heat exchange circuit 111.

[00157] The process fluid heat exchange circuit 111 includes a heat exchanger 112 having an adiabatic precooling pad 114 and an indirect heat exchanger such as a fluid cooling coil 116. The adiabatic precooling pad 114 has a precooling pad 118 and an evaporative liquid distribution system 120 for distributing evaporative liquid onto the precooling pad 118. The evaporative liquid distribution system 120 includes a sump 121 for collecting evaporative liquid from the precooling pad 118 and a sump pump 122 operable to pump the evaporative liquid from the sump 120 to the precooling pad 118.

[00158] The heat transfer apparatus 110 includes a fan 124 to generate air flow across the precooling pad 118 and the fluid cooling coil 116. The adiabatic precooling pad 114 reduces the dry bulb temperature of the air before the air reaches the fluid cooling coil 116 which improves the efficiency of heat transfer between the air and a fluid cooling coil 116. The

heat transfer apparatus 110 further includes a chiller 130 having a condenser 132 and an evaporator 134 that are configured to transfer heat to or from a process fluid from the cooling load 136. The heat transfer apparatus 110 has a thermal energy storage, such as a PCM tank 138, and a closed-loop pump 140 that is used to recharge the PCM tank 138 as discussed in greater detail below. The heat transfer apparatus 110 is organized as a base module 142 that may be added to other base modules in series or parallel to provide a desired amount of cooling capacity for the cooling load 136. The components of the heat transfer apparatus 110 may be within a single outer structure or may be arranged in multiple outer structures as desired for a particular embodiment.

[00159] Regarding FIGS. 4A and 4B, a method 150 is provided for operating the heat transfer apparatus 110. The method 150 is provided as a chart organized by thermal duty 152 that increases from an easy 154 thermal duty to a hard 156 thermal duty. The thermal duty of the heat transfer apparatus 110 may be determined by one or variables, such as ambient air temperature (e.g., wet bulb and/or dry bulb), ambient air humidity, the temperature and/or humidity of air inside of the heat transfer apparatus 110, process fluid set temperature, process fluid pressure, process fluid flow rate, time of day, season, or a combination thereof. The method 150 has logic 158 that facilitates changing of the heat transfer apparatus 110 between operating modes 160 as the thermal duty 152 changes. In one embodiment, the controller 113 progresses from an “easier” operating mode 160 to a “harder” operating mode 160 in response to the heat transfer apparatus 110 in the “easier” operating mode 160 being unable to satisfy a process fluid set temperature requested by, for example, an HVAC system controller.

[00160] The method 150 further includes variables 162 of components of the heat transfer apparatus 110 that vary as the heat transfer apparatus 110 changes between the operating modes 160. In method 150, the controller 113 has received a request to minimize water consumption such that the method 150 is representative of a water saving sequence option. The request may be received from a remote device via the communication circuitry 46 or may be determined by the controller 113 based upon data available to the controller 113 such as an ambient air variable, a process fluid variable, a variable indicative of a state of a component of the heat transfer apparatus 110, or a combination thereof. Further, the PCM tank 138 is capable of discharging in the method 150.

[00161] More specifically, the operating modes 160 include a dry cooling mode 164 that may be the default mode that the controller 113 begins with in response to a request for the heat transfer apparatus 110 to provide a process fluid to the cooling load 136 at a process fluid

set temperature. In the dry cooling mode 164, the variables 162 include a fan status 166, a sump pump status 168, a status 170 of whether process fluid is flowing through the fluid cooling coil 116, a status 172 of whether the evaporator 134 and PCM tank 138 are bypassed, a status 174 of the chiller 130, a status 176 of the closed-loop pump 140, and a status 178 of whether process fluid is flowing through the condenser 132 of the chiller 130. The variables 162 further include a status 180 of whether the process fluid is flowing through the evaporator 134 of the chiller 130, a status 182 of whether the process fluid is flowing through the PCM tank 138, a status 184 of the charge of the PCM tank 138, and a status 186 regarding the mode of the PCM tank 138. The status 186 indicates whether the PCM tank 138 is available to discharge or charge during the different operating modes 160 of the method 150.

[00162] In the dry cooling mode 164, the fan 124 is on, the sump pump 122 is off, the process fluid flows through the fluid cooling coil 116, and the evaporator 134 of the chiller 130 and the PCM tank 138 are fully bypassed. Further, in the dry cooling mode 164, the chiller 130 is off, the closed-loop pump 140 is off, the process fluid bypasses the condenser 132 of the chiller 130, and the process fluid is unable to flow through the evaporator 134 of the chiller 130. Still further, in the dry cooling mode 164, the process fluid bypasses the PCM tank 138 and the PCM tank 138 has a charge of greater than or equal to 0%.

[00163] As the thermal duty 152 gets harder or the thermal load increases, the controller 113 changes from the dry cooling mode 164 to another operating mode 160 based upon a determination 188 of whether the PCM tank 138 has a charge of greater than a predetermined minimum threshold such as 10%, 5%, or 0%. In the method 150, the predetermined minimum threshold is 0%.

[00164] If the PCM tank 138 has a charge of greater than the predetermined minimum threshold, the controller 113 enters a dry cooling and phase change material mode 190. In the dry cooling and phase change material mode 190, a portion of the process fluid enters the evaporator 134 of the chiller 130 and the PCM tank 138 and a portion of the process fluid bypasses the evaporator 134 and the PCM tank 138 as indicated by reference numerals 192 and 194 in method 150. Further, in the dry cooling and phase change material mode 190, the PCM tank 138 is in a discharge mode as indicated by reference numeral 196.

[00165] If, however, the controller 113 determines 188 that the PCM tank charge is not greater than the predetermined minimum threshold, the controller 113 may skip the dry cooling and PCM mode 190 and advance to a dry cooling chiller mode 200. The dry cooling and chiller mode 200 permits greater cooling capacity than the dry cooling mode 164. In the

dry cooling and chiller mode 200, a portion of the process fluid flows through the condenser 132 and the evaporator 134 of the chiller 130 as shown by reference numerals 202, 204 and the chiller 130 is on as shown by reference numeral 206. Because the PCM tank 138 has a charge of 0%, the process fluid does not flow through the PCM tank 138 as shown by reference numeral 208.

[00166] If the thermal duty 152 continues to increase when the heat transfer apparatus 110 is in the dry cooling and chiller mode 200, the controller 113 determines 210 whether the PCM tank charge is greater than 0%. If the PCM tank charge is greater than 0%, the controller 113 changes the heat transfer apparatus 110 to the dry cooling, chiller, and PCM mode 212 to accommodate the increase in thermal duty 152. As shown in FIGS. 4A and 4B, the controller 113 may enter the dry cooling, chiller, and PCM mode 212 after being in the dry cooling and chiller mode 200 from the dry cooling and chiller mode 200 when the tank charge is 0% or, alternatively, the controller 113 may enter the dry cooling, chiller, and PCM mode 212 from the dry cooling and PCM mode 190 if the charge of the PCM tank 138 is greater than zero. In the dry cooling, chiller, and PCM mode 212, a portion of the process fluid flows through the chiller condenser 132 and chiller evaporator 134 as shown by reference numerals 214, 216 and the chiller 130 is on as shown by reference numeral 218. Because the PCM tank 138 has a charge greater than zero, the process fluid is directed through the PCM tank 138 as shown by reference numeral 220 which cools the process fluid and the PCM tank 138 is in a discharge mode as shown by reference numeral 222.

[00167] The controller 113 may change the operation of the heat transfer apparatus 110 from the dry cooling, chiller, and PCM mode 212 to an adiabatic cooling and PCM mode 224 upon the controller 113 determining 226 that the PCM tank charge is greater than 0% and the thermal duty 152 continuing to increase. In the adiabatic cooling and PCM mode 224, the sump pump 122 is on as shown by reference numeral 228 to pump the evaporative liquid to the precooling pad 118. In the adiabatic cooling PCM mode 224, the chiller 130 is off as shown by reference numeral 230 and the process fluid does not flow through the chiller condenser 132 or the chiller evaporator 134 as shown by reference numerals 232, 234. The process fluid flows through the PCM tank 138 as shown by reference numeral 236 and the PCM tank 138 is in the discharge mode 238 to remove heat from the process fluid.

[00168] The method 150 includes the controller 113 changing the heat transfer apparatus 110 from the adiabatic cooling and PCM mode 224 to an adiabatic cooling and chiller mode 240 in response to the controller 113 determining 242 the PCM tank 138 has a charge greater than 0% and the thermal duty 152 continuing to increase. In the adiabatic cooling

and chiller mode 240, the sump pump 122 is on as shown by reference numeral 241 to wet the precooling pad 118 and decrease the dry bulb temperature of air in the heat transfer apparatus 110 before the air reaches the fluid cooling coil 116. The chiller 130 is on and at least a portion of the process fluid flows through the chiller condenser 132 and chiller evaporator 134 as shown by reference numerals 244, 246, 248. Because the PCM tank 138 has a charge of 0% at step 242, the process fluid does not flow through the PCM tank 138 in the adiabatic cooling and chiller mode 240 as shown by reference numeral 250.

[00169] The heat transfer apparatus 110 may enter the adiabatic cooling and chiller mode 240 from the adiabatic cooling and PCM mode 224 if the PCM tank has a charge of 0%. Alternatively, the heat transfer apparatus 110 may enter the adiabatic cooling and chiller mode 240 from the dry cooling and chiller mode 200 or dry cooling, chiller, and PCM mode 212 if the controller 113 determines the PCM tank 138 has a charge of 0% either at step 210 or 226, and the thermal duty 152 continues to increase.

[00170] The controller 113 may reconfigure the heat transfer apparatus 110 from the adiabatic cooling and PCM mode 224 to an adiabatic cooling, chiller, and PCM mode 252 in response to the controller 113 determining 242 that the PCM tank 138 has a charge greater than 0% and the thermal duty 152 increasing to the hard 156 level. In the adiabatic cooling, chiller, and PCM mode 252, the sump pump 122 is on as shown by reference numeral 254, the chiller 130 is on as shown by reference numeral 256, at least a portion of the process fluid flows through the chiller condenser 132 and the chiller evaporator 134 as shown by reference numerals 258, 260, and the process fluid flows through the PCM tank 130 as shown by reference numeral 262. The PCM tank 138 is in a discharge mode as shown by reference numeral 264 and removes heat from the process fluid.

[00171] The controller 113 may advance through the operating modes 160 according to the logic 158 as the thermal duty 152 increases or decreases. Alternatively, the controller 113 may hop from one operating mode 160 to another operating mode (e.g., mode 164 to mode 252 or vice versa) in response to a sudden change in the thermal duty 152 placed on the heat transfer apparatus 110.

[00172] With reference to FIGS. 5A and 5B, the controller 113 may utilize a method 270 in response to receiving a request to minimize energy consumption and the PCM tank 138 being capable of discharging to provide trim cooling. The method 270 includes operating modes 272 that the controller 113 may advance through as a thermal duty 274 changes from an initial or easy 276 level to a maximum or hard 278 level. The method 270 is similar in many respects to the method 150. One difference is that the method 270 utilizes

adiabatic cooling during modes 280, 282, 284, 286 to limit energy consumption.

[00173] With reference to FIGS. 6A and 6B, the controller may utilize a method 300 in response to the controller 113 receiving a request to minimize water consumption and the PCM tank 138 is capable of being charged. The method 300 includes operating modes 302 that the controller 113 progresses through as the thermal duty 304 changes. The method 300 is similar in many respects to the method 150 discussed above and includes variables 306 that vary as the controller 113 progresses through the modes 302. One difference between methods 150 and 300 is that the modes 302 include a dry cooling closed-loop chiller mode 310 wherein the process fluid does not flow through the chiller evaporator 134 or the PCM tank 138 as shown by reference numerals 312, 314. Instead, a secondary process fluid, which may be the same or different than the process fluid flowing through the fluid cooling coil 116, is circulated by the closed-loop pump 140 as shown by the reference numeral 316. The closed-loop pump 140 pumps the secondary process fluid between the chiller evaporator 134, which cools the secondary process fluid, to the PCM tank 138 to cool the phase change material in the PCM tank 138 and charge the PCM tank 138. The process fluid flows through the fluid cooling coil 116 during operating mode 310 to satisfy the thermal load placed on the heat transfer apparatus 110.

[00174] Likewise, in the adiabatic cooling and closed loop chiller mode 316, the process fluid does not flow through the chiller evaporator 134 and PCM tank 138 as shown by reference numerals 318, 320. Instead, a secondary process fluid is circulated by the closed-loop pump 140 to permit the chiller evaporator 134 and the secondary process fluid to remove heat from the PCM tank 138 and charge the PCM tank 138. In the adiabatic cooling and closed loop chiller mode 316, the process fluid is cooled via the fluid cooling coil 116 and the adiabatic precooler 114 precooling the air upstream of the fluid cooling coil 116.

[00175] The operating modes 302 of method 300 include a dry cooling and chiller mode 309 wherein the chiller 130 operates and process fluid flows through the chiller evaporator 134 to be cooled as shown by reference numeral 311. Further, in dry cooling and chiller mode 309, a portion of the cooled process fluid flows through the PCM tank 138 to charge the PCM tank 138 as shown by reference numeral 313.

[00176] The operating modes 302 include an adiabatic cooling mode 317 wherein the chiller 130 is off. However, in the adiabatic cooling mode 317, process fluid cooled by the fluid cooling coil 116 flows to the PCM tank 138 to charge the PCM tank 138 as shown by reference numeral 319. The operating modes 302 further include an adiabatic cooling and chiller mode 321 wherein process fluid cooled by the fluid cooling coil 116 and the chiller

evaporator 134 is routed to the PCM tank 138 to charge the PCM tank 138 as shown by reference numeral 323.

[00177] With reference to FIGS. 7A and 7B, the controller 113 may utilize a method 330 in response to receiving a request to minimize energy consumption and the PCM tank 138 is capable of being charged. The method 330 includes operating modes 332 that the controller 113 progresses through in response to a thermal duty 334 for the heat transfer apparatus 110 increasing.

[00178] With reference to FIG. 8, a heat transfer apparatus 350 is provided that is a second example of the heat transfer apparatus 10 discussed above. The heat transfer apparatus 350 has a process fluid heat exchange circuit 351 that receives process fluid from a cooling load 353 at an elevated temperature and cools the process fluid so that the process fluid heat exchange circuit 351 can return cooled process fluid to the cooling load 353 at a process fluid set temperature, for example. The heat transfer apparatus 350 is similar in many respects to the heat transfer apparatus 110 except that the heat transfer apparatus 350 lacks a closed-loop pump and associated valving for circulating a secondary process fluid in a closed-loop to recharge a PCM tank 368. The heat transfer apparatus 350 includes an adiabatic precooling pad 352 having an evaporative liquid distribution system 354 for distributing evaporative liquid onto a precooling pad 356 and a pump 358 of a sump 360 to pump collected evaporative liquid to the precooling pad 356. The heat transfer apparatus 350 further includes a fluid cooling coil 362, a fan 364, a chiller 366, and a PCM tank 368.

[00179] Regarding FIGS. 9A and 9B, a method 380 is provided that a controller 370 of the heat transfer apparatus 350 may use in response to receiving a request to minimize water consumption and the PCM tank 368 being capable of discharging. The method 380 includes modes 382 that the controller 370 progresses through according to logic 384 as a thermal duty 386 varies between an initial or easy 388 level and a maximum or hard 390 level. The method 380 includes variables 392 indicative of the state of the components of the heat transfer apparatus 350 that change throughout the different modes 382.

[00180] Regarding FIGS. 10A and 10B, a method 400 is provided that the controller 370 may implement in response to receiving a request to minimize energy consumption and the PCM tank 368 being capable of discharging. The method 400 includes modes 402 that the controller 370 progresses through according to logic 404 as a thermal duty 406 of the heat transfer apparatus 350 changes. The method 400 includes variables 403 for the components of the heat transfer apparatus 350 that vary according to the different operating modes 402.

[00181] With reference to FIGS. 11 and 11B, a method 410 is provided that the controller

370 may utilize in response to receiving a request to minimize water consumption and the PCM tank 368 being capable of being charged. The method 410 has modes 412 that the controller 370 progresses through as a thermal duty 414 of the heat transfer apparatus 350 changes. The method 410 has variables 415 of components of the heat transfer apparatus 350 that vary according to the different modes 412. One difference between the methods 300 and 410 is that the method 410 charges the PCM tank 368 using the process fluid that is received from a cooling load 353 rather than utilizing a closed-loop circulation of secondary process fluid. In this manner, the cooling provided by the fluid cooling coil 362 and/or chiller 366 is used to both cool the process fluid and to charge the PCM tank 368. The difference in operation is due to the lack of the closed-loop pump in the heat transfer apparatus 350.

[00182] Regarding FIGS. 12A and 12B, a method 420 is provided that the controller 370 may implement in response to receiving a request to minimize energy consumption and the PCM tank 368 being capable of being charged. The method 420 includes operating modes 422 that the controller 370 switches between as a thermal duty 424 of the heat transfer apparatus 350 changes. The method 420 includes variables 426 of the components of the heat transfer apparatus 350 that vary according to the different modes 422. In the method 420, the PCM tank 368 is charged using the process fluid communicated with the cooling load 353 rather than a closed-loop charging operation as in the method 330 discussed above.

[00183] With reference to FIG. 13, a heat transfer apparatus 430 is provided that is a third example of the heat transfer apparatus 10 discussed above. The heat transfer apparatus 430 is similar in many respects to the heat transfer apparatus 110 discussed above. The heat transfer apparatus 430 has a process fluid heat exchange circuit 431 that is operable in different modes to cool process fluid from a cooling load 433 and provide a supply of process fluid to the cooling load 433 at a requested process fluid set temperature, for example. The cooling load 433 may be, for example, a computer datacenter or another industrial process.

[00184] The heat transfer apparatus 430 has a secondary closed-loop pump 432 and valves 434, 436 to facilitate charging of a PCM tank 438 as discussed in greater detail below. The heat transfer apparatus 430 includes an adiabatic precooling pad 442, a sump 444 and a pump 446 to pump collected evaporative liquid to the precooling pad 442. The heat transfer apparatus 430 further includes a fluid cooling coil 448, a fan 450, and a chiller 452 having a condenser 454 and an evaporator 456. The fan 450 is operable to draw air 458 across a precooling pad 442 and the fluid cooling coil 448. The heat transfer

apparatus 430 includes a primary closed-loop pump 460 and valves 462, 464. The heat transfer apparatus 430 has a controller 466 for operating the components of the heat transfer apparatus 430 in different modes.

[00185] For example, the controller 466 may operate the heat transfer apparatus 430 in Mode 1 as shown in FIG. 14. The adiabatic precooler 440 and fan 450 are not shown in FIG. 14 to provide a less obstructed view. In Mode 1, the controller 466 operates valves 470, 472, 474, 476 of the process fluid heat exchange circuit 431 to bypass the chiller 452 and the PCM tank 438. In Mode 1, the process fluid from the cooling load 433 is cooled only by the heat exchange between air flow across the fluid cooling coil 448 by the fan 450. In Mode 1, the adiabatic precooler 440 may be operated as needed to provide adiabatic cooling by decreasing the dry bulb temperature of the air upstream of the fluid cooling coil 448.

[00186] The heat transfer apparatus 430 has a Mode 2 as shown in FIG. 15. In Mode 2, the valve 470 receives process fluid at inlet 470A and modulates the flow of process fluid through the valve 470 so that a portion of the process fluid is directed to the condenser 454 of the chiller 452 and the remaining process fluid is bypassed around the condenser 454. The valve 472 receives heated process fluid at inlet 472A from the condenser 454 and process fluid from the cooling load 433 at inlet 472B. The valve 472 combines the flows of process fluid at an outlet 472C that provides the mixed process fluid to the fluid cooling coil 448. The valve 470 may be adjusted to direct more or less process fluid to the condenser 454 as needed to facilitate sufficient cooling by the evaporator 456 of the chiller 452.

[00187] The adiabatic precooler 440 may be operated as needed to reduce the dry bulb temperature of the air upstream of the fluid cooling coil 448. The fluid cooling coil 448 exchanges heat between the process fluid and airflow to provide the cooled process fluid to a valve 474. The valve 474 modulates the flow of process fluid between outlets 474B, 474C. The outlet 474C directs the cooled process fluid to the evaporator 456 of the chiller 452 which further cools process fluid. The process fluid from outlet 474B bypasses the evaporator 456 and the PCM tank 438 before reaching the valve 476. The valve 476 combines the process fluid flows received at inlets 476A, 476B into a flow that travels from an outlet 476C of the valve 476 to the cooling load 433. In this manner, a portion of the cooling load is handled by the fluid cooling coil 448 (and adiabatic precooler 440 as needed) and a portion of the cooling load is handled by the chiller 452. Mode 2 may be used during high load or high ambient air temperature conditions, and/or when the PCM tank 438 is fully discharged, as a way to meet the cooling duty required for the heat transfer apparatus 430. Mode 2 may also be used to save water by using the chiller 452 to provide cooling capacity

which reduces the cooling load required of the adiabatic precooler 440 and fluid cooling coil 448. More specifically, Mode 2 permits the speed of the fan 450 to be reduced which reduces a water evaporation rate from the pad or other adiabatic medium of the adiabatic precooler 440.

[00188] Regarding FIG. 16, the controller 466 may operate the heat transfer apparatus 430 in Mode 3 wherein valves 470, 480 bypass flow of process fluid around the chiller 452. The valve 474 directs a portion of the process fluid from the fluid cooling coil 448 toward the PCM tank 438 and the remaining portion of the process fluid bypasses the PCM tank 438. In this manner, in Mode 3, part of the cooling load 433 is handled by the fluid cooling coil 448 and adiabatic precooler 440 as needed and part of the cooling load 433 is handled by discharging of the PCM tank 438. Mode 3 may be used during very high cooling load situations, high ambient air temperature situations, and/or may be used to save energy and/or water by reducing the load on the fluid cooling coil 448, fan 450, and adiabatic precooler 440.

[00189] Regarding FIG. 17, the controller 466 may operate in Mode 4 wherein the valve 470 directs at least a portion of the process fluid from the cooling load 433 to the condenser 454 of the chiller 452. The valve 474 modulates the flow of process fluid so that a portion of the process fluid flows to the evaporator 456 of the chiller 452 and the remaining process fluid bypasses the chiller 452 and the PCM tank 438. Further, the valves 482, 483 direct the process fluid from the evaporator 456 to the PCM tank 438 and the valve 484 combines the cooled process fluid from the PCM tank 438 and the process fluid from the fluid cooling coil 448. In Mode 4, part of the cooling load is handled by the fluid cooling coil 448 and optionally the adiabatic precooler 440, part of the cooling load is handled by the chiller 452, and part of the cooling load is handled by the PCM tank 438. Mode 4 may be used during high cooling load situations, high ambient air temperature conditions, as a way to satisfy a cooling duty requirement, and/or may be used to save water by reducing the load on the fluid cooling coil 448, adiabatic precooler 440 or save energy by reducing the load on the fan 450.

[00190] Regarding FIG. 18, the controller 466 may operate the heat transfer apparatus 430 in Mode 5 wherein there is a first loop 490 of process fluid traveling between the cooling load 433 and the fluid cooling coil 448 and a second loop 492 of closed-loop process fluid circulated between the evaporator 456 of the chiller 452 and the PCM tank 438 via the primary closed-loop pump 460. The valve 470 directs a portion of the process fluid from the cooling load 433 through the condenser 454 such that the portion of process fluid absorbs

heat from the condenser 454 before traveling to the fluid cooling coil 448. The fluid cooling coil 448 is used to absorb heat from both the cooling load 433 and the process of recharging the PCM tank 438. The adiabatic precooler 440 may be turned on in Mode 5 to increase the cooling capacity of the fluid cooling coil 448 as needed. Mode 5 may be used to charge a fully or partially depleted PCM tank 438 while continuing to reject heat from the cooling load 433.

[00191] Regarding FIG. 19A, the controller 466 may operate the heat transfer apparatus 430 in Mode 6 wherein the process fluid heat exchange circuit 431 has a primary closed loop 510 similar to the closed loop 492 in FIG. 18 and a secondary closed loop 511. More specifically, the valves 434, 436 are closed to the cooling load 433 and the secondary closed-loop pump 432 circulates the secondary closed-loop process fluid 500 between the condenser 454 of the chiller 452 and the fluid cooling coil 448 such that the fluid cooling coil 448 removes heat added to the secondary closed-loop process fluid 500 by the condenser 454.

[00192] In Mode 6, the primary closed-loop pump 460 circulates a secondary process fluid 512 between the evaporator 450 and the PCM tank 438 throughout the primary closed loop 510. In this manner, the evaporator 450 removes heat from the primary closed-loop process fluid which is then used to charge the PCM tank 438. Mode 6 may be used to recharge a fully or partially depleted PCM tank 438 when the heat transfer apparatus 430 is not required to satisfy the cooling load 433, such as during evening hours. The adiabatic precooler 440 may be operated to provide increased cooling capacity as needed.

[00193] Regarding FIG. 19B, the controller 466 may operate the heat transfer apparatus 430 in Mode 7 wherein valve 474 modulates the flow of process fluid from the fluid cooling coil 448 to a bypass line 475 and to valve 485. The valve 485 further modulates the flow of process fluid to the PCM tank 438 and the evaporator 456 of the chiller 452. The cooled process fluid from the evaporator 456 and the PCM tank 438 are combined at valve 487 and directed to valve 484. Valve 484 mixes the process fluid flow from valve 487 and bypass line 475 and directs the mixed process fluid to the cooling load 433. The mixing of process fluid 484 raises the temperature of the process fluid to an acceptable temperature for the cooling load 433.

[00194] In Mode 7 of FIG. 19B, the evaporator 456 and PCM tank 438 are connected in parallel. In Mode 4, the evaporator 456 and PCM tank 438 are connected in series. Mode 4 may be utilized for situations with a higher temperature differential, such as greater than 20°F, between the process fluid return temperature (the temperature of process fluid received from the cooling load 433) and the process fluid supply temperature (the

temperature of the process fluid the heat transfer apparatus 430 provides to the cooling load 433). By contrast, Mode 7 may be utilized for situations where there is a lower temperature differential such as equal to or less than 10°F. When there is a temperature differential in the 11-19°F range, the controller 466 may select Mode 4 or Mode 7 based at least in part upon the required process fluid supply temperature, the PCM melting temperature, and the flow ratio between different components of the process fluid heat exchange circuit 431.

[00195] For example, in FIG. 19B there is a 9°F temperature differential between the process fluid return temperature of 93°F and the process fluid supply temperature of 84°F, so the controller 466 may determine to operate the heat transfer apparatus 430 in Mode 7 rather than Mode 4. Mode 7 may work better for smaller temperature differentials between process fluid return and supply temperatures because the temperature differential across the evaporator 456 and the PCM tank 438 is larger than if the evaporator 456 and PCM tank 438 were in series. More specifically, the evaporator 456 may have a lower efficiency where there is a smaller differential (e.g., less than 5 degrees) in temperature of process fluid entering and leaving the evaporator 456. Likewise, the PCM tank 438 may have a lower efficiency if there is a smaller differential (e.g., less than 5 degrees) in temperature of process fluid entering and leaving the PCM tank 438. Operating in mode 7 thereby increases the temperature differentials across the evaporator 456 and PCM tank 438 which increases efficiency when there is a lower temperature differential between the temperatures of the return and supply process fluid.

[00196] Regarding FIG. 19C, the controller 466 may operate the heat transfer apparatus 430 in Mode 8 when the ambient air temperature is low. More specifically, the fluid cooling coil 448 is receiving process fluid at 90°F and providing cooled process fluid at 50°F. The 50°F process fluid may be too cold for the cooling load 433. The valve 484 mixes 58°F process fluid from the PCM tank 438 and 50°F process fluid from the fluid cooling coil 448. The valve 436 mixes the 90°F process fluid from valve 434 and the cooler process fluid from valve 484 to deliver 80°F process fluid to the cooling load 433. The heated process fluid bypass provided by valves 434, 436 raises the temperature of the process fluid to meet a minimum temperature requirement of the cooling load 433 while permitting charging of the PCM tank 438.

[00197] Regarding FIG. 19D, the controller 466 may operate the heat transfer apparatus 430 in Mode 9 when there is no cooling load 433. Since the cooling load 433 does not require cooling, the valves 434, 436 are configured to stop or limit the flow of process fluid to/from

the cooling load 433. In Mode 9, the valves 470, 485 are configured to cause the process fluid to bypass the condenser 454 and evaporator 456. Further, in Mode 9, valves 487, 489 facilitate the secondary closed-loop pump 432 circulating process fluid between the fluid cooling coil 448 and the PCM tank 438. In this manner, the fluid cooling coil 448 may operate to charge the PCM tank 438 in the absence of a cooling load 433. The process heat exchange circuit 431 includes a bypass line 491 to permit process fluid to flow around the secondary closed-loop pump 432 when the secondary closed-loop pump 432 is not in use such as Mode 8 (see FIG. 19C).

[00198] The controller 466 may operate the heat transfer apparatus 430 in Mode 10 as shown in FIG. 19E when the fan 450, adiabatic cooler 440, and/or chiller 452 have limited or no cooling capacity such as when the heat transfer apparatus 430 is being operated to save energy or when there is a malfunction of the heat transfer apparatus 430. The process fluid heat exchange circuit 431 includes valves 495, 497 to bypass the process fluid around the fluid cooling coil 448 in Mode 10 as shown in FIG. 19E. Further, in Mode 10, the valves 470, 485 bypass process fluid around the chiller 452. Thus, in Mode 10, the PCM tank 438 is discharging to cool the process fluid as required by the cooling load 433. The process fluid heat exchange circuit 431 has a bypass line 499 for permitting the process fluid to bypass the fluid cooling coil 448 in Mode 10.

[00199] The controller 466 may operate the heat transfer apparatus 430 in Mode 11 as shown in FIG. 19F. Mode 11 is similar to Mode 5 of FIG. 18. Mode 11 may provide a more efficient operation when the heat transfer apparatus 430 provides process fluid to the cooling load 433 at a lower supply temperature, such as less than 84 °F, whereas Mode 5 may provide a more efficient operation when the heat transfer apparatus 430 provides process fluid to the cooling load 433 at a higher supply temperature, such as equal to or greater than 84 °F. The controller 466 may therefore choose between Mode 5 and Mode 11 depending on the supply temperature set point for the heat transfer apparatus 430.

[00200] In Mode 11, valve 482 directs a portion of the cooled process fluid from evaporator 456 to the PCM tank 438 to recharge the PCM tank 438. The valve 482 also directs the remaining cooled process fluid from the evaporator 456 to valve 487 and valve 484. The valve 484 mixes the process fluid from the evaporator 456 with process fluid from the fluid cooling coil 448 that was bypassed around the chiller 452 and PCM tank 438 by the valve 474. In this manner, Mode 11 permits the evaporator 456 and the PCM tank 438 to supplement the cooling provided by the fluid cooling coil 448 so that the heat transfer apparatus 430 can provide process fluid to the cooling load 433 at a lower supply

temperature set point, e.g., 72 °F.

[00201] With reference to FIGS. 23C-23F, the controller 466 may operate the heat transfer apparatus 430 according to a method 457 wherein the controller 466 changes the heat transfer apparatus 430 between operating modes 557 according to one of the methods 1900A, 1900B, 2100A, 2100B discussed below with respect to FIGS. 85-97. Alternatively, the controller 466 may change the heat transfer apparatus 430 between operating modes 557 according to the method 2500 discussed below with respect to FIGS. 98A-98D.

[00202] For each of the operating modes 557, the method 557 includes variables 559 for components of the heat transfer apparatus 430. The variables 559 include a variable 559A indicating whether the secondary process fluid pump 432 is operating. Further, the variables 559 include variables 559B indicating that all of the process fluid is flowing through the fluid cooling coil 448.

[00203] With reference to FIGS. 20A and 20B, the controller 466 may utilize a method 520 in response to receiving a request to minimize water consumption and the PCM tank 438 being capable of discharging. The method 520 includes operating modes 522 and logic 524 that the controller 466 utilizes to advance through the operating modes 522 in response to changes of a thermal duty 526 of the heat transfer apparatus 430 as determined by the controller 466. The method 520 has variables 528 of the components of the heat transfer apparatus 430 that change as the heat transfer apparatus 430 changes between the modes 522.

[00204] Regarding FIGS. 21A and 21B, the controller 466 may utilize a method 530 in response to receiving a request to minimize energy consumption and the PCM tank 438 being capable of discharging. The method 530 includes operating modes 532 and logic 534 the controller 466 utilizes to advance through the operating modes 532 as a thermal duty 536 of the heat transfer apparatus 430.

[00205] Regarding FIGS. 22A and 22B, the controller 466 may utilize a method 540 in response to receiving a request to minimize water consumption and the PCM tank 438 is capable of being charged. The method 540 includes operating modes 542 that the controller 466 may advance through as a thermal duty 544 of the heat transfer apparatus 430 varies. The method 540 has variables 545 of the components of the heat transfer apparatus 530 that vary as the heat transfer apparatus 530 changes between the modes 542. The modes 542 include a closed-loop dry cooling mode 546 in accordance with Mode 6 of FIG. 19 when the adiabatic precooler 440 is not operating. In one embodiment, the heat transfer apparatus 430 includes an actuator to move the adiabatic precooler 440 from an operating

position wherein a pad of the adiabatic precooler 440 is in a path of airflow through the heat transfer apparatus 430 to a bypass position wherein the pad is out of the path of the airflow. When the pad is in the bypass position, the energy consumption of the fan 450 may be reduced. The operating modes 542 further include a closed-loop adiabatic cooling mode 548 that corresponds to Mode 6 in FIG. 19 when the adiabatic precooler 440 is operating. In either mode 546, 548, the heat transfer apparatus 430 is closed off from the cooling load 433 and is able to charge the PCM tank 438.

[00206] Regarding FIGS. 23A and 23B, the controller 466 may utilize a method 550 in response to receiving a request to minimize energy consumption and the PCM tank 438 is capable of being charged. The method 550 includes modes 552 that the controller 466 advances through as the thermal duty 554 of the heat transfer apparatus 430 varies. The method 550 includes variables 556 of the components of the heat transfer apparatus 430 that change as the heat transfer apparatus 430 is reconfigured between the operating modes 552. The operating modes 552 include a closed-loop adiabatic cooling mode 558 that corresponds generally to Mode 6 in FIG. 19 and the adiabatic precooler is operated to improve the efficiency of the fluid cooling coil 448.

[00207] Regarding FIG. 24, heat transfer apparatus 560 is a fourth example of the heat transfer apparatus 10 of FIG. 1. The heat transfer apparatus 560 is similar in structure and operation to the heat transfer apparatus 350 discussed above. One difference is that the heat transfer apparatus 560 has a heat exchanger 562 that includes a direct heat exchanger 564 having an evaporative liquid distribution system 566 that distributes evaporative liquid onto the fill 568, a sump 570 to collect the evaporative liquid, and a pump 572 to pump the collected evaporative liquid back to fill 568. The heat transfer apparatus 560 has a fan 574 that generates air flow 576 relative to the direct heat exchanger 554 such that the evaporative liquid is cooled as the evaporative liquid travels along the fill 568 and is as contacted by the air flow 576. The pump 572 transfers cooled evaporative liquid from the sump 570 to an indirect heat exchanger 580 of the heat exchanger 562. The indirect heat exchanger 580 transfer heat between the evaporative liquid and a process fluid 582 that is received from a cooling load 584.

[00208] Regarding FIG. 25, a heat transfer apparatus 590 is provided that is a fifth example of the heat transfer apparatus 10 discussed above. The heat transfer apparatus 590 is similar to the heat transfer apparatus 560 discussed above. One difference between the heat transfer apparatuses 560, 590 is that the heat transfer apparatus 590 has a direct heat exchanger 592 that transfers heat directly from a process fluid 594 received from a cooling

load 596 to an airflow 598 generated by a fan 600. The direct heat exchanger 592 may include, for example, fill sheets and/or fill blocks. Trickle fill, splash fill, or fill-less approaches may be used.

[00209] With respect to FIG. 26, a heat transfer apparatus 610 in accordance with a second approach is provided. The heat transfer apparatus 610 includes a heat exchanger 612 having an adiabatic precooler 614 with an adiabatic pad 616 and an indirect heat exchanger such as a fluid cooling coil 618. The heat transfer assembly 610 further includes a thermal energy storage such as a PCM tank 620 to provide trim chilling as needed for the heat transfer apparatus 610 to satisfy a thermal load on the heat transfer apparatus 610. The heat transfer apparatus 610 has one or more air inlets 622, one or more air outlets 624, and a fan 626 operable to cause movement of air from the air inlets 622 to the air outlets 624 across the precooling pad 616 and the fluid cooling coil 618.

[00210] Regarding FIG. 27, a more detailed schematic representation of the heat transfer apparatus 610 is provided. The heat transfer apparatus 610 is similar in many respects to the heat transfer apparatus 10 discussed above except that the heat transfer apparatus 610 lacks the chiller 28. The heat transfer apparatus 610 includes an outer structure such as a housing 630 that contains the heat exchanger 612, a process fluid distribution system 632, a controller 634, and a PCM tank 620. The PCM tank 620 contains a phase change material having a melting temperature of, for example greater than 65°F. The heat transfer apparatus 610 has a process fluid inlet 636 to receive a heated process fluid from a cooling load and a process fluid outlet 638 to return cooled process fluid to the cooling load.

[00211] Regarding FIG. 28, a heat transfer apparatus 640 is a first example of the heat transfer apparatus 610 of FIG. 26. The heat transfer apparatus 640 has a process fluid heat exchange circuit 641 for receiving heated process fluid from a cooling load 654 and returning cooled process fluid to the cooling load 654. The process fluid heat exchange circuit 641 includes an adiabatic precooler 642, fluid cooling coil 644, a closed-loop pump 646, a PCM tank 648, and a controller 650. Because the heat transfer apparatus 640 lacks a chiller like the chiller 452 of FIG. 13, the heat transfer apparatus 640 utilizes the adiabatic precooler 642 and the fluid cooling coil 644 to provide cooling for the process fluid from a cooling load 654 as well as recharging the PCM tank 648.

[00212] Regarding FIG. 29, the heat transfer apparatus 640 has a Mode 1 wherein the controller 650 operates the heat transfer apparatus 640 such that the heated process fluid from the cooling load 654 travels to the fluid cooling coil 644 and is returned to the cooling load 654 while bypassing the PCM tank 648. The adiabatic precooler 642 may be operated to

lower the dry bulb temperature of air contacting the fluid cooling coil 644 to provide an increased cooling capacity for the heat transfer apparatus 640 when the controller 650 is in Mode 1.

[00213] Regarding FIG. 30, the heat transfer apparatus 640 has a Mode 2 wherein both the fluid cooling coil 644 and the PCM tank 648 handle the cooling load 654. The process fluid heat exchange circuit 641 includes a valve 660 that modulates the process fluid flow from the fluid cooling coil 644 so that a portion of the process fluid travels to the PCM tank 648 and is cooled as the PCM tank 648 discharges. In this manner, the PCM tank 648 may be discharged during peak thermal loads to supplement cooling provided by the fluid cooling coil 644. The adiabatic precoolers 642 may be operated to lower the dry bulb temperature of air contacting the fluid cooling coil 644 to provide an increased cooling capacity for the heat transfer apparatus 640 when the controller 650 is in Mode 2.

[00214] Regarding FIG. 31, the heat transfer apparatus 640 has a Mode 3 wherein a valve 662 modulates the flow of process fluid from the cooling load 654 so that a portion 664 of the process fluid from the cooling load 654 is directed to a valve 666 for mixing with process fluid from the fluid cooling coil 644 and the PCM tank 648. In Mode 3, the adiabatic precoolers 642 may be utilized which decreases the temperature of the process fluid leaving the fluid cooling coil 644. Due to the lower process fluid temperature from the fluid cooling coil 644, the PCM tank 648 can be charged. The process fluid leaving the fluid cooling coil 644 and the PCM tank 648 is combined with the circulated process fluid 664 via valve 666 so that the process fluid returned to the cooling load 654 still has the same return temperature as in Mode 2. Mode 3 may be utilized when ambient and load conditions allow for the fluid cooling coil 644 to significantly cool the process fluid. The recirculated portion 664 of the process fluid is used to raise the temperature of the process fluid from the fluid cooling coil 664 and PCM tank 648 and ensure the process fluid is returned to the cooling load 654 at the requested process fluid set temperature.

[00215] Regarding FIG. 32, the heat transfer apparatus 640 has a Mode 4 wherein valves 670, 672 are closed to the cooling load 654 and the closed-loop pump 646 is operated to circulate a closed-loop fluid 674 between the fluid cooling coil 644 and the PCM tank 648 to recharge the PCM tank 648. The adiabatic precoolers 642 may be operating or non-operating as needed for a particular situation. By not operating the adiabatic precoolers 642, the controller 650 reduces water consumption of the heat transfer apparatus 640. By operating the adiabatic precoolers 642 during Mode 4, the controller 650 may minimize energy consumption of the heat transfer apparatus 640.

- [00216] Regarding FIG. 33, the controller 650 may utilize a method 690 in response to receiving a request to minimize water consumption and the PCM tank 648 is capable of discharging. The controller 650 changes between operating modes 692 using logic 694 as the thermal duty 696 of the heat transfer apparatus 640 varies. The method 690 includes variables 698 of the components of the heat transfer apparatus 640 that change as the controller 650 changes between different modes 692.
- [00217] Regarding FIG. 34, the controller 650 may utilize a method 700 in response to receiving a request to minimize energy consumption and the PCM tank 648 being capable of discharging. The method 700 includes operating modes 702 and logic 704 that the controller 650 utilizes to change between the modes 702 as a thermal duty 706 of the heat transfer apparatus 640 varies. The method 700 includes variables 708 of the heat transfer apparatus 640 that change as the controller 650 changes between the modes 702.
- [00218] Regarding FIG. 35, the controller 650 may utilize a method 710 in response to receiving a request to minimize water consumption and the PCM tank 648 is capable of being charged. The method 710 includes modes 712 that the controller 650 may change between as a thermal load 714 of the heat transfer apparatus 640 changes. The modes 712 include a closed-loop dry cooling mode 716 that is similar to Mode 4 shown in FIG. 32 wherein the closed-loop pump 646 operates and a closed-loop fluid is circulated between the fluid cooling coil 644 and the PCM tank 648 to recharge the PCM tank 648. In the closed-loop dry cooling mode 716, the adiabatic precooler 742 is off. By contrast, the operating modes 712 include a closed-loop adiabatic cooling mode 718 similar to Mode 4 of FIG. 32 wherein the adiabatic precooler 642 is operating.
- [00219] Regarding FIG. 36, the controller 650 may utilize a method 720 in response to receiving a request to minimize energy consumption and the PCM tank 648 being capable of being charged. The method 720 includes operating modes 722 that the controller 650 may change between in response to changes of a thermal duty 724 of the heat transfer apparatus 640. The method 720 includes variables 726 of the heat transfer apparatus 640 that change as the heat transfer apparatus 640 changes between the modes 722.
- [00220] Regarding FIG. 37, a heat transfer apparatus 730 is provided that is a second example of the heat transfer apparatus 610 discussed above. The heat transfer apparatus 730 is similar in many respects to the heat transfer apparatus 640 except that the heat transfer apparatus 730 lacks the closed-loop pump 646. The heat transfer apparatus 730 includes a process fluid heat exchange circuit 731 including an adiabatic precooler 732, a fluid cooling coil 734, a fan 736, and a PCM tank 741. The heat transfer apparatus 730 has a

controller 738 that operates the process fluid heat exchange circuit 731 to return process fluid to the cooling load 740 with a particular process fluid variable, such as temperature, flow rate, pressure, or a combination thereof. The PCM tank 741 removes heat from the process fluid when the PCM tank 741 is operated to satisfy maximum thermal load conditions, to reduce water consumption, or reduce energy consumption as appropriate.

[00221] Regarding FIG. 38, the processor 738 may utilize a method 750 in response to receiving a request to minimize water consumption and the PCM tank 740 being capable of discharging. The method 750 includes modes 752 and logic 754 that the controller 738 utilizes to change between the modes 752 as a thermal duty 756 of the heat transfer apparatus 730 changes. The method 750 includes variables 760 of the components of the heat transfer apparatus 730 that change as the heat transfer apparatus 730 changes between modes 752.

[00222] Regarding FIG. 39, the controller 738 may utilize a method 770 in response to receiving a request to minimize energy consumption and the PCM tank 741 being capable of discharging. The method 770 includes operating modes 772 of the heat transfer apparatus 730 and logic 774 that the controller 738 utilizes to change between the operating modes 772 as a thermal duty 776 of the heat transfer apparatus 730 changes. The method 770 includes variables 778 of the components of the heat transfer apparatus 730 that change as the controller 738 changes between the modes 772.

[00223] Regarding FIG. 40, the controller 738 may utilize a method 780 in response to receiving a request to minimize water consumption and the PCM tank 741 being capable of being charged. The method 780 includes operating modes 782 that the controller 738 changes between as a thermal duty 784 of the heat transfer apparatus 730 changes. The method 780 includes variables 786 of the components of the heat transfer apparatus 730 that change as the heat transfer apparatus 730 changes between modes 782.

[00224] Regarding FIG. 41, the controller 738 may utilize a method 790 in response to receiving a request to minimize energy consumption and the PCM tank 748 being capable of being charged. The method 790 includes the controller 738 having an adiabatic cooling mode 792 wherein a sump pump 794 (see FIG. 37) of the adiabatic precooler 732 is on and a valve 796 directs at least a portion of the cooler process fluid to the PCM tank 741 to charge the PCM tank 741.

[00225] Regarding FIG. 42, heat transfer apparatus 800 is a third example of the heat transfer apparatus 610 discussed above. The heat transfer apparatus 800 is similar to the heat transfer apparatus 640 discussed above except that the heat transfer apparatus 800

has a direct heat exchanger 802 to transfer heat between air flow 804 generated by a fan 806 and evaporative liquid. The evaporative liquid is collected and directed through an indirect heat exchanger 808 to transfer heat between process fluid received from a cooling load 810 and the evaporative fluid of the direct heat exchanger 802.

[00226] Regarding FIG. 43, heat transfer apparatus 810 is a fourth example of the heat transfer apparatus 610 discussed above. The heat transfer apparatus 810 is similar to the heat transfer apparatus 640 except that the heat transfer apparatus 810 has a direct heat exchanger 812 for transferring heat between air flow 814 generated by a fan 816 and process fluid received from a cooling load 818.

[00227] Regarding FIG. 44, a heat transfer apparatus 850 is provided in accordance with a third approach of the present disclosure. The heat transfer apparatus 850 includes a housing 851 having one or more air inlets 854, one or more air outlets 857, and one or more fans 859 for generating an airflow 859 from the air inlet 854 to the air outlet 856. The air inlets 854 include primary louvers 856 and secondary louvers 858 that are selectively closable to restrict the path of air flow through the heat transfer apparatus 850. For example, the primary louvers 856 may be closed and the secondary louvers 858 may be opened to bypass air around the membrane vacuum dehumidification system 860.

[00228] The heat transfer apparatus 850 has one or more dehumidifiers, such as a membrane vacuum dehumidification system 860 to remove water from the air flow in an area 862 upstream of an adiabatic precooler 864 having a precooling pad 866. The heat transfer apparatus 850 has a heat exchanger such as fluid cooling coil 868 downstream of the precooling pad 866. The membrane vacuum dehumidification system 860 removes water from the air and decreases the air wet bulb temperature. The precooling pad 866 cools the air upstream of the fluid cooling coil 868 and decreases the air dry bulb temperature to be very close to the air wet bulb temperature. The dry and cooled air contacting the fluid cooling coil 868 provides more efficient heat transfer between the air flow 859 and the fluid cooling coil 868.

[00229] Regarding FIG. 45, heat transfer apparatus 880 is a first example of the heat transfer apparatus 850 of FIG. 44. The heat transfer apparatus 880 includes primary louvers 882, secondary louvers 884, and a process fluid cooling system 881. The process fluid cooling system 881 includes a membrane vacuum dehumidification system 886, an adiabatic precooler 888, a fluid cooling coil 890, and a fan 892. The heat transfer apparatus 880 further includes a vacuum pump 894 of the membrane vacuum dehumidification system 886 and a controller 896 for controlling operation of the heat transfer apparatus 880. The

adiabatic precooler 888 includes a precooling pad 900, an evaporative liquid distribution system 902, a sump 904, and a sump pump 906. The heat transfer apparatus 880 includes a water collection system 910 having a condensed water pump 912 that directs water collected and condensed from the membrane vacuum dehumidification system 886 to the sump 904. In this manner, the heat transfer apparatus 880 may utilize at least a portion of the water collected from the membrane vacuum dehumidification system 886 as makeup water for the sump 904 which may decrease the water consumption of the heat transfer apparatus 880. The fluid cooling coil 890 receives hot process fluid from a cooling load 916 and returns cooled process fluid to the cooling load 916. The fan 892 is operable to direct air along a first path 920 when the primary louvers 882 are open and the secondary louvers 884 are closed. When the primary louvers 882 are closed and the secondary louvers 884 are open, operating the fan 892 causes air to enter through secondary louvers 884 along a second path 922. The membrane vacuum dehumidification system 886 and the adiabatic precooler 888 may be selectively operated to increase efficiency of heat transfer between the fluid cooling coil 890 and the air flow through the heat transfer apparatus 880.

[00230] Regarding FIGS. 46-50, the heat transfer apparatus 880 is shown in different modes to illustrate the different cooling capacities of the heat transfer apparatus 880 in the different modes. Regarding FIG. 46, the heat transfer apparatus 880 is in Mode 1 wherein the primary louvers 882 are open, the secondary louvers 920 are closed, the membrane vacuum dehumidification system 886 is operating, the adiabatic precooler 888 is operating, and the fluid cooling coil 890 is transferring heat between the air flow and the process fluid from the cooling load 916.

[00231] Regarding FIG. 47, the heat transfer apparatus 880 is in Mode 2 wherein the primary louvers 882 are closed and the secondary louvers 884 are open such that air flow bypasses the membrane vacuum dehumidification system 886. The air travels along the second flow path 922 through the precooling pad 900 and to the fluid cooling coil 890. In Mode 2, the adiabatic precooler 888 is operating such that the precooling pad 900 decreases the dry bulb temperature of the air flow upstream of the fluid cooling coil 890.

[00232] Regarding FIG. 48, the heat transfer apparatus 880 is in Mode 3 wherein the primary louvers 882 are closed, the secondary louvers 884 are open, and air enters the heat transfer apparatus 880 around the second flow path 922 and bypasses the membrane vacuum dehumidification system 886. In Mode 3, the sump pump 906 is off such that the evaporative liquid distribution system 902 is not directing liquid onto the precooling pad 900. In this manner, the air in an area 930 upstream of the fluid cooling coil 890 is the same

wet bulb and dry bulb temperatures as the ambient air. Mode 3 may be utilized when there is a low cooling load on the heat transfer apparatus 880 or when the heat transfer apparatus 880 is being operated to minimize energy consumption.

[00233] Regarding FIG. 49, the heat transfer apparatus 880 is in Mode 4 wherein the primary louvers 882 are open and the secondary louvers 884 are closed. The fan 892 draws air into the heat transfer apparatus 880 along the first flow path 920. The membrane vacuum dehumidification system 886 is operating to reduce the humidity of air upstream of the precooling pad 900. The adiabatic precooler 888 is off so that the air flow has similar wet bulb and dry bulb temperatures before and after the precooling pad 900. Thus, in Mode 4, the heat transfer apparatus 880 utilizes the membrane vacuum dehumidification system 886 to dry the air upstream of the fluid cooling coil 890. Mode 4 may be utilized when the heat transfer apparatus 880 is operated to minimize water consumption.

[00234] Regarding FIG. 50, the controller 896 may utilize a method 940 in response to receiving a request to minimize energy consumption. The heat transfer apparatus 880 may switch between operating modes 942 as a thermal duty 944 required by the heat transfer apparatus 880 varies. The method 940 has variables 946 of the components of the heat transfer apparatus 880 that vary as the controller 896 changes between operating modes 942. The variables 946 may include a variable 947 indicative of the operation of the condensed water pump 912. In operating modes 942, the condensed water pump 912 is off to save energy.

[00235] Regarding FIG. 51, the controller 896 may perform a method 950 in response to receiving a request to minimize water consumption. The heat transfer apparatus 880 switches between operating modes 952 as a thermal duty 954 of the heat transfer apparatus 880 varies. The method 950 includes variables 956 that vary as the heat transfer apparatus 880 changes between operating modes 952.

[00236] In the method 950, the sump pump 906 is off when the heat transfer apparatus 880 is in a dry cooling mode 958 to conserve water. However, when the thermal duty increases and the controller 896 changes to an adiabatic cooling and membrane vacuum dehumidification mode 960, the sump pump 906 operates to provide additional adiabatic cooling to the air and increase the cooling capacity of the heat transfer apparatus 880.

[00237] Regarding FIG. 52, the controller 896 may perform a method 960 in response to receiving a request to generate water via the membrane vacuum dehumidification system 886. The method 960 includes modes 962 that the controller 896 varies between as a thermal duty 964 of the heat transfer apparatus 880 varies. The method 960 includes

variables 966 representative of the status of components of the heat transfer apparatus 880 that change as the heat transfer apparatus 880 changes between operating modes 962. The variables 966 include a variable 968 indicative of whether the condensed water pump 912 is operating. Because the controller 896 has received a request to generate water, the condensed water pump 912 is operating in both operating modes 962.

[00238] Regarding FIG. 53, heat transfer apparatus 980 is a second example of a heat transfer apparatus 850 discussed above. The heat transfer apparatus 980 includes primary louvers 982, secondary louvers 984, and tertiary louvers 986 that are selectively operable to bypass a membrane vacuum dehumidification system 988, an adiabatic precooler 990, or both as desired for picking an operating mode. The membrane vacuum dehumidification system 988 includes a vacuum pump 992 to facilitate dehumidification of the air and a condensed water pump 994 for pumping condensed and collected water from the membrane vacuum dehumidification system 988 to a sump 996 of the adiabatic precooler 990. The adiabatic precooler 990 includes a liquid distribution system 998, a precooling pad 1000, and a sump pump 1002. The heat transfer apparatus 980 further includes a controller 1004, a fan 1006, and a fluid cooling coil 1008 that receives process fluid from a cooling load 1010.

[00239] Regarding FIG. 54, the controller 1004 may perform a method 1020 in response to receiving a request to minimize energy consumption. The method 1020 includes operating modes 1022 that the heat transfer apparatus 980 may switch between as a thermal duty 1024 of the heat transfer apparatus 980 varies. The method 1020 includes variables 1026 indicative of the status of components of the heat transfer apparatus 980 that vary as the heat transfer apparatus 980 changes between the modes 1022. The variables 1026 include a variable 1028 representative of whether the tertiary louvers 986 are open or closed. In the method 1020, the tertiary louvers 986 are closed when the controller 1004 is in either of the operating modes 1022.

[00240] Regarding FIG. 55, the controller 1004 may perform a method 1030 in response to receiving a request to minimize water consumption. The method 1030 includes operating modes 1032 that the heat transfer apparatus 980 may change between as the thermal duty 1034 varies. The method 1030 includes variables 1034 of the heat transfer apparatus 980 that change as the controller 1004 changes between the operating modes 1032. The operating modes 1032 include a dry cooling operating mode 1036 wherein the primary louvers 982 and secondary louvers 984 are closed and the tertiary louvers 986 are open as indicated by variables 1038, 1040, 1042. By closing the primary and secondary louvers 982,

984, the air may bypass the membrane vacuum dehumidification system 988 and the adiabatic precooler 990 and instead contact the fluid cooling coil 1008 to remove heat from the process fluid from the cooling load 1010.

[00241] Regarding FIG. 56, the controller 1004 may perform a method 1050 in response to receiving a request to generate water from the membrane vacuum dehumidification system 988. The method 1050 includes operating modes 1052, 1054 with variables 1056 that change as the controller 1004 switches between the operating modes 1052, 1054. As indicated by variable 1058, the condensed water pump 994 is operated in either operating mode 1052, 1054.

[00242] Regarding FIG. 57, heat transfer apparatus 1070 is a third example of the heat transfer apparatus 850 discussed above. The heat transfer apparatus 1070 is similar in many respects to the heat transfer apparatuses 880, 980 discussed above. The heat transfer apparatus 1070 includes primary and secondary louvers 1072, 1074 and a fan 1076 that generates airflow in the heat transfer apparatus 1070. The heat transfer apparatus 1070 further includes a membrane vacuum dehumidification system 1078, an indirect heat exchanger 1080 to transfer heat from process fluid received from a cooling load 1082, and a direct heat exchanger 1084. The direct heat exchanger 1084 includes fill 1086, a sump 1088, a liquid distribution system 1090, and a sump pump 1092. The sump pump 1092 circulates a secondary liquid to the indirect heat exchanger 1080 to receive heat from the process fluid of the cooling load 1082. The liquid distribution system 1090 distributes, such as sprays, the heated secondary liquid onto the fill 1086. The secondary liquid is cooled by the airflow as the secondary liquid travels along the direct heat exchanger 1084. The cooled secondary liquid is then pumped again from the sump 1088 to the indirect heat exchanger 1080.

[00243] Regarding FIG. 58, heat transfer apparatus 1100 is a fourth example of the heat transfer apparatus 850 discussed above. The heat transfer apparatus 1100 is similar in many respects to the heat transfer apparatus 1070 discussed above. One difference is that the heat transfer apparatus 1100 includes a direct heat exchanger 1102 that receives process fluid from a cooling load 1104. The direct heat exchanger 1102 includes a process fluid distribution system 1108 that distributes, such as sprays, the process fluid onto fill 1110. The process fluid is cooled by air flow through the direct heat exchanger 1102 and is collected in a sump 1106. The direct heat exchanger 1102 has a sump pump 1108 to direct the cooled process fluid back to the cooling load 1104. The heat transfer apparatus 1100 includes a fan 1120 that is operable to draw air through primary and secondary louvers 1122, 1124 that are selectively closable to control the flow of air through the heat transfer apparatus 1100.

[00244] With reference to FIGS. 59 and 60, a heat transfer apparatus 1150 is provided having a process fluid heat exchange circuit 1152 that receives process fluid from a cooling load 1154 and cools the process fluid to a requested temperature. The process fluid heat exchange circuit includes a chiller 1154 and a heat exchanger 1156. The heat exchanger exchanges heat between the process fluid and ambient air. The heat exchanger 1156 may include an adiabatic precooler and an indirect heat exchanger. The heat transfer apparatus 1150 has a chiller on mode as shown in FIG. 59 wherein a valve 1158 of the process fluid heat exchange circuit 1152 directs heat from the heat exchanger 1156 to the chiller 1154. The heat transfer apparatus 1150 further includes a chiller off mode as shown in FIG. 60. In the chiller off mode, the valve 1158 bypasses the process fluid around the chiller 1154. The chiller off mode of FIG. 60 may be used when there is a lower thermal load on the heat transfer apparatus 1150.

[00245] With reference to FIG. 61, the heat transfer apparatus 1170 includes a housing 1172 with an air inlet 1174, an air outlet 1176, and one or more fans 1178 for generating air flow therebetween. The heat transfer apparatus 1170 has an adiabatic precooler 1180 with a precooling pad 1182, a finned coil 1184, and a condenser coil 1186 of a chiller 1188. The condenser coil 1186 and the evaporator 1190 of the chiller 1188 are in an interior 1192 of the housing 1172, and the condenser coil 1186 in one embodiment is in the path of air traveling between the air inlet 1174 and air outlet 1176. In some embodiments, the condenser coil 1186 may eliminate plume by heating the moist air. Further, the heat transfer apparatus 1170 may have a compact configuration due to the condenser coil 1186 and the evaporator 1190 being in the interior 1192 of the housing 1172. The finned coil 1184 receives hot process fluid from a return 1194 and directs cooled process fluid to a valve 1196. The valve 1196 modulates the flow of cooled process fluid from the finned coil 1184 to the evaporator 1190. The evaporator 1190 further cools the process fluid and directs the cooled process fluid along a conduit 1198 to a cooled process fluid supply 1200. The valve 1196 may modulate the flow of the cooled process fluid from the finned coil 1184 so that some, all, or none of the cooled process fluid from the finned coil 1184 travels to the evaporator 1190. The chiller 1188 has an expansion valve 1202 and a compressor 1204 and utilizes a refrigerant to remove heat from the process fluid in the evaporator 1190 and transfer the heat to the air flow via the condenser coil 1186. The heat transfer apparatus 1170 lacks a thermal energy storage.

[00246] Regarding FIGS. 62 and 63, the heat transfer apparatus 1220 is provided that includes a chiller 1224 and a heat exchanger 1226 that operate to cool process fluid from a

cooling load 1228. The chiller 1224 includes an evaporator 1230, a condenser 1240, a compressor 1242, and an expansion valve 1244. The heat transfer apparatus 1220 has a pump 1250 that circulates process fluid from a cooling load 1228, to the condenser 1240, to the heat exchanger 1226, to the evaporator 1230, and back to the cooling load 1228. The heat transfer apparatus 1220 has a chiller on mode as shown in FIG. 62 wherein the compressor 1242 circulates refrigerant between the evaporator 1230 and the condenser 1240 and facilitates heat transfer from the process fluid to the refrigerant at the evaporator 1230. In this manner, the chiller 1224 further reduces the temperature of the process fluid from the heat exchanger 1226. The heat transfer apparatus 1220 further includes a chiller off mode as shown in FIG. 63 wherein the compressor 1242 does not circulate refrigerant between the evaporator and the condenser 1240. However, the pump 1250 is still operable to direct the process fluid from the cooling load 1228 to the heat exchanger 1226 with the process fluid traveling through the condenser 1240 and the evaporator 1230.

[00247] With reference to FIGS. 64-67, the heat transfer apparatus 1300 is provided having a process fluid heat exchange circuit 1302 that includes a glycol chiller 1304, a pump 1306, a thermal energy storage such as an ice tank 1308, a heat exchanger 1310 such as a glycol/water heat exchanger, and a heat exchanger 1312 such as an air/water heat exchanger. The heat exchanger 1310 is part of a water loop 1305 that receives heated water from a cooling load 1314. The heat exchanger 1310 transfer heat from the water loop 1305 to a glycol loop 1303.

[00248] In FIG. 64, the heat transfer apparatus 1300 is shown in a cooling load with ice melt mode wherein a valve 1320 directs glycol from the glycol chiller 1304 through the ice tank 1308 and a valve 1322 directs the glycol from the ice tank 1308 to the glycol/water heat exchanger 1310. The glycol chiller 1304 and ice tank 1308 remove heat from the glycol circulating in the glycol loop 1303, which absorbs heat from the water in the water loop 1305 via the heat exchanger 1310.

[00249] Regarding FIG. 65, the heat transfer apparatus 1300 is shown in a cooling load with ice build mode. More specifically, the valve 1322 inhibits the flow of glycol from the ice tank 1308 to the heat exchanger 1310 such that the glycol chiller 1304 removes heat from the glycol loop 1303 and returns chilled glycol to the ice tank 1308 at a temperature below the storage temperature of the ice tank 1308, such as 32°F, thereby building ice in the ice tank 1308. Conversely, the water loop 1305 includes a pump 1330 that permits the water from the cooling load 1314 to flow to the heat exchanger 1312 and be cooled. The cooling load

with ice build mode of FIG. 65 may be utilized when there is a decreased thermal load on the heat transfer apparatus 1300 such as overnight.

[00250] Regarding FIG. 66, the heat transfer apparatus 1300 is shown in a cooling load with chiller and ice tank bypass mode. The valves 1320, 1322 inhibit the flow of glycol through the glycol loop 1303. The pump 1330 circulates water between the cooling load 1314 and the heat exchanger 1312 to permit the heat exchanger 1312 to cool the water. The cooling load with chiller and ice tank bypass mode of FIG. 66 may be utilized to save energy or when the thermal load on the heat transfer apparatus 1300 is low.

[00251] Regarding FIG. 67, the heat transfer apparatus 1300 is shown in a cooling load with ice tank bypass mode. More specifically, the valve 1320 inhibits the flow of glycol to the ice tank 1308. Instead, the glycol is circulated by a pump 1306 from the glycol chiller 1304 to the heat exchanger 1310. The cooling provided by the glycol chiller 1304 may thereby be utilized to cool water in the water loop 1305 as the water travels through the heat exchanger 1310.

[00252] Regarding FIGS. 68 and 69, a heat transfer apparatus 1350 is provided that is similar to the heat transfer apparatus 1170. The heat transfer apparatus 1350 includes a housing 1352, an adiabatic precooler 1353 including a precooling pad 1354, a finned coil 1356, and condenser coil 1358, and an evaporator 1360 of a chiller 1362. Regarding FIG. 69, the heat transfer apparatus 1350 is provided in a perspective view to show that the heat transfer apparatus 1350 includes a thermal energy storage, such as an ice tank 1370, side-by-side the evaporator 1360 of the chiller 1362.

[00253] Regarding FIGS. 70-73, a heat transfer apparatus 1390 is provided that has a chiller 1392, a thermal energy storage such as a PCM tank 1394, and a heat exchanger 1396 for cooling process fluid from a cooling load 1398. The PCM tank 1394 contains a phase change material having a storage temperature higher than 50°F, such as 65°F, so that the same process fluid can be used in first and second fluid loops 1411, 1413 of the heat transfer apparatus 1390 (see FIG. 71). The storage temperature may refer to the melting or freezing temperature of a phase change material. The melting and freezing temperatures may be the same or different depending on the phase change material. Examples of phase change materials that may be used include PureTemp 18 from PureTemp LLC and BioPCM®-Q18 from Phase Change Solutions, Inc.

[00254] Regarding FIG. 70, the heat transfer apparatus 1390 is shown in a cooling load with PCM discharge mode wherein valve 1400 directs process fluid from the chiller 1392 through the PCM tank 1394 and a valve 1402 directs the cooled process fluid from the PCM tank 1394 to the cooling load 1398. The valve 1404 directs process fluid from the heat exchanger

1396 to the chiller 1392. In this manner, the chiller 1392 and the PCM tank 1394 cool the process fluid below the temperature of process fluid output from the heat exchanger 1396.

[00255] Regarding FIG. 71, the heat transfer apparatus 1390 is shown in a cooling load with a PCM charge mode. In this mode, the valves 1402, 1404 permit a pump 1410 to circulate a secondary process fluid between the chiller 1392 and PCM tank 1394 in the first fluid loop 1411. The chiller 1392 outputs the secondary process fluid at a temperature lower than the freezing temperature of the PCM in the PCM tank 1394 to recharge the PCM tank 1394. Further, in the cooling load with PCM charge mode of FIG. 71, the heat transfer apparatus 1390 is able to provide cooling capacity for the cooling load 1398 by way of a pump 1414 circulating a primary process fluid between the heat exchanger 1396 and the cooling load 1398 in the second fluid loop 1413.

[00256] Regarding FIG. 72, the heat transfer apparatus 1390 is shown in a cooling load with PCM bypass tank mode. More specifically, the valve 1400 bypasses the process fluid received from the chiller 1392 around the PCM tank 1394 and directs the process fluid to the cooling load 1398. Further, the valve 1404 permits process fluid from a heat exchanger 1396 to travel to the chiller 1392.

[00257] Regarding FIG. 73, the heat transfer apparatus 1390 is shown in a cooling load with chiller and PCM tank bypass mode. More specifically, in the mode of FIG. 73, the valves 1402, 1404 are closed to bypass the process fluid around the chiller 1392 and the PCM tank 1394.

[00258] Regarding FIGS. 74-76, a heat transfer apparatus 1430 is provided that is similar in many respects to the heat transfer apparatus 1150 discussed above. One difference between the heat transfer apparatuses 1150, 1430 is that the heat transfer apparatus 1430 has a valve 1432 between the heat exchanger 1434 and a cooling load 1436 as well as a valve 1438 between the heat exchanger 1434 and a PCM tank 1440. Another difference between the heat transfer apparatuses 1150, 1430 is that the heat transfer apparatus 1150 uses the trim chiller 1154 to provide trim cooling whereas heat transfer apparatus 1430 uses PCM tank 1440 to provide trim cooling.

[00259] The heat transfer apparatus 1430 has a cooling load with PCM discharge mode as shown in FIG. 74, a cooling load with PCM charge mode as shown in FIG. 75, and a cooling load with PCM tank bypass mode as shown in FIG. 76. In the mode of FIG. 75, the valve 1432 may modulate the flow of process fluid from the cooling load 1436 to direct some of the process fluid back to the cooling load 1436 and mix with the cooled process fluid from the PCM tank 1440. The PCM tank 1440 has a storage temperature higher than 70°F such as

78°F. The mode of FIG. 75 uses recirculation of process fluid to raise the temperature of the process fluid before the process fluid is returned to the cooling load 1436.

[00260] The heat transfer apparatuses discussed herein may take various shapes. In some embodiments, the components of the heat transfer apparatus are packed in a single housing. In other embodiments, the components may be standalone structures that are operably connected. For example, a heat transfer apparatus 1450 is provided in FIG. 77 that includes two stacked air/process fluid heat exchangers 1452, 1454 and a separate thermal energy storage 1456.

[00261] Regarding FIG. 78, a heat transfer apparatus 1460 is provided that includes a housing 1462 having an air inlet 1464, an air outlet 1466, and one or more fans 1468 operable to generate air flow between the air inlet 1464 and the air outlet 1466. The heat transfer apparatus 1460 includes an adiabatic precooling pad 1472 and an indirect heat exchanger such as a finned coil 1474. The finned coil 1474 receives hot process fluid via a return 1476. The heat transfer apparatus 1460 includes a valve 1480 that modulates flow of cooled process fluid from the finned coil 1474 to a thermal energy storage such as a PCM tank 1482. The process fluid may travel from the valve 1480, to the PCM tank 1482, and then be returned to the cooled process fluid supply 1484 downstream of the valve 1480. The PCM tank 1482 is in an interior 1486 of the housing 1462 which may be advantageous in some embodiments to permit airflow generated by the one or more fans 1468 to cool the PCM tank 1482.

[00262] Regarding FIG. 79, a heat transfer apparatus 1500 is provided having a process fluid heat exchange circuit 1502 that includes a dehumidifier such as a membrane mass exchanger 1504, a heat exchanger 1506 such as an air/process fluid heat exchanger, and a pump 1508. The membrane mass heat exchanger 1504 receives air 1510 and reduces the wet bulb temperature of the air before the air reaches the heat exchanger 1506. The heat exchanger 1506 receives process fluid from a cooling load 1512. By dehumidifying the air upstream of the heat exchanger 1506, the efficiency of operation of the heat exchanger 1506 can be increased.

[00263] Regarding FIG. 80, a heat transfer apparatus 1530 is provided that includes a housing 1532, a primary air inlet 1534 with a primary louver 1536, a secondary air inlet 1538 with a secondary louver 1540, and an air outlet 1542. The heat transfer apparatus 1530 further includes a membrane mass exchanger 1550, an adiabatic precooling pad 1552 with a precooling pad 1554, and an indirect heat exchanger such as a finned coil 1556. The membrane mass exchanger 1550 may include tubular or sheet membranes that permit water vapor to pass

therethrough for collection and removal from the air stream which dehumidifies the air upstream of the precooling pad 1554. In a first mode, the secondary louvers 1540 may be closed and the primary louvers 1536 opened so that air flows through the membrane mass exchanger 1550 to the precooling pad 1554 and the finned coil 1556. Further, the heat transfer apparatus 1530 has a second mode wherein the primary louvers 1536 are closed and the secondary louvers 1538 are opened so that air may travel through the secondary air inlet 1538 to the precooling pad 1554 bypassing the membrane mass exchanger 1550. The finned coil 1556 receives hot process fluid from a return 1570 and directs cooled process fluid to a supply 1572 that directs process fluid back to the cooling load.

[00264] Regarding FIG. 81, a membrane mass exchanger 1660 is provided as an example of the membrane mass exchanger 1550 discussed above. The membrane mass exchanger 1660 includes an array of air passageways 1662, sheet membranes 1664 and permeate passageways 1666. Air travels in direction 1670 into air inlets 1669, travels along the air passageways 1662 while contacting the sheet membranes 1664, and exits the air passages 1662 via outlets 1672. The membrane mass exchanger 1660 includes a compressor or vacuum pump 1682 that operates to create a vacuum in the permeate passageways 1666. The presence of the vacuum in the permeate passageways 1666 on the side of the sheet membrane 1664 opposite the air passageway 1662 draws water vapor in the airflow through the sheet membrane 1664 and into the permeate passageway 1666. Water vapor collected in the permeate passageways 1666 travels through conduit 1680, to the vacuum pump 1682, and to a water output 1684. The water output 1684 may include, for example, an air and water separator and a condenser to condense collected water vapor into liquid water for pumping to the adiabatic precooling pad 1552 or another process. The condenser may include, for example, a cooled metallic surface.

[00265] With reference to FIG. 82, a heat transfer apparatus 1700 is provided that includes an air inlet 1702, a dehumidifier 1704 such as a membrane mass exchanger 1706, an adiabatic precooling pad 1708 that includes precooling pads 1710, an indirect heat exchanger such as a tube and fin heat exchanger 1712, a direct heat exchanger such as fill 1714, a plenum 1716, and an air outlet 1718 with a fan 1720. The fan 1720 generates airflow from the air inlet 1702 to the air outlet 1718. The dehumidifier 1704 includes a liquid desiccant supply 1730 having a pump 1732 that pumps liquid desiccant collected from a sump 1734 to the membrane mass exchanger 1706. Ambient air enters the air inlet 1702 such that the liquid desiccant in the membrane mass exchanger 1706 removes water vapor from the air. This decreases the wet bulb temperature of the air at region B.

[00266] Next, the air travels through the precooling pad 1710 that is wetted by a water from a liquid supply 1750 having a pump 1754 that pumps water from a sump 1752. The water on the precooling pad 1710 reduces the dry bulb temperature at region C.

[00267] The dehumidified, dry air next travels across the tube and fin heat exchanger 1712 and transfers heat to a process fluid that enters an inlet 1760 of the tube and fin heat exchanger 1712 at an elevated temperature and leaves an outlet 1762 of the tube and fin heat exchanger at a reduced temperature.

[00268] The liquid desiccant supply 1730 includes a liquid desiccant sump 1770 with an electric heater that heats the liquid desiccant to recharge the liquid desiccant that has collected water vapor at the membrane mass exchanger 1706. Alternatively or additionally, the liquid desiccant sump 1770 may utilize waste heat, such as from a manufacturing operation, to heat the liquid desiccant. The liquid desiccant supply 1730 further includes a pump 1780 to direct liquid desiccant to a spray 1788 onto the fill 1714. The air travels from region D to region E and absorbs heat from the liquid desiccant. The cooled liquid desiccant is then returned to the membrane mass exchanger 1706 by the pump 1732.

[00269] With reference to FIG. 83, a heat transfer apparatus 1800 is shown that has a process fluid heat exchange circuit 1802 including an indirect heat exchanger such as a fluid cooling coil 1804, a thermoelastic chiller such as a shape memory alloy (SMA) cooler 1806, and a thermal energy storage such as PCM tank 1808 that operate to provide a process fluid to a cooling load 1810 at a requested temperature, pressure, flow rate, or a combination thereof. The SMA cooler 1806 has a condenser side 1812 and an evaporator side 1814. The PCM tank 1808 has a storage temperature such as 65°F. The SMA cooler 1806 produces heat when deformed by compression and absorbs heat when the compression is released and the SMA returns to its original shape as shown by the phase diagram 1820 in FIG. 84. The SMA cooler 1806 may have a first plurality of cassettes of SMA alloys on the condenser side 1812 that are compressing to generate heat and a second plurality of cassettes of SMA alloys of the evaporator side 1814 that are expanding to absorb heat. The SMA cooler 1806 has valving that operatively flips the first and second plurality of cassettes of SMA alloy between the first plurality of cassettes on the condenser side 1812 and the second plurality of cassettes on the evaporator side 1814 once the SMA alloy of the first plurality of cassettes have fully compressed and the SMA alloy of the second plurality of cassettes have fully expanded. In this manner, the SMA cooler 1806 may be operated as a chiller to further reduce the temperature of the process fluid from the fluid cooling coil 1804 prior to the process fluid being directed to the PCM tank 1804. It will be appreciated that the SMA cooler

1806 may be utilized with the other embodiments discussed herein in place of or in addition to the refrigerant-based chillers discussed herein. The SMA cooler 1806 and the other chillers discussed herein may have their own embedded controller that communicates with the master controller of the heat transfer apparatus.

[00270] Regarding FIGS. 13 and 85, the controller 466 of the heat transfer apparatus 430 may operate the heat transfer apparatus 430 using a method 1900A represented by the state machine diagram of FIG. 85. The controller 466 is set, such as by a user or by another system controller, to operate the heat transfer apparatus 430 to achieve a target optimization criterion such as minimizing energy consumption, minimizing water consumption, or minimizing cost. The controller 466 may operate the heat transfer apparatus 430 using the method 1900A or the method 1900B (see FIG. 89) when the target optimization criterion is to minimize water consumption. Conversely, the controller 466 may utilize method 2100A (see FIG. 92) or method 2100B (see FIG. 95) when the target optimization criterion is to minimize energy consumption.

[00271] Regarding FIGS. 85 and 89, the controller 466 utilizes the method 1900A when cooling load 433 requires cooling from the heat transfer apparatus 430 and utilizes the method 1900B when the cooling load 433 requires minimal or no cooling from the heat transfer apparatus 430. The methods 1900A, 1900B include operating the heat transfer apparatus 430 in operating modes 1902, 1904, 1906, 1908, 1910, 1912, 1914, 1916, 1918, 1920, 1922, 1924, 1926, 1928, 1930, 1932. The operating modes 1902-1932 correspond to Modes 1-11 discussed above with respect to FIGS. 14-19F. The indication of “wet” or “dry” in FIGS. 85 and 89 indicates whether the pre-cooling pad 442 is wetted or not for the associated operating mode 1902-1932. For example, operating mode 1910 in FIG. 85 corresponds to Mode 3 of FIG. 16 when the pump 406 is not operating to wet the precooling pad 432. By contrast, operating mode 1912 represents Mode 3 of FIG. 16 when the pump 446 is operating to pump liquid onto the precooling pad 442 so that air traveling through the precooling pad 442 is adiabatically cooled before reaching the fluid cooling coil 448. When the target optimization criterion is to minimize water consumption, the heat transfer apparatus 430 operates in a dry mode as long as possible until the heat transfer apparatus 430 is unable to satisfy the cooling load 433. In the energy saving mode, the heat transfer apparatus 430 is operated in a wet mode as long as possible until the ambient temperature drops to a certain point such as 35°F.

[00272] Regarding FIG. 86, the methods 1900A, 1900B, 2100A, 2100B utilize set parameters 1950, measured parameters 1952, calculated coil EDB parameters 1954, and one or more

historical parameters 1956 to select an initial operating mode 1902-1932 for the heat transfer apparatus 430 as well as select different operating modes for the heat transfer apparatus 430 as the thermal duty of the heat transfer apparatus 430 changes. The methods 1900A, 1900B, 2100A, 2100B may utilize current detected parameters as inputs and/or predicted future parameters as inputs, such as predicted future ambient conditions and/or cooling load requirements.

[00273] Regarding the set parameters 1950, the set parameters 1950 may include a supply temperature set point that represents the temperature of process fluid leaving the heat transfer apparatus 430 and being supplied to the cooling load 433. For example, the cooling load 433 may be a computer datacenter that requires process fluid to be returned to the cooling load 433 at a specific temperature.

[00274] The set parameters 1950 further include a control range parameter. The control range parameter is used to compensate for minor temperature variations and hysteresis during operation of the heat transfer apparatus 430 when determining whether to change the operating mode of the heat transfer apparatus 430. The control range parameter may be, for example, in the range of 1°F – 10°F. The methods 1900A, 1900B may utilize a first control range parameter for water saving operation whereas the methods 2100A, 2100B may utilize a second control range parameter for energy saving operation.

[00275] The control range parameter is also used by the controller 466 to decide whether to change the operating mode 557 (see FIGS. 23C and 23E) of the heat transfer apparatus 430. When the fan 450 is at a maximum fan speed, if the process fluid supply temperature (the temperature of process fluid the heat transfer apparatus 430 provides to the cooling load 443) becomes higher than the supply temperature set point by a temperature difference that equals the control range parameter, the controller 466 changes the operating mode of the heat transfer apparatus 430. Conversely, if the fan 450 is at a minimum fan speed, if the process fluid supply temperature becomes lower than the supply temperature set point by a temperature difference that equals the control range parameter, the controller 466 changes the operating mode of the heat transfer apparatus 430.

[00276] The set parameters 1950 further include a PCM charging temperature such as 50°F. If the PCM tank 438 receives process fluid at the PCM charging temperature or lower, the PCM tank 438 is able to recharge. For example, in the operating mode 1920 (which corresponds to Mode 5 in FIG. 18 or Mode 11 in FIG. 19F), the PCM charging temperature will be used as the required leaving fluid temperature of the evaporator 456 of the chiller 452 in order for the process fluid leaving the evaporator 456 to cause recharging of the PCM

tank 438. As another example, in mode 1922, the PCM charging temperature will be used as the required leaving fluid temperature of the fluid cooling coil 448.

[00277] The set parameters 1950 include a PCM inventory charging threshold, such as 90% charge, which the controller 466 will always try to maintain. The PCM inventory discharging threshold is used to determine whether a working mode with PCM discharging should be skipped or not, such as when there is a 10% charge of the PCM tank 438.

[00278] The set parameters 1950 include a dry switch point of the heat transfer apparatus 430. The dry switch point is the minimum temperature that the heat transfer apparatus 430 may be operated in a wet mode, such as 35°F.

[00279] The measured parameters 1952 include a dry bulb temperature of the ambient air and a relative humidity of the ambient air. The heat transfer apparatus 430 includes sensors to measure the dry bulb temperature and the relative humidity of the ambient air. The measured parameters 1952 further include a process fluid return temperature, which is the temperature of fluid the heat transfer apparatus 430 receives from the cooling load 433. The measured parameters 1952 include the total process fluid flow rate, which is the flow rate of process fluid the heat transfer apparatus 430 receives from the cooling load 433. The measured parameters 1952 further include a PCM inventory, which is the current inventory or charge of the PCM tank 438.

[00280] The calculated coil EDB parameters 1954 include a CoilEDB parameter, which is the air temperature after the precooling pad 442 but before the fluid cooling coil 448. The CoilEDB parameter 1954 may be determined using the entering dry bulb temperature (EDB) of the ambient air, entering wet bulb temperature (EWB) of the ambient air, and saturation efficiency. In one approach, CoilEDB is calculated using the following formula:

$$[\text{Eq. 1}] \text{CoilEDB} = \text{EDB} - \text{SaturationEfficiency} * (\text{EDB} - \text{EWB})$$

[00281] The EWB value in Eq. 1 is calculated using the following formula:

[Eq. 2]

$$\begin{aligned} \text{EWB} = & \text{EDB} * \tan^{-1}(0.151977 * \sqrt{Rh + 8.313659}) + \tan^{-1}(\text{EDB} + Rh) - \\ & \tan^{-1}(Rh - 1.676331) + \left(0.00391838 * Rh^{\frac{3}{2}} * \tan^{-1}(0.023101 * Rh)\right) - 4.686035 \end{aligned}$$

- [00282] Wherein EWB represents Entering Wet Bulb Temperature of the ambient air in °C; EDB is the Entering Dry Bulb temperature of the ambient air in °C; and Rh represents Relative Humidity of the ambient air in %.
- [00283] The Saturation Efficiency value in Eq. 1 is the efficiency of the precooling pad 442, such as 97%. The Saturation Efficiency value in Eq. 1 indicates how close the precooling pad 442 can cool the air to the wet bulb temperature.
- [00284] The historical parameter 1956 includes the coil EDB maximum detected during a preceding time period, such as the last 24, 48, or 72 hours, which is referred to as CoiledB_Max. The CoiledB_Max provides a rough guideline in for maximum temperature that could be encountered during operation of the heat transfer apparatus 430 based upon the maximum temperature that was encountered during the preceding time period, e.g., the last 48 hours. Generally speaking, the methods 1900A, 1900B, 2100A, 2100B take into account whether an operating mode 1902-1932 could handle the CoiledB_Max before deciding to operate the heat transfer apparatus 430 in the operating mode 1902-1932.
- [00285] The controller 466 also uses the CoiledB_Max to determine whether an operating mode 557 (see FIGS. 23C and 23E) that requires PCM discharging should be skipped to save PCM inventory. For example and with reference to FIG. 85, the controller 466 may operate the heat transfer apparatus 430 in mode 1902 (Mode 1, dry) in the morning of a first day. The CoiledB_Max in this example is a maximum CoiledB temperature calculated during 2 PM-6 PM of the previous day. The CoiledB_Max is sufficiently high that the controller 466 will need to operate the heat transfer apparatus 430 in at least mode 1914 (Mode 4, dry) wherein the PCM tank 438 is discharging to satisfy the supply process fluid temperature set point. As the ambient temperature increases during the first day and the thermal load on the heat transfer apparatus 430 increases, the controller 466 evaluates logic operations 2023, 2024, 2025, and 2026 and decides whether one of the logic operations 2023, 2024, 2025, 2026 is true.
- [00286] As shown in the portion of table 1970 in FIG. 88B, the conditions 1972D of logical operation 2026 include a first condition of: 1) if the current PCM inventory is less than the PCM inventory discharging threshold; or if the max CoiledB (also referred to as CoiledB_Max) is greater than CoiledB_SP_3D. The conditions 1972D include a second condition of: whether the supply temperature (the process fluid provided by the heat transfer apparatus 430) is greater than the sum of the process fluid set point and the control range. If both conditions of the conditions 1972D are true, the controller 466 will change the

heat transfer apparatus 430 from operating condition 2026 (Mode 1, dry) to operating condition 1906 (Mode 2, dry).

[00287] In this example, the CoiledB_Max is greater than the current CoiledB set point for Mode 3, dry (referred to as "CoiledB_SP_3D") and the expected return temperature of process fluid from the heat transfer apparatus 430 during 2 PM – 6 PM of the first day will be higher than the sum of the supply temperature set point for operating mode 1910 (Mode 3, dry) and the control range. The controller 466 decides logical condition 2026 is true and reconfigures the heat transfer apparatus 430 from operating condition 1902 (Mode 1, dry) to operating condition 1906 (Mode 2, dry), skipping operating condition 1910 (Mode 3, dry) as shown in FIG. 85. By skipping operating condition 1910, the controller 466 avoids discharging the PCM tank 438 which saves the charge of the PCM tank 438 for later in the first day, i.e., 2PM-6PM when the CoiledB_Max is expected to occur.

[00288] During 2 PM – 6 PM of the first day, the controller 466 can change the heat transfer apparatus 430 from operating in mode 1906 (Mode 2, dry) to mode 1914 (Mode 4, dry) if the conditions of logical operation 2031 are true, i.e., if: 1) the PCM inventory is no less than the PCM inventory discharging threshold of set parameters 1950; the CoiledB_Max during the past 48 hours is no greater than CoiledB_SP_4D; and 3) the process fluid supply temperature (the temperature of process fluid leaving the heat transfer apparatus 430) is calculated to be greater than the sum of the supply process fluid temperature set point and the control range of set parameters 1950. As the controller 466 operates the heat transfer apparatus 430 in operating mode 1914, the controller 466 evaluates logical operations 2033, 2034 periodically, such as every ten seconds, to decide whether to change the heat transfer apparatus 430 to operating mode 1904 (Mode 1, wet) or mode 1906 (Mode 2, dry).

[00289] If the inventory of the PCM tank falls below the PCM inventory discharging threshold during the 2 PM – 6 PM time period of the first day, the heat transfer apparatus 430 will be unable to continue operating in mode 1914 (Mode 4, dry). The controller 466 calculates the temperature of the process fluid the heat transfer apparatus 430 will supply to the cooling load 433. Using this calculated supply temperature, the controller 466 evaluates logical operations 2034, 2033 to determine whether to change the heat transfer apparatus 430 to mode 1906 (Mode 2, dry) or mode 1904 (Mode 1, wet). Regarding logical operation 2034 in the portion of table 1970 of FIG. 88B, the controller 466 will change the heat transfer apparatus 430 from operating mode 1914 to mode 1904 if: 1) the calculated supply temperature is greater than the sum of the supply temperature set point and the control

range; and 2) the calculated CoiledB is no less than the dry switch point of set parameters 1950.

[00290] With reference to FIG. 85, when the heat transfer apparatus 430 is powered up, the controller 466 begins the method 1900A at step 1901A by determining which mode 1902-1924 to start with by evaluating logical operations 2001-2012 using the time, dry bulb temperature, relative humidity, process fluid return rate, total process fluid flow rate, PCM inventory of parameters 1950, 1952, 1954, 1956 and CoiledB_Max. The step 1901A involves calculating a current CoiledB, which is compared with CoiledB set points for the different operating modes 1902-1924.

[00291] For example, the current CoiledB calculated at step 1901A will be compared with the CoiledB_SP_1D which represents the CoiledB parameter associated with operating mode 1902. Operating mode 1902 corresponds to a dry operation of Mode 1 (see FIG. 14). As another example, the current CoiledB calculated at step 1901A is compared with CoiledB_SP_2W, which is the CoiledB parameter for operating mode 1908. Operating mode 1908 represents wet operation of Mode 2 (see FIG. 15). The numbers "1" and "2" in CoiledB_SP_1D and CoiledB_SP_2W correspond to the first and second modes. Other uses of CoiledB_SP_XY in this disclosure use "X" to identify one of Modes 1-11 of FIGS. 14-19F and the "Y" value to indicate whether the pre-cooling pad 442 is being run wet ("W") or dry ("D").

[00292] The CoiledB_SP parameters for the operating modes 1902-1932 are determined based at least in part upon the supply temperature set point of the set parameters 1950, the process fluid return temperature of the measured parameters 1952, and the total process fluid flow rate of the measured parameters 1952. The CoiledB_SP for a given operating mode 1902-1932 is the maximum CoiledB the operating mode can handle while the heat transfer apparatus 430 provides process fluid at or below the supply temperature set point, assuming the fan 450 is operated at 100% fan speed and the PCM tank 438 is fully charged. For example, CoiledB_SP_4D is the max CoiledB (air dry bulb temperature before the cooling coil 448, but after the pad 442) to run operating mode 1914 (Mode 4, dry) while the heat transfer apparatus 430 provides process fluid at or below the supply temperature set point. If the current CoiledB calculated by the controller 466 is higher than CoiledB_SP for the current operating mode, the heat transfer apparatus 430 will not be able to provide enough cooling capacity even if the PCM tank 438 is fully charged and fan 450 is at 100% fan speed.

[00293] As an example, the CoiledB_SP_4D may be determined using a flow rate or flow ratio for the condenser 454 and evaporator 456, the leaving fluid temperature of the evaporator 456 during PCM discharging, the flow rate or flow ratio of the PCM tank 438, and the leaving fluid temperature of the PCM tank 438 (72°F in FIG. 17) during discharging of the PCM tank 438. Further, the CoiledB_SP_4D may be solved for using the following equations:

$$[\text{Eq. 3}] \text{ CoiledB_SP} = \text{function}(\text{fluid cooler EFT, fluid cooler LFT, TotalFlowRate})$$

[00294] Wherein fluid cooler EFT is the temperature of process fluid entering the fluid cooling coil 448, fluid cooler LFT is the temperature of process fluid leaving the fluid cooling coil 448 required to be able to meet the supply temperature set point, and TotalFlowRate is the total flow rate of process fluid entering (or leaving) the heat transfer apparatus 430. The fluid cooler LFT and fluid cooler EFT may be calculated using the following functions:

$$[\text{Eq. 4}] \text{ fluid cooler LFT} = \text{function}(\text{SupplyTempSP, TotalFlowRate, evaporator LFT during discharging, evaporator flow rate, PCM tank LFT during discharging, PCM tank flow rate})$$

$$[\text{Eq. 5}] \text{ fluid cooler EFT} = \text{function}(\text{ReturnTemp, TotalFlowRate, fluid cooler LFT, evaporator LFT during discharging, condenser flow rate, evaporator flow rate})$$

[00295] Fluid cooler LFT is the process fluid temperature required to be able to meet SupplyTempSP (set point) requirement. Fluid cooler LFT is calculated based on heat balance assuming evaporator flow rate or flow ratio, evaporator LFT during discharging, PCM tank flow rate or flow ratio, and PCM tank LFT during discharging have been pre-set.

[00296] Fluid cooler EFT is calculated based on heat balance assuming condenser flow rate or flow ratio, evaporator flow rate or flow ratio, and evaporator LFT during discharging have been pre-set. The fluid cooler LFT, ReturnTemp of the process fluid received by the fluid cooling coil 448, and the TotalFlowRate of the heat transfer apparatus 430 are used in the calculation.

[00297] The controller 466 progresses through the control logic of the methods 1900A, 1900B, 2100A, 2100B as the thermal duty placed on the heat transfer apparatus 430 changes to select a sequence of operating modes that satisfies the cooling load 433 while achieving the target optimization criterion. The methods 1900A, 1900B, 2100A, 2100B

permit a rapid start-up of the heat transfer apparatus 430 because the best initial operating mode 1902-1932 is selected at steps 1901A, 1901B, 2101A, 2101B rather than progressing through a fixed sequence of operating modes. Additionally, the operating modes of methods 1900A, 1900B, 1900C, 1900D that include PCM discharge (e.g., mode 1912) may be skipped to save PCM inventory for later use. As discussed above, the CoiledDB_Max is used to determine whether operating modes with PCM discharging should be skipped. It will be appreciated that PID loops or other approaches may be used to determine a fan speed, chiller condenser/evaporator flow rates, evaporator leaving fluid temperature set point, and PCM tank flow rate for the various working modes of the methods 1900A, 1900B, 2100A, 2100B.

[00298] Regarding FIG. 87, a table 1960 is provided with a column 1961 of logical operations 2001-2012 of method 1900A, a column 1962 of the conditions of the logical operations 2001-2012, and a column 1964 of initial operating modes that the controller 466 may select using the logical operations 2001-2012. For example, at step 1901A, if the parameter for current PCM inventory is less than the PCM inventory charging threshold and CoiledDB calculated at step 1901A is no greater than the CoiledDB set point for dry operation in Mode 8 as indicated by the condition 1962A, then the controller 466 configures the heat transfer apparatus 430 to operate in mode 1922 corresponding to dry operation in Mode 8 (see FIG. 19C) as shown by reference numeral 1964A in the table 1960. In other words, the controller 466 utilizes the parameters 1950, 1952, 1954, 1956 to select a true condition from the conditions of column 1962. The controller follows the logical operation 2001-2012 that corresponds to the true condition to select the initial operating mode for the heat transfer apparatus 430.

[00299] Regarding FIGS. 88A-88C, a table 1970 is provided having a column 1971 of logical operations 2013-2044 of the method 1900A. The table 1970 has a column 1976 of current operating mode associated with the logical operations 2013-2044, a column 197 identifying the condition of each logical operation 2013-2044, and a column 1974 of next operating modes that should be selected if the conditions of column 1972 are true. For example, with reference to logical operation 2023 in table 1970, the heat transfer apparatus 430 is currently operating according to operating mode 1902, which corresponds to Mode 1, dry operation, of FIG. 14. Regarding FIG. 85, the logical operation 2023 determines whether the method 1900A will progress from operating mode 1902 to operating mode 1920 which corresponds to wet operation in Mode 5 of FIG. 18 or wet operation in Mode 11 of FIG. 19F. More specifically, at logical operation 2023, the controller 466 evaluates a condition 1972A

(see FIG. 88B). The condition 1972A requires: 1) the current PCM inventory is less than the PCM inventory charging threshold; 2) the process fluid supply temperature is lower than a parameter equal to the supply temperature set point minus the control range; and 3) the dry bulb temperature of the ambient air entering the heat transfer apparatus 430 is no less than the dry switch point. If the condition 1972A is true, the controller 466 changes the heat transfer apparatus 430 from operating mode 1902 to operating mode 1920, which responds to the wet operation of Mode 5 of FIG. 18 or the wet operation of Mode 11 of FIG. 19F. The controller 466 selects between Mode 5 and Mode 11 using the supply temperature set point. For example, if the supply temperature set point is below a threshold temperature (e.g., 84 °F), the controller 466 selects Mode 11. If the supply temperature is equal to or greater than the threshold temperature, the controller 466 selects mode 5.

[00300] If the condition 1972A is not true, the controller 466 evaluates conditions 1972B, 1972C, 1972D of logical operations 2024, 2025, 2026 (see FIGS. 85 and 88B) to determine whether to change the heat exchange apparatus 430 into operating mode 1918, 1910 or 1906. If none of the conditions 1972A, 1972B, 1972C, 1972D are true, the controller 466 will continue to operate the heat exchange apparatus 430 in the operating mode 1902. The controller 466 may evaluate the conditions 1972A-1972D after a predetermined time period, such as every 10 seconds, or after an event, such as a malfunction of a component or an increase in a parameter above a threshold such as a sudden increase in thermal load on the heat transfer apparatus 430.

[00301] Regarding FIG. 89, the controller 466 may utilize the method 1900B when the target optimization criterion is to minimize water consumption and when the cooling load 433 is not requiring cooling from the heat transfer apparatus 430. Upon startup of the heat transfer apparatus 430, the controller 466 performs step 1901B that is similar to step 1901A discussed above. Regarding FIG. 90, a table 1980 is provided that includes a column 1981 of logical operations 2045-2048 of the method 1900B, a column 1982 of the conditions of the logical operations 2045-2048, and a column 1984 of initial operating modes for the heat transfer apparatus 430. For example, if the current PCM inventory is less than the PCM inventory charging threshold and the CoilEDB calculated at step 1901B is no greater than the Coil EDB set point for dry operation of Mode 9, as indicated by condition 1982A in table 1980, the controller 466 will select operating mode 1930 as the initial operating mode for the heat transfer apparatus 430, which corresponds to Mode 9 dry of FIG. 19D.

[00302] Regarding FIG. 91, a table 1990 is shown that includes a column 1991 of logical operations 2049-2058 of the method 1900B, a column 1992 of current operating modes of

the heat transfer apparatus 430, a column 1994 of the conditions of the logical operations 2049-2058, and a column 1996 of next operating modes of the heat transfer apparatus 430. Since there is no cooling load 433 requiring cooling from the heat transfer apparatus 430 in method 1900B, the controller 466 may stop the method 1900B in response to the PCM inventory reaching 100%. For example, when the heat transfer apparatus 430 is in mode 1930, corresponding to dry operation in Mode 9 of FIG. 19D, the controller 466 considers conditions 1994A, 1994B associated with logical operations 2049, 2050 to determine if one of the conditions 1994A, 1994B is true. If condition 1994B is true, the controller 466 will stop the method 1900B and await the cooling load 433 to require cooling from the heat transfer apparatus 430 or another trigger, such as an expiration of a period of time or a command from a system controller to again initiate one of the methods 1900A, 1900B, 2100A, 2100B.

[00303] Regarding FIG. 92, the controller 466 may implement the method 2100A in response to the heat transfer apparatus 430 being operated to minimize energy consumption and the cooling load 433 requiring cooling from the heat transfer apparatus 430. The method 2100A is similar in many respects to the method 1900A discussed above and is used to select an initial and subsequent operating modes for the heat transfer apparatus 430 from the operating modes 1902-1924. The method 2100A begins at step 2101A that is similar to the step 1901A discussed above.

[00304] The method 2100A begins at step 2101A that is similar to the step 1901A discussed above. Regarding FIG. 93, a table 2070 is provided that includes a column 2072 of logical operations 2101-2112 that are evaluated at step 2101A of method 2100A, a column 2074 of conditions associated with the logical operations 2101-2112, and a column 2076 of initial operating modes that may be selected by the controller 466 in response to the logical operations 2101-2112 being true. For example, the controller 466 will select as the initial mode 1918 via logical operation 2102 upon satisfying condition 2074A, which requires: 1) the current PCM inventory is less than the PCM inventory charging threshold; 2) the CoiledB calculated at operation 2101A is greater than the CoiledB set point for dry operation of Mode 8 (see FIG. 19C), but no greater than the CoiledB set point for dry operation of Mode 5 (see FIG. 18); and 3) the air dry bulb is less than the dry switch point.

[00305] Once the controller 466 has selected the initial operating mode at step 2101A of method 2100A, the controller 466 can evaluate whether to change the heat transfer apparatus 430 to a different operating mode by evaluating logical operations 2113-2142 of the method 2100A. Regarding FIGS. 94A-94C, a table 2080 is provided that includes a

column 2082 of the logical operations 2113-2142, a column 2084 of current operating modes, a column 2086 of conditions associated with logical operations 2113-2142, and a column 2088 indicating the next operating mode to be implemented by the heat transfer apparatus 430 upon the associated condition of the logical operation 2113-2142 being satisfied. The controller 466 may evaluate whether to change the mode of the heat transfer apparatus 430 after every 10 seconds, every 5 minutes, or every 15 minutes as some examples.

[00306] As one example and with reference to logical operations 2120 and 2121 in FIG. 94A, the controller 466 may be operating the heat transfer apparatus 430 in operating mode 1910 which represents the dry operation of Mode 3 of FIG. 16. Regarding FIG. 92, the controller 466 will evaluate logical operations 2120 and 2121 to determine whether either condition 2086A or 2086B is true. If the condition 2086A (see FIG. 94A) associated with logical operation 2120 is true, the controller 466 will change the heat transfer apparatus 430 from the operating mode 1910 (Mode 3, dry) to operating mode 1902 (Mode 1, dry).

[00307] Regarding FIG. 95, the controller 466 may utilize method 2100B when the heat transfer apparatus 430 is being operated to minimize energy consumption and the cooling load 433 is requiring no or limited cooling from the heat transfer apparatus 430. The controller 466 utilizes the method 2100B to select an initial and subsequent operating modes of the heat transfer apparatus 430 from the operating modes 1926, 1928, 1930, 1932. The initial operating mode is selected first by analyzing real time data and recorded data at step 2101B which is similar to step 1901A discussed above.

[00308] Regarding FIG. 96, a table 2180 is provided that includes a column 2182 listing logical operations 2143-2146 of the method 2100B. The table 2180 includes a column 2184 of the conditions of the logical operations 2143-2146. The table 2180 further includes a column 2186 that indicates the initial modes to be used upon the conditions of the logical operations 2143-2146 being satisfied.

[00309] Regarding FIG. 97, a table 2190 is provided that may be utilized to determine the next operating mode with method 2100B when the heat transfer apparatus 430 is being operated to minimize energy consumption and the cooling load 433 is requiring no or limited cooling from the heat transfer apparatus 430. The table 2190 includes a column 2192 of logical operations 2147-2156 of the method 2100B, a column 2194 with current operating modes of the heat transfer apparatus 430, a column 2198 of next operating modes of the heat transfer apparatus 430, and a column 2196 of the conditions of the logical operations 2147-2156 used to select one of the next operating modes of column 2198. The table 2190 is

similar to the table 1990 discussed above and includes stopping operation of the method 2100B in response to the current PCM inventory reaching 100% such as upon condition 2196A.

[00310] Regarding FIGS. 98A-98H, a method 2500 is provided for operating the heat transfer apparatus 430 of FIG. 13 using the modes of FIGS. 14-19F. The controller 466 may use the method 2500 instead of the methods 1900A, 1900B, 2100A, 2100B. The controller 466 progresses through method 2500 upon startup of the heat transfer apparatus 430 and subsequently such as according to a predetermined schedule (e.g., every 10 seconds) and/or in response to an event such as receiving a command from a system controller, a malfunction of a component of the heat transfer apparatus 430, and/or a significant change in a detected parameter such as cooling required by the cooling load 433.

[00311] The controller 466 progresses through the method 2500 to identify an operating mode for the heat transfer apparatus 430 that can meet a capacity requirement and has the lowest water consumption rate if the heat transfer apparatus 430 is being operated to minimize water consumption. Alternatively, the controller 466 progresses through the method 2500 to identify an operating mode that can meet a capacity requirement and has the lowest energy consumption rate if the heat transfer apparatus 430 is being operated to minimize energy consumption. If the identified operating mode is the same as the current operating mode, the controller 466 will keep the heat transfer apparatus 430 operating in the current operating mode. If the identified operating mode is different than the current operating mode, the controller 466 will change the heat transfer apparatus 430 to the identified operating mode. The method 2500 thereby permits the controller 466 to jump to an optimal operating mode rather than cycling through intermediate modes to get to the optimal operating mode, which improves the efficiency of operation of the heat transfer apparatus 430.

[00312] For operating modes 1914 and 1916, the controller 466 selects mode 4 when there is a larger temperature differential between the process fluid supply and return temperatures as discussed above with respect to FIG. 19B. The controller 466 selects Mode 7 at operating modes 1914 and 1916 when there is a smaller temperature differential between the process fluid supply and return temperatures.

[00313] The method 2500 includes an analyzing step 2502 that is similar to the step 1901A discussed above. The method 2500 utilizes predefined parameters including a supply temperature set point, a control range (such as 1-10°F), a chiller set point during PCM charging (e.g., 50°F), a CoiledB_Max from the last 48 hours. The step 2502 includes using

predefined values for a CoiledB_SP_3D, CoiledB_SP_4D, and CoiledB_SP_3W, which are based on supply temperature set point and the total flow rate of process fluid.

[00314] The method 2500 includes a step 2504 that checks the PCM inventory or charge. The PCM inventory is kept at a certain range so that the PCM can be used as needed especially in Mode 10 of FIG. 19E.

[00315] Method 2500 includes step 2506 where the controller 466 determines a SupplyTemp_cal, which is a calculation of the temperature of the fluid provided from the heat transfer apparatus 430 to the cooling load 433 based upon inputs 2508. The inputs 2508 provided at step 2506 correspond to the operating conditions of the dry operation of Mode 5 of FIG. 18. Specifically, the step 2506 involves determining the SupplyTemp_cal from a lookup table using inputs representing that the pre-cooling pad 442 is dry, the fan 450 is operating at 100% speed, and the evaporator 456 of the chiller 452 is operating to cool process fluid traveling in a second loop 492 to charge the PCM tank 438. In another approach, SupplyTemp_cal is determined using one or more equations.

[00316] At step 2510, the controller 466 checks whether the calculated SupplyTemp_cal is less than the supply temperature set point minus the controller range. In other words, the controller 466 at step 2510 is checking whether the temperature of process fluid provided from the heat transfer apparatus 430 when operating dry in Mode 5 is lower than the set point required for the supply of process fluid to the cooling load 433 as reduced by the control range. The control range is a value used to compensate for temporary temperature variations and hysteresis of the heat transfer apparatus 430. If the condition of step 2510 is true, then the controller 466 proceeds to step 2512 where the controller 466 operates the heat transfer apparatus 430 dry in Mode 5 of FIG. 18.

[00317] If the condition of step 2510 is false, the controller 466 proceeds to step 2514 where the controller 466 determines a SupplyTemp_cal from using inputs 2516 that correspond to the Mode 5 of FIG. 18, but with the pump 446 operating to wet the precooling pad 442 upstream of the fluid cooling coil 448. If the SupplyTemp_cal is determined at step 2518 to be sufficiently below the temperature required by the cooling load 433, the controller 466 proceeds to step 2520 and operates the heat transfer apparatus 430 wet in Mode 5.

[00318] If neither dry Mode 5 nor wet Mode 5 are deemed acceptable at steps 2510, 2518, the controller 466 proceeds to step 2522 and subsequent steps to identify an operating mode that causes the heat transfer apparatus 430 to provide process fluid to the cooling load 433 at a temperature that is less than the value of the supply temperature set point minus the control range value.

- [00319] At step 2524, the controller determines whether the CoiledB_Max from the last 48 hours is less than the CoiledB_SP_3D. If not, the method 2500 proceeds to step 2526 and skips consideration of implementation of Mode 3, dry, to save the capacity of the PCM tank 438 for a difficult thermal duty that may occur soon. Likewise, the method 2500 includes step 2528 wherein the controller 466 may skip deciding whether to utilize Mode 4 or 7, dry, to save the charge of the PCM tank 438 for a more difficult thermal duty that may occur soon. Still further, at step 2530, the controller 466 may skip determination 2532 of whether wet operation in Mode 3 of FIG. 16 can satisfy the supply temperature set point and control range to save the charge of the PCM tank for a more difficult thermal duty that may occur during the day.
- [00320] For the operating modes of the method 2500, proportional-integral-derivative (PID) loops or other approaches may be used to determine fan speed, chiller evaporator and condenser flow rates, leaving fluid temperature set point, and/or PCM tank flow rate for a particular embodiment.
- [00321] The methods 1900A, 1900B, 2100A, 2100B, and 2500 have been described with respect to the heat transfer apparatus 430. It will be appreciated that the methods 1900A, 1900B, 2100A, 2100B, and 2500 may be used with other heat transfer apparatuses disclosed herein. Further, the methods 1900A, 1900B, 2100A, 2100B, and 2500 may have steps added or removed as required for a particular application of the methods.
- [00322] Regarding FIG. 99, a heat transfer system 2600 is provided that includes heat transfer apparatuses 2602A-N that receive heated process fluid from a structure, such as a building 2608, via a fluid process supply 2604 and provide cooled process fluid to a process fluid return 2606. The fluid process supply 2604 and process fluid return 2606 may include conduit, such as pipes, and other process fluid handling devices such as pumps and valves to control the flow of process fluid between the heat transfer apparatuses 2602A-N and the industrial process in the building 2608.
- [00323] The building 2608 houses an industrial process, such as a manufacturing process or a computer data center as some examples. The heat transfer apparatuses 2602A-2602N include their own chillers. For example, the heat transfer apparatuses 2602A-2602N may be, for example, the heat transfer apparatus 10 of FIG. 1, the heat transfer apparatus 1350 of FIG. 69, or a heat transfer apparatus 2700 of FIG. 102.
- [00324] With temporary reference to FIG. 102, the heat transfer apparatus 2700 has a fluid cooler 2702 that includes a fluid cooling coil 2704, an adiabatic cooler 2706 upstream of the fluid cooling coil 2704, an air inlet 2709, an air outlet 2710, and a fan 2708. The fan 2708 is

operable to generate airflow from the air inlet 2709, through the adiabatic precoolers 2706, across the fluid cooling coil 2704, and outward from the air outlet 2710. The heat transfer apparatus 2700 includes a chiller 2712 within an outer structure 2714 of the heat transfer apparatus 2700.

[00325] Regarding FIG. 100, a heat transfer apparatus 2800 is provided that includes heat transfer apparatuses 2802 that receive heated process fluid from an industrial process in the building 2814 via a process fluid supply 2804 and return cooled process fluid to the building 2814 via a process fluid return 2806. Each of the heat transfer apparatuses 2802 has a process fluid inlet 2810 connected to the process fluid supply 2804 and a process fluid outlet 2812 connected to the process fluid return 2806. The heat transfer system 2800 removes heat from the process fluid that is received from a building 2814.

[00326] Regarding FIG. 101, a heat transfer system 2900 is provided that includes heat transfer apparatuses 2902A-2902N each having a fluid cooler 2904 and a separate chiller and pump subsystem 2906. The chiller and pump subsystem 2906 may be housed in a room of the building 2914 or a separate structure. The heat transfer apparatuses 2902A-2902N may be, for example, the heat transfer apparatus 1150 of FIG. 59, the heat transfer apparatus 1220 of FIG. 62, the heat transfer apparatus 1302 of FIG. 64, and the heat transfer apparatus 1390 of FIG. 70 as some examples. Each heat transfer apparatus 2902A-2902N receives heated process fluid via a process fluid supply 2910 and provides cooled process fluid to the building 2914 via a process fluid return 2912. The heat transfer apparatuses 2902A-2902N have conduit 2916 connecting the fluid cooler 2904 and the chiller and pump subsystem 2906.

[00327] Regarding FIG. 103, a heat transfer apparatus 3000 is provided that is an example of the heat transfer apparatus 2700 of FIG. 102. The heat transfer apparatus 3000 includes a fluid cooler 3002 having an adiabatic precoolers 3004 with a precooling pad 3006, a sump 3008, and a pump 3010 to provide liquid from the sump 3008 to the precooling pad 3006. The fluid cooler 3002 further includes a fluid cooling coil 3012 that receives process fluid from a valve 3014 and directs cooled fluid to a valve 3016. The heat transfer apparatus 3000 includes a chiller 3020 having a condenser 3022 and an evaporator 3024. The valves 3014, 3016 are operable to direct process fluid to, or bypass, the condenser 3022 and evaporator 3024. The valves 3014, 3016 are further able to modulate the percentage of process fluid that bypasses and travels to the condenser 3022 and evaporator 3024, such as from 0% to 100% of the process fluid from a cooling load 3030. The cooling load 3030 may be, for example, a computer data center.

[00328] With reference to FIG. 103, the heat transfer apparatus 3000 has a first operating mode where the valve 3014 bypasses process fluid around the condenser 3022 and the valve 3016 bypasses the evaporator 3024 by directing the process fluid to bypass piping 3032. In the first operating mode, the heat transfer apparatus 3000 utilizes free cooling to cool the process fluid from the cooling load 3030. Stated differently, the fluid cooler 3002 removes heat from the process fluid to cool the process fluid from a temperature of 105°F to 84°F, as one example.

[00329] Regarding FIG. 104, the heat transfer apparatus 3000 is shown in a second operating mode wherein the valve 3014 directs a portion of the process fluid from the cooling load 3030 to the condenser 3022 such that the process fluid absorbs heat from the condenser 3022. The heat transfer apparatus 3000 has a connection 3040 where the process fluid from the condenser 3022 at 115°F mixes with process fluid at 105°F from the cooling load 3030. The fluid cooling coil 3012 receives the mixed process fluid at a temperature of 108°F, which is hotter than the 105°F process fluid the fluid cooling coil 3012 receives in the first operating mode (see FIG. 103). By providing a higher temperature process fluid to the fluid cooling coil 3012, the temperature difference between the process fluid in the fluid cooling coil 3012 and the ambient air temperature is greater which increases the efficiency of heat transfer from the fluid cooling coil 3012 to the air flowing across the fluid cooling coil 3012.

[00330] In the second operating mode of FIG. 104, the valve 3016 modulates or directs a portion of the process fluid from the fluid cooling coil 3012 to the evaporator 3024. The heat transfer apparatus 3000 has a connection 3042 that mixes the process fluid from the evaporator 3024 and the fluid cooling coil 3012. The mixing of the process fluid at a connection 3042 results in the process fluid being returned to the cooling load 3030 at a temperature of 84°F. In this manner, the heat transfer apparatus 3000 may utilize free cooling in the first operating mode wherein the cooling demand is lower or when the ambient temperature is lower and may utilize the free cooling and mechanical cooling the second operating mode when the cooling demand is higher or when the ambient temperature is higher.

[00331] Regarding FIG. 105, a heat transfer apparatus 3100 is provided that includes a fluid cooler 3102 having a first fluid circuit 3106. The first fluid circuit 3106 includes a direct heat exchanger 3104 and a portion of a heat exchanger 3108. The direct heat exchanger 3104 may be, for example, an open evaporative heat exchanger that distributes a liquid onto fill after the liquid has absorbed heat from the heat exchanger 3108. The direct heat exchanger 3104 has a sump 3110 that collects the liquid and a pump 3112 to direct the collected liquid

back to the heat exchanger 3108. The liquid may be, for example, water or a mixture of water and propylene glycol. The heat transfer apparatus 3100 has a second fluid circuit 3130 that receives a process fluid from the cooling load 3132. The process fluid may be, for example, water or a mixture of water and propylene glycol. The second fluid circuit 3130 includes a portion of the heat exchanger 3108 and a chiller 3120 having a condenser 3122 and evaporator 3124.

[00332] The heat transfer apparatus 3100 includes valves 3134, 3136 for directing the process fluid toward, or around, the condenser 3122 and evaporator 3124. The heat transfer apparatus 3100 has a first mode (see FIG. 105) where the valves 3134, 3136 bypass the process fluid around the condenser 3122 and the evaporator 3124 such that the fluid cooler 3102 cools the process fluid from the cooling load 3132. The heat transfer apparatus 3100 has a second mode (see FIG. 106) where the valve 3134 directs at least a portion of the process fluid from the cooling load 3132 to the condenser 3122 and the valve 3136 directs at least a portion of the process fluid from the heat exchanger 3108 to the evaporator 3124.

[00333] Regarding FIG. 107, a heat transfer apparatus 3200 is provided having a fluid cooler 3202, such as a direct heat exchanger 3204, and a chiller 3206. The direct heat exchanger 3204 may include, for example, an open evaporative heat exchanger that distributes process fluid onto fill and such that the process fluid may be contacted by airflow 3207.

[00334] The heat transfer apparatus 3200 has a first operating mode (see FIG. 107) wherein valves 3210, 3212 bypass the process fluid around the chiller 3206. In the first operating mode, the direct heat exchanger 3204 provides the cooling for a cooling load 3220. The heat transfer apparatus 3200 has a second operating mode (see FIG. 108) wherein the valve 3210 directs at least a portion of the process fluid from the cooling load 3220 to a condenser 3230 of the chiller 3206 and the valve 3212 directs at least a portion of the process fluid from the direct heat exchanger 3204 to an evaporator 3232 of the chiller 3206. Thus, in the second operating mode of FIG. 108, the heat transfer apparatus 3200 utilizes both the direct heat exchanger 3204 and the chiller 3206 to provide cooling to the cooling load 3220.

[00335] Regarding FIG. 109, a heat transfer apparatus 3300 is provided that includes a fluid cooler 3302 and a chiller 3304. The fluid cooler 3302 includes an adiabatic precoolers 3303 and a fluid cooling coil 3306. The chiller 3304 has a hot side heat exchanger 3310 and a cold side heat exchanger 3312. The chiller 3304 may be, for example, an elastocaloric (such as shape memory alloy) heat pump, a magnetocaloric heat pump, or a vapor-compression-based chiller. The heat transfer apparatus 3300 has valves 3320, 3322 that are operable to control the flow of process fluid from a cooling load 3330 in the heat transfer apparatus

3300. More specifically, the heat transfer apparatus 3300 has a first operating mode wherein the valves 3320, 3322 bypass the process fluid around the chiller 3304 such that the fluid cooler 3302 provides cooling for the cooling load 3330. The heat transfer apparatus 3300 also has a second operating mode (see FIG. 110) wherein the valve 3320 directs at least a portion of the process fluid from the cooling load 3330 to the hot side heat exchanger 3310 and the valve 3322 directs at least a portion of the process fluid from the fluid cooling coil 3306 to the cold side heat exchanger 3312.

[00336] The heat transfer apparatuses 3000, 3100, 3200, 3300 are shown in FIGS. 103-110 as having their components integrated within outer structures 3003, 3101, 3201, 3301. In other embodiments, the heat transfer apparatuses 3000, 3100, 3200, 3300 may utilize chillers that are external structures 3001, 3101, 3201, 3301 in a manner similar to the heat transfer apparatuses of 2902A-2902N of FIG. 101.

[00337] With reference to FIGS. 111, 115, 116, 119, methods 3500, 3600, 3700, 3800 are provided for operating the heat transfer apparatuses 3000, 3100, 3200, 3300. The methods 3500, 3600, 3700, 3800 are similar in many respects to the methods discussed above. The methods 3500, 3600, 3700, 3800 will be discussed with respect to heat transfer apparatus 3000, but it will be appreciated that the methods 3500, 3600, 3700, 3800 may be utilized with the heat transfer apparatuses 3100, 3200, 3300 as well as other heat transfer apparatuses discussed above.

[00338] Regarding FIG. 111, when the heat transfer apparatus 3000 is powered up, a controller 3001 of the heat transfer apparatus 3000 begins a method 3500. At step 3502, the controller 3001 determines an initial operating mode for the heat transfer apparatus 3000 by evaluating logical operations 3504, 3506, 3508, 3510 using parameters 3580, 3582, 3584 (see FIG. 112) to select one of the operating modes 3501, 3503, 3505, 3507. The step 3502 involves calculating current CoiledB, which is compared with CoiledB set points for the different operating modes 3501, 3503, 3505, 3507.

[00339] Once the controller 3001 has determined the initial operating mode for the heat transfer apparatus 3000 at step 3502, the controller 3001 configures the heat transfer apparatus 3000 into the operating mode, i.e., operating mode 3501, 3503, 3505, or 3507. During operation of the heat transfer apparatus 3000, the controller periodically or in response to an event (e.g., a user input, a broken fan or pump, a sudden change increase in cooling load) evaluates the logical operations 3512-3522 to determine whether to reconfigure the heat transfer apparatus 3000 to a different operating mode.

[00340] Referring to FIG. 113, a table 3550 is provided having a column 3552 of the logical operations 3504-3510 of the method 3500, a column 3554 of conditions 3556 of the logical operations 3504-3510, and a column 3558 of initial operating modes 3501-3507 that are selected if the associated conditions 3556 are true.

[00341] With reference to FIG. 114, a table 3570 is provided having a column 3572 of logical operations 3512-3522, a column 3574 of current operating modes 3501-3507 of the heat transfer apparatus 3000, a column 3576 of conditions 3577 of the logical operations 3512-3522, and a column 3578 of the operating modes 3501-3507 that are selected if the associated conditions 3577 are true.

[00342] Regarding FIG. 115, a method 3600 is provided that is similar in many respects to the method 3500 and may be utilized by the controller 3001 to operate the heat transfer apparatus 3000. One difference between the methods 3500, 3600 is that the method 3600 begins at step 3602 and advances 3604 to operate the heat transfer apparatus 3000 in the operating mode 3501 anytime the heat transfer apparatus 3000 begins operating. In this manner, the controller 3001 always operates the heat transfer apparatus 3000 in the operating mode 3501 upon startup of the heat transfer apparatus 3000 which may be desirable in some embodiments.

[00343] After the heat transfer apparatus 3000 has started to operate in operating mode 3501, the controller 3001 evaluates logical operation 3512 to determine whether the controller 3001 should reconfigure the heat transfer apparatus 3000 to operating mode 3505. The controller 3001 evaluates logical operation 3512 in response to, for example, the passage of a predetermined period of time, a change in operating conditions, or a user input. The controller 3001 sequentially progresses between the operating modes 3501-3507 using logical operations 3512-3522 in a manner similar to the other methods discussed herein.

[00344] Regarding FIG. 116, the controller 3001 may utilize a method 3700 to select an initial operating condition 3701, 3703, 3705, 3707 upon startup of the heat transfer apparatus 3000 as well as to reconfigure the heat transfer apparatus 3000 throughout the operating modes 3701-3707 in response to changing conditions. The method 3700 includes determining at step 3702 an initial operating mode for the heat transfer apparatus 3000. The step 3702 includes evaluating logical operations 3704, 3706, 3708, 3710 using the parameters 3580, 3582, 3584 of FIG. 112 as well as CoilEDB set points for the operating modes 3701-3707.

- [00345] Regarding FIG. 117, a table 3750 is provided that includes a column 3752 of the logical operations 3704-3710, a column 3754 of conditions 3756 of the logical operations 3704-3710, and a column 3758 of operating modes 3760 that may be selected upon the conditions 3756 of the logical operations 3704-3710 being true.
- [00346] Once the controller 3001 has selected the initial operating mode 3701-3707, the controller 3001 continuously or periodically evaluates whether to reconfigure the heat transfer apparatus 3000 to a different one of the operating conditions 3701-3707 using the logical operations 3712-3724 of method 3700 and one or more of the parameters 3582, 3584.
- [00347] With reference to FIG. 118, a table 3770 is provided that includes a column 3772 of reference numerals of the logical operations 3712-3724, a column 3774 of current operating modes, a column 3776 of conditions 3778 of the logical operations 3712-3724, and a column 3780 of the operating modes 3701-3707 that are selected upon the conditions 3778 of the logical operations 3712-3724 being true. In this manner, the controller 3001 may progressively reconfigure the heat transfer apparatus 3000 to the various operating modes 3701-3707 as the operating conditions change.
- [00348] Regarding FIG. 119, a method 3800 is provided that is similar in many respects to the method 3700 discussed above. The method 3800 may be utilized by the controller 3001 to reconfigure the heat transfer apparatus 3000 between operating modes 3701-3707. One difference between the methods 3700, 3800 is that the method 3800 begins at step 3802 and utilizes logical operations 3804, 3806 to determine whether to start the heat transfer apparatus 3000 in either operating mode 3701 or operating mode 3703. Logical operation 3804 checks whether the air dry bulb is lower than a dry switch point. If so, the controller 3001 configures the heat transfer apparatus 3000 to operate in the operating mode 3701. If the air dry bulb is no lower than the dry switch point, the logical operation 3806 causes the controller 3001 to reconfigure the heat transfer apparatus 3000 to operate in the operating mode 3703.
- [00349] FIG. 120 is a state machine diagram of a method 4000 that may be used by a controller of one of the heat transfer apparatuses disclosed herein to control the heat transfer apparatus. The method 4000 is similar to the method 3500 discussed above and includes operating modes 4002, 4004, 4006. The method 4000 includes logical operations 4008 for determining an initial operating mode at step 4010 as well as changing between the operating modes 4002, 4004, 4006 during operation of the heat transfer apparatus. The controller evaluates the logical operations 4008 using associated parameters, such as dry

bulb temperature, relative humidity, process fluid return temperature, and process fluid flow rate.

[00350] One difference between the methods 3500, 4000 is that the method 4000 does not include a mode wherein the fluid cooler of the heat transfer apparatus is operating in a wet mode and the chiller of the heat transfer apparatus is off. Instead, the chiller of the heat transfer apparatus is used for trim cooling in modes 4004, 4006. The chiller of the heat transfer apparatus may be operated at a higher capacity in mode 4006 since the fluid cooler is operating in a wet mode whereas the fluid cooler operates in a dry mode in mode 4004.

[00351] Regarding FIG. 121, a method 4100 is provided that is similar in many respects to the method 4000. The method 4100 includes operating modes 4102, 4104, 4106 and logical operations 4108 that are utilized to change the heat transfer apparatus between the different operating modes 4102, 4104, 4106. Upon startup of the heat transfer apparatus, the heat transfer apparatus is operated in mode 4102. The controller subsequently evaluates the logical operations 4108 to sequentially progress through modes 4102, 4104, 4106. For example, if the heat transfer apparatus is operating in mode 4102, the controller evaluates the logical operation 4108A to decide whether to reconfigure the heat transfer apparatus to mode 4104.

[00352] Regarding FIG. 122, the heat transfer system 4200 is provided that is used to cool a process fluid from an industrial process inside of a building 4202, such as racks of computers. The system 4200 includes different types of central chiller plant modules 4204, 4206 that may be operated differently to provide different cooling capacities of the system 4200 as needed to handle the cooling load of the building 4202. The central chiller plant module 4204 includes fluid coolers 4210 that provide cooling for one or more chillers inside of the mechanical room 4212. The mechanical room 4212 may include, for example, a chiller, a heat exchanger, and/or a pump. The central chiller plant module 4206 includes open cooling towers 4214 that provide cooling for one or more chillers in a mechanical room 4216.

[00353] Regarding FIG. 123, a heat transfer apparatus 4300 is provided that includes a hybrid cooler 4302 and a chiller 4304 to reject heat from process fluid from a cooling load 4305. The hybrid cooler 4302 may be operated in dry or wet modes. In one embodiment, the hybrid cooler 4302 may be operable in dry, wet, or adiabatic modes. The heat transfer apparatus 4300 is shown as an integrated unit with the hybrid cooler 4302 and chiller 4304 provided within a housing 4306 of a module 4308. In other embodiments, such as the heat transfer apparatus of FIG. 146, the heat transfer apparatus 4300 may have a distributed configuration wherein the hybrid cooler 4302 and chiller 4304 are separate units.

[00354] Regarding FIG. 124, a heat transfer apparatus 4400 is provided that includes a hybrid cooler 4402, a chiller 4404, and a thermal energy storage 4406. The heat transfer apparatus 4400 may operate the hybrid cooler 4402 in dry, wet, or adiabatic modes. The thermal energy storage 4406 may be used to provide trim or supplemental heat transfer in combination with, or instead of, heat transfer provided by the chiller 4404. The thermal energy storage 4406 may include a phase change material tank. An example of a thermal energy storage is an ice thermal storage system.

[00355] Regarding FIG. 125, a heat transfer apparatus 4500 is provided as a first example of the heat transfer apparatus 4300. The heat transfer apparatus 4500 includes a chiller 4502 and a hybrid cooler 4504 to remove heat from a cooling load 4514. The hybrid cooler 4504 has a dry cooling coil 4506, a direct heat exchanger 4508, and a heat exchanger 4510. The heat exchanger 4510 transfers heat between glycol of a glycol loop 4512 associated with the cooling load 4514 and water of a water loop 4516 of the hybrid cooler 4504.

[00356] The direct heat exchanger 4508 includes heat transfer media, such as fill sheets and an evaporative liquid distribution system 4521 for providing water of the water loop 4516 to the heat transfer media. The liquid distribution system 4521 may include spray nozzles to spray water onto the fill sheets, a sump 4520 to collect water from the fill sheets, and a pump 4522 to pump fluid from the sump 4520 to the spray nozzles.

[00357] The hybrid cooler 4504 has a fan 4507, such as one or more fans, to generate airflow relative to the dry cooling coil 4506 and the fill sheets of the direct heat exchanger 4508. Air traveling through the direct heat exchanger 4508 cools the water distributed onto the fill sheets by the evaporative liquid distribution system 4521. The dry cooling coil 4506 and the direct heat exchanger 4508 have parallel airflow paths as shown in FIG. 125. In another embodiment, the dry cooling coil 4506 and direct heat exchanger 4508 are arranged in series with the same air stream sequentially cooling the direct heat exchanger 4508 and the dry cooling coil 4506.

[00358] The hybrid cooler 4504 has the capability to utilize the dry cooling coil 4506, the direct heat exchanger 4508, or both. The heat transfer apparatus 4500 operates the dry cooling coil 4506 when the hybrid cooler 4504 is operating in a dry mode, operates the direct heat exchanger 4508 when the hybrid cooler 4504 is operating in a wet mode, and operates both the dry cooling coil 4506 and direct heat exchanger 4508 when the hybrid cooler 4504 is operating in a hybrid mode. The hybrid cooler 4504 has valves 4530, 4532 to selectively bypass process fluid around the dry cooling coil 4506 and/or the heat exchanger

4510 according to the mode of the hybrid cooler 4504 set by a controller 4529 of the heat transfer apparatus 4500.

[00359] In FIG. 125, the heat transfer apparatus 4500 is shown in a first, water saver mode wherein the hybrid cooler 4504 is in the dry mode and the heat transfer apparatus 4500 utilizes free cooling. More specifically, valves 4540, 4542 bypass process fluid from the cooling load 4514 around the chiller 4502, the valve 4530 directs the process fluid through the dry cooling coil 4506, and the valve 4532 bypasses the process fluid around the heat exchanger 4510. The dry cooling coil 4506 transfers heat to the airflow generated by the fan 4507. In this manner, the dry cooling coil 4506 provides cooling for the process fluid from the cooling load 4514.

[00360] Regarding FIG. 126, the heat transfer apparatus 4500 is shown in a second, energy saver mode wherein the hybrid cooler 4504 operates in a wet mode and the chiller 4502 is off. The heat transfer apparatus 4500 in the second mode utilizes free cooling to reject heat from process fluid received from the cooling load 4514.

[00361] In the second mode, the valves 4540, 4542 bypass process fluid around the chiller 4502 and the valve 4530 directs process fluid around the dry cooling coil 4506. The valve 4532 directs fluid through the heat exchanger 4510 and the pump 4522 is operated to circulate water in the water loop 4516. Further, the fan 4507 directs airflow through the fill of the direct heat exchanger 4508. The water of the water loop 4516 absorbs heat from the glycol loop 4512 at the heat exchanger 4510, is sprayed onto the fill of the direct heat exchanger 4508, loses heat to the airflow directed through the fill, and is collected in sump 4520 before being pumped to the heat exchanger 4510.

[00362] Regarding FIG. 127, the heat transfer apparatus 4500 is shown in a third, hybrid cooling mode wherein the hybrid cooler 4504 operates in a hybrid mode and utilizes free cooling to reject heat from the cooling load 4514. More specifically, in the third mode the valves 4540, 4542 bypass process fluid around the chiller 4502, valves 4530, 4532 direct process fluid through the dry cooling coil 4506 and heat exchanger 4510, and pump 4522 circulates water in the water loop 4516. Further, the fan 4507 directs airflow through the fill of the direct heat exchanger 4508 and the dry cooling coil 4506.

[00363] Regarding FIG. 128, the heat transfer apparatus 4500 is shown in a fourth, water saver trim cooling mode that utilizes dry cooling and the chiller 4502. More specifically, in the fourth mode, the valves 4540, 4542 direct at least a portion of the process fluid through the chiller 4502, the valve 4530 directs the process fluid through the dry cooling coil 4506, and the valve 4532 bypasses the process fluid around the heat exchanger 4510. The chiller

4502 has a condenser 4550 that transfers heat to process fluid directed to the condenser 4550 by the valve 4540. The chiller 4502 has an evaporator 4552 that removes heat from process fluid directed to the evaporator 4522 by the valve 4542.

[00364] Regarding FIG. 129, the heat transfer apparatus 4500 is shown in a fifth, energy saver trim cooling mode that utilizes wet cooling and the chiller 4502. More specifically, the valves 4540, 4542 direct at least a portion of the process fluid through the chiller 4502, the valve 4530 bypasses process fluid around the dry cooling coil 4506, and the valve 4532 directs the process fluid to the heat exchanger 4510. The pump 4522 directs water from the sump 4520 to the heat exchanger 4510 to absorb heat from the process fluid and onto the fill of the direct heat exchanger 4508. The water sprayed onto the fill of the direct heat exchanger 4508 is cooled by airflow through the heat exchanger 4508 and collected in the sump 4520. The valve 4542 directs at least a portion of the cooled process fluid from the heat exchanger 4510 to the evaporator 4552 of the chiller 4502.

[00365] Regarding FIG. 130, the heat transfer apparatus 4500 is shown in a sixth, maximum cooling mode wherein the dry cooling coil 4506, direct heat exchanger 4508, heat exchanger 4510, and chiller 4502 are all utilized to cool process fluid from the cooling load 4514.

[00366] With reference to FIG. 131, the heat transfer apparatus 4600 is provided that is a second example of the heat transfer apparatus 4300 provided above. The heat transfer apparatus 4600 includes a chiller 4602 and a hybrid cooler 4604. The heat transfer apparatus 4600 is similar in many respects to the heat transfer apparatus 4500 discussed above.

[00367] One difference between the heat transfer apparatuses 4500, 4600 is that the hybrid cooler 4604 of the heat transfer apparatus 4600 has a valve 4608 that can direct process fluid to a heat exchanger 4610, a dry cooling coil 4612, or both the heat exchanger 4610 and the dry cooling coil 4612. The hybrid cooler 4604 further includes a direct heat exchanger 4614 that may include fill, a sump 4616, and a pump 4618. The direct heat exchanger 4614 utilizes a water loop 4620 to remove heat from a glycol loop 4622 of the heat transfer apparatus 4600 via the heat exchanger 4610.

[00368] In FIG. 131, the apparatus 4600 is shown in a first, water saver mode wherein only the dry cooling coil 4612 removes heat from the process fluid from a cooling load 4630. In FIG. 132, the apparatus 4600 is shown in a second, energy saver mode wherein the direct heat exchanger 4614 and heat exchanger 4610 remove heat from the process fluid of the cooling load 4630. In FIG. 133, the heat transfer apparatus 4600 is shown in a third, hybrid mode wherein the valve 4608 directs process fluid to both the heat exchanger 4610 and the

dry cooling coil 4612. In the third, hybrid mode, valves 4640, 4642 direct process fluid around the chiller 4602.

[00369] Regarding FIG. 134, the heat transfer apparatus 4600 is shown in a fourth, water saver trim cooling mode wherein the valves 4640, 4642 direct at least a portion of the process fluid through the chiller 4602 and the valve 4608 directs process fluid to the dry cooling coil 4612.

[00370] Regarding FIG. 135, the heat transfer apparatus 4600 is shown in a fifth, energy saver trim cooling mode wherein the chiller 4602, heat exchanger 4610, and direct heat exchanger 4614 are operated to remove heat from the process fluid. The valves 4640, 4642 direct at least a portion of the process fluid to the chiller 4602 and the valve 4608 directs the process fluid to the heat exchanger 4610. The heat exchanger 4610 transfers heat from the process fluid to the water loop 4620 via the heat exchanger 4610.

[00371] Regarding FIG. 136, the heat transfer apparatus 4600 is shown in a sixth, maximum cooling mode wherein the chiller 4602, heat exchanger 4610, direct heat exchanger 4614, and dry cooling coil 4612 operate to remove heat from the process fluid of the cooling load 4630. More specifically, the valves 4640, 4642 direct at least a portion of the process fluid to the chiller 4602 and the valve 4608 direct process fluid to both the heat exchanger 4610 and the dry cooling coil 4612. In this manner, the airflow across the direct heat exchanger 4614 and the dry cooling coil 4612 removes heat from the heat transfer apparatus 4600 in addition to the mechanical cooling provided by the chiller 4602.

[00372] Regarding FIG. 137, a heat transfer apparatus 4700 is provided that is similar in many respects to the heat transfer apparatuses 4500, 4600 discussed above. One difference is that the heat transfer apparatus 4700 includes a hybrid cooler 4702 with an adiabatic cooler 4704 upstream in an airflow path from a dry cooling coil 4706. The adiabatic cooler 4704 includes one or more precooling media such as one or more precooling pads 4708, a pump 4710 to pump water onto the precooling pads 4708, and a sump 4712 to collect water from the precooling pads 4708. The adiabatic cooler 4704 includes a water loop 4713 that recirculates the water between the sump 4712 and the precooling pads 4708. In another embodiment, the adiabatic cooler 4704 is a once-through system wherein water does not recirculate in the water loop 4713. In the once-through system, the sump 4712 is not utilized. The once-through adiabatic cooler 4704 may be used, for example, in an embodiment that utilizes stacked adiabatic coolers.

[00373] The hybrid cooler 4702 further includes a direct heat exchanger 4714, a sump 4716, a pump 4718, and a heat exchanger 4720. The direct heat exchanger has a water loop 4715

that is distinct from the water loop 4713. In another embodiment, the water loops 4713, 4715 may be connected and share water.

[00374] The hybrid cooler 4702 further includes valves 4722, 4724 to selectively direct process fluid to the dry cooling coil 4706, the heat exchanger 4720, or both the dry cooling coil 4706 and heat exchanger 4720. The heat transfer apparatus 4700 further includes a chiller 4730 that may be used instead of, or in addition to, the hybrid cooler 4702 to remove heat from the process fluid.

[00375] In FIG. 137, the heat transfer apparatus 4700 is shown in a mode wherein the dry cooling coil 4706, pre-cooling pad 4708, heat exchanger 4720, direct heat exchanger 4714, and chiller 4730 are operated to remove heat from the process fluid of the cooling load 4750. In another mode, the pump 4710 is turned off and no adiabatic precooling is performed on the air upstream of the dry cooling coil 4706, but the dry cooling coil 4706, heat exchanger 4720, direct heat exchanger 4714, and chiller 4730 are operated to remove heat from the process fluid of the cooling load 4750.

[00376] Regarding FIG. 138, a heat transfer apparatus 4800 is provided that is similar to the heat transfer apparatus 4700 discussed above and includes a hybrid cooler 4802. One difference is that the hybrid cooler 4802 has a heat exchanger 4804 and a dry cooling coil 4806 in parallel. The hybrid cooler 4802 has a valve 4810 for directing the process fluid to the heat exchanger 4804, the dry cooling coil 4806, or both the heat exchanger 4804 and the dry cooling coil 4806.

[00377] Regarding FIG. 139, the heat transfer apparatus 4900 is provided that is a fifth example of the heat transfer apparatus 4300 discussed above. The heat transfer apparatus 4900 has a hybrid cooler 4902 with a dry cooling coil 4904, an indirect heat exchanger 4906, a direct heat exchanger 4908, and an evaporative liquid distribution system 4910 with a water loop 4911. The dry cooling coil 4904 may include one or more tubes and fins connected to the one or more tubes. The hybrid cooler 4902 has valves 4912, 4914, 4915, 4917 that are operable to direct process fluid of a cooling load 4916 to a chiller 4918, dry cooling coil 4904, indirect heat exchanger 4906, or a combination thereof.

[00378] Regarding FIGS. 140-142, the hybrid cooler 4902 of the heat transfer apparatus 4900 is operable in an energy saver mode, an adiabatic mode, and water saver mode. More specifically, in the energy saver mode, the hybrid cooler 4902 has a fan 4930 that directs air through the direct heat exchanger 4908, the indirect heat exchanger 4906, and a dry cooling coil 4904. The evaporative liquid distribution system 4910 distributes an evaporative liquid, such as water, onto the indirect heat exchanger 4906 to absorb heat from the indirect heat

exchanger 4906. The water falls onto the direct heat exchanger 4908, is cooled by airflow through the direct heat exchanger 4908, and is collected in a sump 4932 of the evaporative liquid distribution system 4910.

[00379] With reference to FIG. 141, in an adiabatic mode, the evaporative liquid distribution system 4910 sprays water onto the indirect heat exchanger 4906 which is not currently receiving process fluid. The water falls from the indirect heat exchanger 4906 onto the direct heat exchanger 4908. The water on the direct heat exchanger 4908 adiabatically cools the air traveling through the direct heat exchanger 4908 before the air reaches the dry cooling coil 4904, which improves the heat transfer efficiency of the dry cooling coil 4904.

[00380] Regarding FIG. 142, in the water saver mode, the indirect heat exchanger 4906 and the dry cooling coil 4904 receive process fluid and transfer heat from the process fluid to airflow generated by the fan 4930. Further, the evaporative liquid distribution system 4910 does not spray liquid onto the indirect heat exchanger 4906 to limit water consumption.

[00381] Regarding FIG. 143, a heat transfer apparatus 5000 is provided that is similar in many respects to the heat transfer apparatus 4900 discussed above. The heat transfer apparatus 5000 has a hybrid cooler 5002 with a dry cooling coil 5004, a direct heat exchanger 5006, and an evaporative liquid distribution system 5008 for distributing water onto the dry cooling coil 5004. Water distributed onto the dry cooling coil 5004 absorbs heat from the dry cooling coil 5004 and travels to the direct heat exchanger 5006, which exchanges heat from the water to air traveling through the direct heat exchanger 5006. The hybrid cooler 5002 has a valve 5010 configured to direct process fluid toward, or bypass process fluid around, the dry cooling coil 5004. Further, the heat transfer apparatus 5000 has valves 5020, 5022 configured to direct process fluid to, or bypass fluid around, the chiller 5012. In FIG. 143, the heat transfer apparatus 5000 is shown in a mode wherein the chiller 5012 and dry cooling coil 5004 reject heat from the process fluid of cooling load 5014, while the direct heat exchanger 5006 rejects heat from water distributed onto the dry cooling coil 5004.

[00382] Regarding FIG. 144, a heat transfer apparatus 5100 is provided that is another example of the heat transfer apparatus 4300 discussed above. The heat transfer apparatus 5100 has a hybrid cooler 5102 with a dry cooling coil 5104 and a direct heat exchanger 5106. The heat transfer apparatus 5100 has a glycol loop 5107 that receives water as a process fluid from a cooling load 5112. The hybrid cooler 5102 has valves 5108, 5110 that are operable to selectively direct the water through one, both, or neither of the dry cooling coil 5104 and direct heat exchanger 5106 according to the operating mode of the heat transfer

apparatus 5100. The heat transfer apparatus 5100 further includes valves 5120, 5122 that are operable to selectively direct some, all, or none of the water through a chiller 5114 of the heat transfer apparatus 5100 according to the operating mode of the heat transfer apparatus 5100.

[00383] Regarding FIG. 145, a heat transfer apparatus 5200 is provided that is similar to the heat transfer apparatus 5100 and has a water loop 5201 with a hybrid cooler 5202 and a chiller 5210. The hybrid cooler 5202 has a direct heat exchanger 5204, a dry cooling coil 5206, and a valve 5208 operable to direct water to one or more of the direct heat exchanger 5204 and the dry cooling coil 5206. In this manner, the direct heat exchanger 5204 and/or the dry cooling coil 5206 may be used in conjunction with a chiller 5210 of the heat transfer apparatus 5200 according to the operating mode of the heat transfer apparatus 5200.

[00384] With reference to FIG. 146, a heat transfer apparatus 5300 is provided that is another example of the heat transfer apparatus 4300. Rather than having all of the components of the heat transfer apparatus 5300 integrated within a single unit, the heat transfer apparatus 5300 has a distributed arrangement of a hybrid cooler 5302 including a dry cooler 5304, a direct heat exchanger 5306, a heat exchanger 5308, and valves 5310, 5311 for selectively directing process fluid to the dry cooler 5304 and/or the heat exchanger 5308. The heat transfer apparatus 5300 also includes a chiller 5312 and a heat exchanger 5314.

[00385] The heat exchanger 5314 separates a glycol loop 5316 of the heat transfer apparatus 5300 from a water loop 5320 of a cooling load 5318. In some embodiments, it may be desirable to use water inside of a building containing the cooling load 5318 since water may be easier to clean up in the event of a spill or leak of the water loop 5320. The direct heat exchanger 5306 is an open cooling tower and has an open tower water loop 5322.

[00386] Regarding FIG. 147, a controller of a heat transfer apparatus having a hybrid cooler as disclosed herein may utilize a method 5400 for controlling the heat transfer apparatus. The controller evaluates logical operations 5408 using parameters 5410 to select an initial operating load as well as to change the heat transfer apparatus between the operating modes 5402, 5404, 5406 during operation of the heat transfer apparatus.

[00387] Regarding FIG. 148, a controller of a heat transfer apparatus having a hybrid cooler as disclosed herein may utilize a method 5500 to control operation of the heat transfer apparatus. The method 5500 includes the heat transfer apparatus starting in mode 5502 upon startup of the heat transfer apparatus. In mode 5502, the heat transfer apparatus utilizes free cooling with only a dry cooling coil of the hybrid cooler. The controller

subsequently evaluates logical operations 5504 to change the heat transfer apparatus between the modes 5502, 5505, 5506 during operation of the heat transfer apparatus.

[00388] Regarding FIG. 149, a controller of a heat transfer apparatus having a hybrid cooler may utilize a method 5600 to change operation of the heat transfer apparatus between operating modes 5602, 5604, 5606, 5608, 5610, 5612. The controller evaluates logical operations 5620 using parameters 5622 to select an initial operating mode as well as to change the heat transfer apparatus between the operating modes 5602, 5604, 5606, 5608, 5610, 5612 during operation of the heat transfer apparatus.

[00389] Regarding FIG. 150, a controller of a heat transfer apparatus having a hybrid cooler may utilize method 5700 to control operation of the heat transfer apparatus. The controller evaluates logical operations 5702 to select an initial one of the operating modes 5704, 5706. The logical operations 5702 include a determination of whether an air dry bulb temperature is lower than a dry operation switch point. The controller subsequently evaluates logical operations 5708 to change the heat transfer apparatus between operating modes 5710, 5712, 5714, 5716.

[00390] Regarding FIGS. 151, 152, 153, 154, the heat transfer apparatuses 5800, 5820, 5840, 5860 are provided that are similar to heat transfer apparatuses discussed above. The heat transfer apparatuses 5800, 5820, 5840, 5860 have heat exchangers 5802, 5822, 5844, 5864 that separate chilled water loops 5804, 5824, 5846, 5866 from glycol loops 5808, 5828, 5848, 5868.

[00391] Regarding FIGS. 155-159, heat transfer apparatuses 5900, 5920, 5940, 5960, 5980 are provided in many respects to heat transfer apparatuses discussed above. One difference is that the heat transfer apparatuses 5900, 5920, 5940, 5960, 5980 each have a bypass, such as valves 5902, 5922, 5942, 5962, 5982, that are operable to selectively direct process fluid to or around fluid coolers 5904, 5924, 5944, 5964, 5984. The valves 5902, 5922, 5942, 5962, 5982 are operable to direct some, all, or none of the process fluid to the respective fluid cooler 5904, 5924, 5944, 5964, 5984 according to the operating mode of the heat transfer apparatus 5900, 5920, 5940, 5960, 5980. The fluid cooler 5904, 5924, 5944, 5964, 5984 may be bypassed for example when the ambient temperature is low and may result in process fluid below a threshold temperature being returned to the associated cooling load.

[00392] Uses of singular terms such as “a,” “an,” are intended to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms. It is intended that the phrase “at least one of” as used herein be interpreted in the

disjunctive sense. For example, the phrase “at least one of A and B” is intended to encompass A, B, or both A and B.

[00393] While there have been illustrated and described particular embodiments of the present invention, it will be appreciated that numerous changes and modifications will occur to those skilled in the art, and it is intended for the present invention to cover all those changes and modifications which fall within the scope of the appended claims.

CLAIMS

What is claimed is:

1. A heat transfer apparatus for an industrial process that requires process fluid at a process fluid set temperature, the heat transfer apparatus comprising:
 - a process fluid heat exchange circuit to receive a process fluid at a temperature different than the process fluid set temperature and provide the process fluid at the process fluid set temperature, the process fluid heat exchange circuit comprising:
 - a mechanical cooler having a hot side heat exchanger and a cold side heat exchanger;
 - a hybrid cooler to receive process fluid from the hot side heat exchanger of the mechanical cooler and provide cooled process fluid to the cold side heat exchanger of the mechanical cooler;
 - an airflow generator operable to cause air to contact the hybrid cooler;
 - the hybrid cooler comprising a direct heat exchanger and an indirect heat exchanger, the hybrid cooler having a dry mode wherein the indirect heat exchanger transfers heat from the process fluid to the air and a hybrid mode wherein the indirect heat exchanger and the direct heat exchanger transfer heat from the process fluid to the air;
 - the process fluid heat exchange circuit having a plurality of modes including:
 - a first mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the dry mode;
 - a second mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the dry mode;
 - a third mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the hybrid mode; and
 - a fourth mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the hybrid mode; and
 - a controller operatively connected to the process fluid heat exchange circuit, the controller configured to operate the process fluid heat exchange circuit in one of the plurality of modes based at least in part upon a determination of a thermal duty of the heat transfer apparatus.
2. The heat transfer apparatus of claim 1 wherein, with the process fluid heat exchange circuit in the first mode and the second mode, the process fluid bypasses the direct heat exchanger.

3. The heat transfer apparatus of claim 1 wherein the hybrid cooler has a wet mode wherein the direct heat exchanger transfers heat from the process fluid to the air;
wherein the plurality of modes of the process fluid heat exchange circuit includes:
a fifth mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the wet mode; and
a sixth mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the wet mode.
4. The heat transfer apparatus of claim 3 wherein, with the process fluid heat exchange circuit in the fifth mode and the sixth mode, the process fluid bypasses the indirect heat exchanger.
5. The heat transfer apparatus of claim 1 wherein the direct heat exchanger comprises:
a heat exchanger to transfer heat between the process fluid and a liquid;
a heat transfer medium; and
a liquid distribution system operable to distribute the liquid onto the heat transfer medium.
6. The heat transfer apparatus of claim 5 wherein the heat transfer medium comprises fill sheets and/or fill blocks.
7. The heat transfer apparatus of claim 1 wherein the hybrid cooler further comprises an adiabatic cooler operable to cool the air upstream of the indirect heat exchanger.
8. The heat transfer apparatus of claim 1 wherein the hybrid cooler has a wet mode wherein the direct heat exchanger transfers heat from the process fluid to the air;
wherein the plurality of modes of the process fluid heat exchange circuit includes:
a fifth mode wherein the process fluid bypasses the mechanical cooler and the hybrid cooler is in the wet mode; and
a sixth mode wherein the mechanical cooler removes heat from the process fluid and the hybrid cooler is in the wet mode;
wherein the hybrid cooler comprises:
a secondary indirect heat exchanger;
a heat transfer medium below the secondary indirect heat exchanger; and

a liquid distribution system operable to distribute liquid onto the secondary indirect heat exchanger and the heat transfer medium therebelow with the hybrid cooler in either the wet mode or the hybrid mode;

wherein, with the process fluid heat exchange circuit in the first mode and the second mode, the hybrid cooler is in the dry mode and the secondary indirect heat exchanger transfers heat between the process fluid and the air;

wherein, with the process fluid heat exchange circuit in the fifth mode and the sixth mode, the hybrid cooler is in the wet mode and the liquid distribution system distributes the liquid onto the secondary indirect heat exchanger and the heat exchange medium; and

wherein, with the process fluid heat exchange circuit in the third mode and the fourth mode, the hybrid cooler is in the hybrid mode and the liquid distribution system distributes liquid onto the secondary indirect heat exchanger and the heat exchange medium.

9. The heat transfer apparatus of claim 1 wherein the direct heat exchanger comprises a heat transfer medium below the indirect heat exchanger and a liquid distribution system operable to distribute a liquid onto the indirect heat exchanger so that the liquid travels from the indirect heat exchanger toward the direct heat exchanger; and

wherein, with the process fluid heat exchange circuit in the third mode, the liquid distribution system distributes liquid onto the indirect heat exchanger; and

wherein, with the process fluid heat exchange circuit in the first mode, the liquid distribution system distributes less liquid onto the indirect heat exchanger than in the third mode.

10. The heat transfer apparatus of claim 1 wherein the process fluid heat exchange circuit further comprises a heat exchanger operatively connected to a cooling load;

wherein the process fluid comprises a first process fluid and a second process fluid;

wherein the process fluid heat exchange circuit comprises a first process fluid loop that includes the mechanical cooler, the hybrid cooler, and a first portion of the heat exchanger; and

a second process fluid loop including the cooling load and a second portion of the heat exchanger, the heat exchanger configured to transfer heat between the first process fluid and the second process fluid.

11. The heat transfer apparatus of claim 1 wherein the process fluid heat exchange circuit does not include a thermal energy storage.

12. The heat transfer apparatus of claim 1 wherein the determination of the thermal duty of the heat transfer apparatus comprises a determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature.
13. The heat transfer apparatus of claim 1 wherein the determination of the thermal duty of the heat transfer apparatus is based at least in part upon a temperature of process fluid supplied by the process fluid heat exchange circuit, the process fluid set temperature, and a control range parameter.
14. The heat transfer apparatus of claim 1 wherein the controller is configured to operate the process fluid heat exchange circuit in one of the operating modes upon startup of the heat transfer apparatus based at least in part upon a dry bulb temperature and dry bulb temperature set points associated with the operating modes.
15. The heat transfer apparatus of claim 1 further comprising an outer structure; and wherein the mechanical cooler, the direct heat exchanger, and the indirect heat exchanger are in the outer structure.
16. The heat transfer apparatus of claim 1 wherein the mechanical cooler comprises a chiller; wherein the hot side heat exchanger comprises a condenser; and wherein the cold side heat exchanger comprises an evaporator.
17. The heat transfer apparatus of claim 1 wherein the process fluid heat exchange circuit in the first mode and the third mode is configured to cause the process fluid to bypass the mechanical cooler by:
directing the process fluid around the mechanical cooler; or
not operating the mechanical cooler while the process fluid flows through the mechanical cooler.
18. A heat transfer apparatus for an industrial process that requires process fluid at a process fluid set temperature, the heat transfer apparatus comprising:
a process fluid heat exchange circuit to receive a process fluid at a temperature different than the process fluid set temperature, the process fluid heat exchange circuit comprising:

a mechanical cooler having a hot side heat exchanger and a cold side heat exchanger;

a fluid cooler to receive the process fluid from the hot side heat exchanger and provide cooled process fluid to the cold side heat exchanger;

an airflow generator operable to cause air to contact the fluid cooler;

the fluid cooler having a wet mode wherein the fluid cooler utilizes a liquid to facilitate heat transfer from the process fluid to the air and a dry mode wherein the fluid cooler utilizes less liquid to facilitate heat transfer from the process fluid to the air than in the wet mode;

the process fluid heat exchange circuit operable in a plurality of modes including:

a first mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the dry mode thereof removes heat from the process fluid;

a second mode wherein the mechanical cooler and the fluid cooler in the dry mode thereof remove heat from the process fluid;

a third mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the wet mode thereof removes heat from the process fluid; and

a fourth mode wherein the mechanical cooler and the fluid cooler in the wet mode thereof remove heat from the process fluid; and

a controller operatively connected to the process fluid heat exchange circuit, the controller configured to change the process fluid heat exchange circuit between the operating modes based at least in part upon a determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature.

19. The heat transfer apparatus of claim 18 wherein the determination of the whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature is based at least in part upon a temperature of the process fluid supplied by the process fluid heat exchange circuit, the process fluid set temperature, and a control range parameter.

20. The heat transfer apparatus of claim 19 wherein the controller, with the process fluid heat exchange circuit in the first mode, is configured to change the process fluid heat exchange circuit to the second mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.

21. The heat transfer apparatus of claim 19 wherein the controller has an energy saving mode wherein the controller, with the process fluid heat exchange circuit in the second mode, is configured to change the process fluid heat exchange circuit to the third mode based at least in part upon a dry bulb temperature satisfying a dry switch point condition.
22. The heat transfer apparatus of claim 19 wherein the controller, with the process fluid heat exchange circuit in the second mode, is configured to change the process fluid heat exchange circuit to the third mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.
23. The heat transfer apparatus of claim 19 wherein the controller, with the process fluid heat exchange circuit in the third mode, is configured to change the process fluid heat exchange circuit to the fourth mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.
24. The heat transfer apparatus of claim 19 wherein the controller is configured to change the process fluid heat exchange circuit from the fourth mode to the third mode, change the process fluid heat exchange circuit from the third mode to the second mode, or change the process fluid heat exchange circuit from the second mode to the first mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being less than a difference between the process fluid supply temperature and the control range parameter.
25. The heat transfer apparatus of claim 19 wherein the controller has an energy saving mode and a water saving mode; and
wherein the control range parameter comprises a first control range parameter for the energy saving mode and a different, second control range parameter for the water saving mode.
26. The heat transfer apparatus of claim 18 wherein the controller is configured to operate the process fluid heat exchange circuit in the first, second, third, or fourth mode based at least in part upon a dry bulb temperature and dry bulb temperature set points associated with the first, second, third, and fourth modes.

27. The heat transfer apparatus of claim 26 wherein the fluid cooler comprises an indirect heat exchanger and an adiabatic cooler operable to cool air upstream of the indirect heat exchanger; and
wherein the dry bulb temperature comprises a dry bulb temperature of the air after the adiabatic cooler and before the indirect heat exchanger.
28. The heat transfer apparatus of claim 18 wherein the wherein the controller is configured to select one of the operating modes for initial operation of the process fluid heat exchange circuit based at least in part upon a temperature of the air, a relative humidity of the air, a return temperature of the process fluid, and the flow rate of the process fluid.
29. The heat transfer apparatus of claim 18 wherein the determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature is based at least in part upon:
a dry bulb temperature ; and
a threshold dry bulb temperature for operating the fluid cooler in the wet mode.
30. The heat transfer apparatus of claim 18 wherein the fluid cooler comprises an indirect heat exchanger and an adiabatic cooler operable to cool air upstream of the indirect heat exchanger.
31. The heat transfer apparatus of claim 18 wherein the fluid cooler comprises a hybrid cooler having a direct heat exchanger and an indirect heat exchanger;
wherein, with fluid cooler in the wet mode, the process fluid bypasses the indirect heat exchanger and the direct heat exchanger removes heat from the process fluid;
wherein, with the fluid cooler in the dry mode, the process fluid bypasses the direct heat exchanger and the indirect heat exchanger removes heat from the process fluid;
wherein the fluid cooler has a hybrid mode wherein the direct heat exchanger and the indirect heat exchanger remove heat from the process fluid.
32. The heat transfer apparatus of claim 18 further comprising an outer structure; and
wherein the mechanical cooler and the fluid cooler are in the outer structure.
33. The heat transfer apparatus of claim 18 wherein the mechanical cooler comprises a chiller;
wherein the hot side heat exchanger comprises a condenser; and
wherein the cold side heat exchanger comprises an evaporator.

34. The heat transfer apparatus of claim 18 wherein the process fluid heat exchange circuit further comprises a heat exchanger for being operatively connected to a cooling load;
wherein the process fluid comprises a first process fluid and a second process fluid;
wherein the process fluid heat exchange circuit comprises a first process fluid loop that includes the mechanical cooler, the fluid cooler, and a first portion of the heat exchanger; and
a second process fluid loop including the cooling load and a second portion of the heat exchanger, the heat exchanger configured to transfer heat between the first process fluid and the second process fluid.
35. The heat transfer apparatus of claim 18 wherein the fluid cooler comprises a hybrid cooler having a direct heat exchanger and an indirect heat exchanger;
wherein, with the fluid cooler in the dry mode, the process fluid bypasses the direct heat exchanger and the indirect heat exchanger removes heat from the process fluid;
wherein, with the fluid cooler in the wet mode, the process fluid bypasses the indirect heat exchanger and the direct heat exchanger removes heat from the process fluid;
wherein the fluid cooler has a hybrid mode wherein the direct heat exchanger and the indirect heat exchanger remove heat from the process fluid;
wherein the process fluid heat exchange circuit has a fifth mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler is in the hybrid mode; and
wherein the process fluid heat exchange circuit has a sixth mode wherein the mechanical cooler and the fluid cooler in the hybrid mode thereof remove heat from the process fluid.
36. A heat transfer apparatus for an industrial process that requires process fluid at a process fluid set temperature, the heat transfer apparatus comprising:
a process fluid heat exchange circuit to receive a process fluid at a temperature different than the process fluid set temperature, the process fluid heat exchange circuit comprising:
a mechanical cooler having a hot side heat exchanger and a cold side heat exchanger;
a fluid cooler operable to receive the process fluid from the hot side heat exchanger and provide cooled process fluid to the cold side heat exchanger;
an airflow generator operable to cause air to contact the fluid cooler;

the fluid cooler having a wet mode wherein the fluid cooler utilizes a liquid to facilitate heat transfer from the process fluid to the air and a dry mode wherein the fluid cooler utilizes less liquid to facilitate heat transfer from the process fluid to the air than in the wet mode;

the process fluid heat exchange circuit operable in a plurality of modes including:

a first mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the dry mode thereof removes heat from the process fluid;

a second mode wherein the mechanical cooler and the fluid cooler in the dry mode thereof remove heat from the process fluid;

a third mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler in the wet mode thereof removes heat from the process fluid; and

a fourth mode wherein the mechanical cooler and the fluid cooler in the wet mode thereof remove heat from the process fluid; and

a controller operatively connected to the process fluid heat exchange circuit, the controller configured to change the process fluid heat exchange circuit between the operating modes based at least in part upon a determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature; and

wherein the determination of the whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature is based at least in part upon a temperature of the process fluid supplied by the process fluid heat exchange circuit, the process fluid set temperature, and a control range parameter.

37. The heat transfer apparatus of claim 36 wherein the controller, with the process fluid heat exchange circuit in the first mode, is configured to change the process fluid heat exchange circuit to the second mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.

38. The heat transfer apparatus of claim 36 wherein the controller has an energy saving mode wherein the controller, with the process fluid heat exchange circuit in the second mode, is configured to change the process fluid heat exchange circuit to the third mode based at least in part upon a dry bulb temperature satisfying a dry switch point condition.

39. The heat transfer apparatus of claim 36 wherein the controller, with the process fluid heat exchange circuit in the second mode, is configured to change the process fluid heat exchange circuit

to the third mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.

40. The heat transfer apparatus of claim 36 wherein the controller, with the process fluid heat exchange circuit in the third mode, is configured to change the process fluid heat exchange circuit to the fourth mode based at least in part upon the temperature of the process fluid supplied by the process fluid heat exchange circuit being greater than a sum of the process fluid set temperature and the control range parameter.

41. The heat transfer apparatus of claim 36 wherein the controller is configured to change the process fluid heat exchange circuit from the fourth mode to the third mode, change the process fluid heat exchange circuit from the third mode to the second mode, or change the process fluid heat exchange circuit from the second mode to the first mode based at least in part upon the process fluid supplied by the process fluid heat exchange circuit being less than a difference between the process fluid supply temperature and the control range parameter.

42. The heat transfer apparatus of claim 36 wherein the controller has an energy saving mode and a water saving mode; and
wherein the control range parameter comprises a first control range parameter for the energy saving mode and a different, second control range parameter for the water saving mode.

43. The heat transfer apparatus of claim 36 wherein the controller is configured to operate the process fluid heat exchange circuit in the first, second, third, or fourth mode based at least in part upon a dry bulb temperature and dry bulb temperature set points associated with the first, second, third, and fourth modes.

44. The heat transfer apparatus of claim 43 wherein the fluid cooler comprises an indirect heat exchanger and an adiabatic cooler operable to cool air upstream of the indirect heat exchanger; and
wherein the dry bulb temperature comprises a dry bulb temperature of the air after the adiabatic cooler and before the indirect heat exchanger.

45. The heat transfer apparatus of claim 36 wherein the wherein the controller is configured to select one of the operating modes for initial operation of the process fluid heat exchange circuit

based at least in part upon a temperature of the air, a relative humidity of the air, a return temperature of the process fluid, and the flow rate of the process fluid.

46. The heat transfer apparatus of claim 36 wherein the determination of whether the process fluid heat exchange circuit is able to provide the process fluid at the process fluid set temperature is based at least in part upon:

- a dry bulb temperature; and
- a threshold dry bulb temperature for operating the fluid cooler in the wet mode.

47. The heat transfer apparatus of claim 36 wherein the fluid cooler comprises an indirect heat exchanger and an adiabatic cooler operable to cool air upstream of the indirect heat exchanger.

48. The heat transfer apparatus of claim 36 wherein the fluid cooler comprises a hybrid cooler having a direct heat exchanger and an indirect heat exchanger;

- wherein, with fluid cooler in the wet mode, the process fluid bypasses the indirect heat exchanger and the direct heat exchanger removes heat from the process fluid;

- wherein, with the fluid cooler in the dry mode, the process fluid bypasses the direct heat exchanger and the indirect heat exchanger removes heat from the process fluid; and

- wherein the fluid cooler has a hybrid mode wherein the direct heat exchanger and the indirect heat exchanger remove heat from the process fluid.

49. The heat transfer apparatus of claim 36 further comprising an outer structure; and
wherein the mechanical cooler and the fluid cooler are in the outer structure.

50. The heat transfer apparatus of claim 36 wherein the mechanical cooler comprises a chiller;
wherein the hot side heat exchanger comprises a condenser; and
wherein the cold side heat exchanger comprises an evaporator.

51. The heat transfer apparatus of claim 36 wherein the process fluid heat exchange circuit further comprises a heat exchanger for being operatively connected to a cooling load;
wherein the process fluid comprises a first process fluid and a second process fluid;
wherein the process fluid heat exchange circuit comprises a first process fluid loop that includes the mechanical cooler, the fluid cooler, and a first portion of the heat exchanger; and

a second process fluid loop including the cooling load and a second portion of the heat exchanger, the heat exchanger configured to transfer heat between the first process fluid and the second process fluid.

52. The heat transfer apparatus of claim 36 wherein the fluid cooler comprises a hybrid cooler having a direct heat exchanger and an indirect heat exchanger;

wherein, with the fluid cooler in the dry mode, the process fluid bypasses the direct heat exchanger and the indirect heat exchanger removes heat from the process fluid;

wherein, with the fluid cooler in the wet mode, the process fluid bypasses the indirect heat exchanger and the direct heat exchanger remove heat from the process fluid;

wherein the fluid cooler has a hybrid mode wherein the direct heat exchanger and the indirect heat exchanger remove heat from the process fluid;

wherein the process fluid heat exchange circuit has a fifth mode wherein the process fluid bypasses the mechanical cooler and the fluid cooler is in the hybrid mode; and

wherein the process fluid heat exchange circuit has a sixth mode wherein the mechanical cooler and the fluid cooler in the hybrid mode thereof remove heat from the process fluid.