EVAPORATIVE PRE-COOLER FOR AIR COOLED HEAT EXCHANGERS

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ABSTRACT
The pre-cooler includes one or more cells which are oriented about an air stream to be cooled. A housing defines a perimeter of the cell with an inlet and outlet for air passing therethrough. Water outlet nozzles within the housing are preferably supported upon bars which orient the nozzles facing in a direction counterclockwise to flow of air through the housing. Each nozzle is coupled to a separate stage with multiple stages of nozzles coupled to separate valves. A controller opens or closes different valves. The controller measures ambient humidity and temperature conditions as well as air flow rates to calculate the amount of water to be added to the air and then opens appropriate numbers of stages of valves so that an appropriate number of nozzles spray water into the air to saturate the air. Flow rate control is thus provided without pressure variations, for optimal nozzle performance.
Fig. 4
EVAPORATIVE PRE-COOLER FOR AIR COOLED HEAT EXCHANGERS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit under Title 35, United States Code §119(e) of U.S. Provisional Application No. 61/273,008 filed on Jul. 29, 2009.

FIELD OF THE INVENTION

[0002] The following invention relates to evaporative coolers which add water to unsaturated air to cause a temperature of the air to be reduced. More particularly, this invention relates to evaporative pre-coolers for use upstream of an inlet air stream of a heat exchanger or other air receiving mechanical equipment, such as a gas turbine, to improve the thermodynamic performance and/or heat transfer effectiveness of the equipment.

BACKGROUND OF THE INVENTION

[0003] The efficiency of both air cooled heat exchangers and gas combustion turbines, as well as other mechanical equipment increases as air temperature decreases. Furthermore, such equipment also generally increases in efficiency as the mass of the air increases, such as high or humidity air versus lower humidity air. Water (and other liquids) when provided in liquid form adjacent unsaturated air will tend to evaporate into the air. This evaporation will continue until the air is saturated. Air is saturated with water in different amounts based on the temperature of the air, with hotter air taking a larger amount of water before reaching saturation.

[0004] A known phenomena when water evaporates into unsaturated air is that the air is cooled. The water transitioning from a liquid state to a gaseous state is transitioning from a lower energy state to a higher energy state. The energy required for this transition to take place is provided to the water in the form of heat that is taken out of the surrounding air. This latent heat of vaporization leaving the air causes a temperature of the air to be reduced.

[0005] A device which utilizes this principle for cooling is often referred to as an evaporative cooler. Another term for such a device, when used for air conditioning of a residential space, is a “swamp cooler.” Such evaporative coolers come in a variety of different configurations. In one configuration, evaporative pre-coolers are placed upstream of heat exchangers such as those provided in a direct expansion air conditioning system, an air cooled chiller, a process cooler, a refrigeration condensing unit or any other form of air cooled heat exchanger. The water is known in such systems to be discharged in the form of a fine spray nebulized by passing the spray at high pressure through a small orifice. Such water spray nozzle arrays are often also referred to as a “mister.”

[0006] Numerous problems exist in implementing such evaporative pre-coolers with such heat exchangers or other air receiving equipment. For instance, large air cooled heat exchangers with multiple independently staged fans have highly complex and variable air flow. One section of a device may have air flow of two feet per second while a different section of the same device may simultaneously have air flow of ten feet per second. Existing monoblock pre-cooler systems cannot adapt to this air flow rate variability, and so either supply too much water or too little.

[0007] Supplying too much water wastes water and can damage a heat exchanger or turbine. In such cases liquid water is entrained into the air stream where it can do damage either through direct impingement or through the deposition of dissolved solids on the heat exchanger.

[0008] Providing too little water flow results in lower efficiency gains than could be achieved using the correct amount of water. Because such fine mist water spray requires substantially constant high pressure for effective operation, merely throttling water flow through a flow rate control valve to provide variable water flow rates results in degradation of performance of the nebulizer and less fine spray, thus providing an incomplete solution.

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[0010] Other types of pre-coolers which utilize saturated water pads and air flow through those pads are less than desirable for a variety of reasons. For instance, they have a tendency to shed large amounts of water into the air flow which then can damage downstream equipment. Furthermore, large amounts of water require recycling, and such recycling systems which recirculate a bulk of the water therein have a tendency to concentrate dissolved solids during recycling, ultimately leading to scale buildup and performance degradation. While chemical treatment (and/or periodic or continuous water discharge) can reduce scale formation and biological growth, such chemical treatments (and/or discharge) can present a negative ecological impact.

[0011] Some pre-cooler systems rely on rapid acting valves to control flow. This strategy presents a challenge to high pressure flush evaporative systems. With a rapid acting strategy there are periods of both ramping up pressure and ramping down pressure. In both cases, pressure at the nozzle is at less than the optimal value for some period of time for a portion of the cycle. This portion of time in each cycle which is spent at sub-optimal pressure degrades high pressure nozzle performance.

SUMMARY OF THE INVENTION

[0014] With this invention, an evaporative pre-cooler is provided for use adjacent an air stream, such as an air stream...
feeding into a heat exchanger or turbine or other equipment which receives air therein. The pre-cooler includes a plurality of water outlets. These water outlets include a nebulizer to discharge a fine spray of water into the air stream. To control the flow rate of water added to the air, the water outlets are divided into separate stages with each stage having at least two water outlets and each water outlet associated with a single separate stage. A valve is provided for each stage to open and close the stage.

Each stage provides a known amount of water flow being discharged into the air stream. Thus, when a certain amount of water flow into the air stream is desired, valves are opened associated with stages whose flow rates sum to the desired amount of water flow. Because the valves are either open or closed, rather than throttling/pressure based flow rate adjustment valves, a high pressure is maintained and both well-nebulized spray and precise water flow rates are delivered into the air stream.

To control the pre-cooler, typically a sensor package is provided which senses characteristics about the airflow to be cooled. This sensor package includes an anemometer or other airflow rate sensor and some measure of the humidity of the air within the air stream, such as wet bulb temperature and dry bulb temperature sensors. With such sensors and by characterizing the humidity of the air to be treated, and knowing an amount of humidity that can be added to the air, as well as knowing the flow rate of the air, an operator (or programmed/calibrated machine) can calculate how much water flow rate to add to the air and then open associated valves of associated stages to provide the moisture required.

When the airflow to be cooled is highly variable, such as at separate inlets of a multi-unit heat exchanger, such as a typical rooftop air conditioning heat exchanger of an industrial building, separate cells can be provided which each measure separate airflow.

Humidity conditions can be shared amongst the individual cells or separately measured also. Calculated amounts of moisture to add at each cell can then be utilized to open and close valves associated with stages so that the precise proper amount of water is supplied in each cell. As an alternative, if the separate heat exchanger units can be controlled so as to have a common airflow rate through, then a common signal can be provided to each cell with a common amount of moisture supplied at each cell. Conceivably also, valves associated with individual stages can supply water to multiple different cells in such systems where the heat exchangers are operating at a common airflow rate.

One form of equipment which effectively implements this system includes cells which are in the form of housings with an open front and an open rear allowing the airflow to pass therethrough. Water outlets are provided in the form of nozzles extending from bars located near the exit of this housing. The nozzles face forward, in a counter-flow direction relative to the air stream, so that a mist pattern from each nozzle tends to remain within the enclosure before the moistened air is driven out of the exit. Housing depth is selected to so keep most of a mist cloud from the nozzles within the housing.

A drift eliminator is preferably provided adjacent the exit which provides multiple separate curving cells through which the moistened air must pass before leaving the housing. The drift eliminator keeps water droplets entrained within the airflow but not yet evaporated from exiting the housing and doing damage downstream from the cell.

Each nozzle is associated with a separate stage. If the stage that a nozzle is associated with is called for by the controller and the associated valve for that stage is opened, high pressure water will flow to the nozzle and a fine spray will be discharged therefrom. Preferably, each bar has multiple lines therein with one line associated with each stage. The nozzles are coupled to one of the lines associated with one of the stages in a pattern which causes nozzles within a common stage to be well separated from each other and in a generally evenly distributed pattern. Thus, when a single stage is on, a well distributed pattern of fine spray is provided within the housing for even moistening of air passing therethrough.

A lower portion of the housing preferably includes a drain therein which can draw away water, such as that resulting from direct contact of the fine spray with walls of the housing, and to some extent excess water pulled from the drift eliminator. In addition, naturally occurring condensate, such as from an evaporation coil can also be collected. This condensed water will tend to be relatively low in dissolved solids. These water sources, together or separately, can be collected and periodically pumped and recycled back to the water outlets. Such periodic recycling not only decreases water demand for the overall system but also acts as a form of purge in that the condensed water that is recirculated tends to be exceptionally low in dissolved solids and so can tend to remove scale deposits which might otherwise collect within the system.

OBJECTS OF THE INVENTION

Accordingly, a primary object of the present invention is to provide an evaporative pre-cooler to decrease a temperature of air upstream of an air inlet of mechanical equipment.

Another object of the present invention is to provide an evaporative pre-cooler which increases a mass of air entering an air inlet of mechanical equipment.

Another object of the present invention is to enhance efficiency of a heat exchanger by pre-cooling air entering the heat exchanger.

Another object of the present invention is to enhance efficiency of a power plant by decreasing a temperature of combustion air entering the power plant.

Another object of the present invention is to enhance efficiency of a power plant by increasing effectiveness of a heat exchanger and/or decreasing the size of heat exchanger required for the power plant by evaporatively pre-cooling air utilized for cooling of working fluid within the heat exchanger.

Another object of the present invention is to provide an evaporative pre-cooler which is adjustable to provide a proper amount of water to air for air saturation, and without excessive water usage.

Another object of the present invention is to provide an evaporative pre-cooler which recirculates condensing portions of water and run-off water utilized thereby to minimize water consumption.

Another object of the present invention is to provide an evaporative pre-cooler which minimizes scale buildup within the pre-cooler system itself and minimizes scale buildup for downstream equipment.

Another object of the present invention is to provide an evaporative pre-cooler which is modular in form to be
deployable in a scalable fashion with smaller and larger mechanical equipment which receives air therein. [0032] Other further objects of the present invention will become apparent from a careful reading of the included drawing figures, the claims and detailed description of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] FIG. 1 is a perspective view of a heat exchanger with a series of pre-cooler cells associated with different heat exchanger units within an overall heat exchanger system and showing how air flows through the pre-cooler cells before entering the heat exchangers.

[0034] FIG. 2 is a perspective view of a single cell with portions thereof cut away and revealing interior details of the cell.

[0035] FIG. 3 is a side elevation full sectional view of the pre-cooler cell of FIG. 2.

[0036] FIG. 4 is a schematic view of an alternative embodiment arrangement for separate stages of water outlets according to an alternative embodiment of this invention.

[0037] FIG. 5 is a detail sectional view taken along line 5-5 ofFIG. 3 and revealing interior details within a bar supporting nozzles according to a preferred embodiment of this invention.

[0038] FIGS. 6-16 are schematic views of a preferred embodiment of this invention and showing how water flow rates from ten percent to one hundred percent of maximum can each be achieved by opening different valves for different stages of water outlets according to this invention.

[0039] FIG. 17 is a flow chart illustrating how water flows within the system of this invention and particularly illustrating how partial water recirculation is achieved.

[0040] FIG. 18 is a table with one exemplary set of numbers for flow rates of air and water within one typical evaporative pre-cooler system according to this invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0041] Referring to the drawings, wherein like reference numerals represent like parts throughout the various drawing figures, reference numeral 10 is directed to a pre-cooler cell (FIGS. 1 and 2) for use alone or together adjacent a heat exchanger HX or system 1 of multiple heat exchangers HX to pre-cool air (arrow A of FIG. 1) entering the heat exchangers HX. The pre-cooler 10 evaporates water into the air to reduce a temperature of the air and increase a mass of the air for enhanced effectiveness of the heat exchanger HX. The cells 10 are configured to have a precise and highly adjustable water flow rate while maintaining a fine spray of water for consistent evaporative effectiveness, maximizing air temperature reduction while avoiding water droplet carryover downstream.

[0042] In essence, and with particular reference to FIG. 2, basic details of the pre-cooler cell 10 of this invention are described, according to a most preferred embodiment. The cell 10 includes a housing 20 as a preferred form of enclosure through which air passes (along arrow A) and receives a fine spray of water (arrow B) to evaporatively cool the air into humid air discharge flow (arrow C). Multiple valves 30 (FIG. 3) control water flow through a manifold 40 and to a plurality of nozzles 60 which are supported on bars 50 within the housing 20. Each of the nozzles 60 is associated with one stage and each stage is associated with one of the valves 30. Multiple nozzles 60 are provided within each stage and the valves 30 can be opened or closed so that a total number of nozzles 60 desired can be opened so that a desired flow rate is achieved.

[0043] Most preferably, the nozzles 60 are oriented in a direction opposite that of air flow A for maximization of residence time and mixing to achieve full evaporation of the fine mist of water discharged from the nozzles 60. A drift eliminator 70 is provided at an outlet side of the housing 20. This drift eliminator 70 prevents less than fully evaporated water vapor from passing out of the housing 20, by providing a curving pathway for the air to travel upon leaving the housing 20, and capturing such water vapor thereon.

[0044] An anemometer 80 is associated with the housing 20 to measure airflow through the cell 10. The anemometer 80 is configured to send a signal to a controller which opens and closes valves 30 according to an operational program, and also potentially taking in other ambient conditions, such as wet bulb temperature and dry bulb temperature to provide the flow rate of water into the cell 10 available for maximum evaporative cooling of the air A, or to achieve other design objectives. Additionally, a dry bulb temperature sensor 90 or other sensor related to humidity can be provided downstream of the cell 10 to monitor the effectiveness of the cell 10 and provide feedback to the controller to increase or decrease water flow through adjustment of the valves 30 responsive to actual measurements provided at each cell 10.

[0045] An overall evaporative cooler system 100 can be configured with water reclamation incorporated therein (FIG. 17). In such a system water condensing within the cell 10 can be drained into a collection tank 110 with an associated booster pump to pump the condensed water back to the cells 10 periodically, such that overall water demands are diminished. An ambient calculator 120 associated with the system 100 can measure system parameters such as wet bulb and dry bulb temperatures, or otherwise measure relative humidity or absolute humidity of the air, and use this information along with anemometer 80 readings to feed into a controller for effective control of the system 100.

[0046] More specifically, and with particular reference initially to FIG. 1, details of systems in which the evaporative pre-cooler of this invention can be used are described, according to a preferred embodiment. FIG. 1 displays a multi-fan air cooled heat exchanger. Multiple cells 10 are arranged around the heat exchanger HX, such as with one cell 10 adjacent each inlet for air adjacent each heat exchanger HX. Air entering the heat exchangers HX (along arrow A) must thus pass through the cells 10 first. Such arrays of heat exchangers HX often have individually staged fan arrangements so that the air speed of air passing through one cell may be different than that passing through another cell.

[0047] In such systems, even though all surrounding air may have a similar humidity, different cells 10 need to supply a different amount of water for evaporation within each cell 10 to accommodate these differing air flow rates. Even if all fans are operated at a single speed, and velocity is common for all of the heat exchangers HX, there is still the opportunity to account for other ambient conditions, such as variability in temperature and/or humidity. For instance, adjacent equipment might be producing consistently higher temperatures on one side of the system 1 than on the other side, so that cells 10 on one side are hotter than on the other side.
Heat exchangers increase in effectiveness proportional to temperature difference between the heat transfer fluids. Hence, the cooler the air entering the heat exchanger HX, the more effective the heat exchanger. Furthermore, the greater the mass of the heat exchange fluid removing heat, the more effective the heat exchanger is, in that each unit mass of heat transfer fluid can carry a greater amount of heat out of the heat exchanger HX. Thus, by cooling the air A and increasing a mass density of the humidified air into humidified air (arrow C), a greater amount of heat transfer can occur through the heat exchanger HX. Either system performance is enhanced in that the fluid being cooled is cooled to a lower temperature, or fans which draw cooling air A into the heat exchanger HX need not run as hard to provide sufficient air A for cooling. Ultimately, heat exchangers HX can be sized smaller if they are configured to operate more effectively.

Furthermore, many power plants operate on power production cycles which have an overall thermal efficiency which is proportional to changes in temperature of the working fluid. The cooler the working fluid is at an inlet of such power cycles, the greater thermal efficiency which can be obtained. For instance, with a combustion gas turbine operating on a Brayton cycle, the cooler the inlet air, the greater the thermal efficiency of the power plant, and hence the greater amount of power that can be generated for a given amount of fuel being combusted.

Depending on the equipment with which the cells 10 are to be utilized, the cells 10 can be scaled in size or can be provided in arrays of greater or lesser numbers of cells 10. When multiple cells 10 are utilized, they can be configured to operate independently and separately with their own controls and their own sensors. Alternatively, the cells 10 can be to at least some extent integrated together such as by utilizing similar sensors, similar valves and similar water supply and water recirculation systems.

With particular reference to FIGS. 2 and 3, details of each individual pre-cooler cell 10 are described, according to a most preferred embodiment. Each pre-cooler cell 10 preferably has a similar configuration to other cells 10. Each cell 10 includes an outer housing 20 which is a substantially complete enclosure except for an inlet 26 and outlet 28 for air A to enter into the cell 10 and exit as humid air out (arrow C of FIGS. 2 and 3). The housing 10 includes a floor 21 opposite a cap 22. Sides 25 extend up from the floor 21 to the cap 22. Preferably, the sides 25 are parallel with each other and the floor 21 and cap 22 are parallel with each other and perpendicular to the sides 25, so that the housing 20 is generally rectangular/square in cross-section.

A lattice 24 is preferably provided which spans the inlet 26. This lattice 24 can tend to keep debris out of the housing 20 or can be used to mount a pre-filter to enhance the same effect, as well as keeping water spray contained. A depth of the housing 20 between the inlet 26 and outlet 28 is sized so that the water spray within the housing 20 from the nozzles 60 tends to remain substantially within the housing 20. Thus, the housing 20 defines a reaction chamber where the water is evaporated fully into the air A, before exiting the housing 20 as humidified cooled air C.

The floor 21 not only defines a wall of the housing 20 but also preferably acts as a drain pan with a drain included at a low point of the floor 21. Thus, any non-evaporated water occurring within the housing 20 is captured for potential recycling, as described in detail below.

A plurality of valves 30 are preferably associated with each cell 10, and typically mounted on the cap 22 under an optional cover 23 to protect the valves 30 from weathering, solar radiation or damage from other surrounding environmental conditions. An array of such valves 30 is preferably configured so that one valve 30 is provided for each stage within each cell 10. In a preferred cell 10 four stages are provided so that four valves 30 are provided. Each valve 30 is coupled to a high pressure water main line 32. This main line 32 preferably supplies each of the cells 10 with high pressure water from a single high pressure pump package 106 (FIG. 17) or other high pressure water source. High pressure water is utilized to ensure that the nozzles 60 maintain optimal performance and nebulize the water being discharged by the nozzles 60.

Each valve 30 includes a body 34 and a control 36 which interacts with a valve element within the body 34. An outlet 38 is provided opposite the high pressure water main line 32. This outlet 38 feeds a manifold 40 which splits up the water for each stage associated with the valve 30 and sends it to multiple separate lines located within multiple separate bars 50 (FIG. 5) for ultimate routing to nozzles 60 associated with the stage to which the valve 30 is coupled.

The valves 30 are preferably of a type which transitions between either a fully open or a fully closed position, as opposed to being a variable flow rate valve. Thus, when the valves 30 are open the pressure drop across the valve 30 is negligible. When the valve 30 is closed, no flow across the valve 30 occurs. The control 36 interacts with the valve element within the body 34 to cause the valve 30 to transition between an open and a closed state depending on signals received from a central controller associated with each cell 10, or conceivably a controller which serves all of multiple cells 10.

Each valve 30 is associated with a single stage, as well as a separate manifold 40 (FIGS. 3 and 4). The manifold 40 has separate lines 42. These lines typically include junctions 44 (FIG. 4) which allow the manifold 40 to direct water to separate lines 42 which are in parallel with each other. These lines 42 can then pass into individual bars 50. Most preferably, each bar 50 has multiple lines 42 therein, with at least one line 42 associated with each stage (FIG. 5). As an alternative, and as shown in FIG. 4, conceivably only one line 42, or multiple lines 42 but less than the number of stages, could be supplied to each bar 50. In the system depicted in FIG. 4, the separation of the stages and the individual valves 30 associated with each stage can be most readily seen. However, the nozzles 60 tend to be somewhat tightly grouped together for less than optimal distribution to all of the air entering the housing 20, in the embodiment of FIG. 4. Thus, preferably each bar 50 has nozzles 60 associated with different stages on each bar 50 to better distribute nozzles 60 within a common stage away from each other.

The nozzles 60 preferably face in a direct counter flow direction (along arrow B of FIGS. 2 and 3). Alternatively, the nozzles 60 could be angled somewhat in different directions to better enhance their ability to direct fine spray of water uniformly within the housing 20. While the embodiment of FIG. 4 shows a single line fed to each bar 50 and with each nozzle 60 of each bar 50 being associated with the stage that that bar 50 is coupled to, most preferably, each bar 50 has multiple lines passing thereinto with the lines coming from different stages and with the nozzles 60 on the bar 50 coupled through tees 43 to different stages within a single bar.
For instance, and with reference to FIG. 5, line 42A is shown associated with stage one and line 42B is shown associated with stage two, with line 42C and line 42D associated with stages three and four, respectively. A tee 43A is formed in line 42A which feeds one of the nozzles 60. A next adjacent nozzle 60 within the same tube 50 has a tee 43B associated with line 42B coupled thereto.

FIGS. 6-16 show various different states for the overall array of nozzles 60. In FIG. 6 a state is shown where all of the stages are closed and hence all of the nozzles 60 are off. In FIG. 7, a ten percent flow arrangement is illustrated where only stage one is open and so the five nozzles 60 associated with stage one are open. In FIG. 8 a state is illustrated for twenty percent flow where only the nozzles 60 associated with stage two are open. Note that twice as many nozzles 60 are associated with stage two as with stage one (ten nozzles 60 rather than five nozzles 60). In FIG. 9 a state is illustrated where only the nozzles 60 associated with stage three are open, so that thirty percent of maximum flow is provided. In FIG. 10 a state is illustrated where only nozzles 60 associated with stage four are open, so that forty percent of maximum water flow is provided.

While the stages herein are shown as having different amounts of water flow accommodated by having different numbers of nozzles 60, a similar effect can be provided by having a common number of nozzles 60 with each stage but having the nozzles 60 sized larger for some of the stages. Alternatively, each of the stages could have a common number of nozzles 60 so that increasing flow rate would involve opening multiple stages.

Most preferably, and as depicted in FIGS. 6-10, stages one, two, three and four include different numbers of nozzles 60 of similar sizes so that they provide respectively ten, twenty, thirty forty percent of maximum flow. To provide fifty percent of maximum flow, multiple stages can be open at the same time, such as stage one and stage four or stage two and stage three. To achieve sixty percent flow, stage four and stage two can be open together or stage one, stage two and stage three can each be open together. To achieve seventy percent of flow, stage four and stage three can be open or stage four, stage two and stage one can be open together. To achieve eighty percent of flow, stage four would be open along with stage three and stage one. To achieve ninety percent of flow, stage four would be open along with stage three and stage two. To have maximum flow provided, each of stages one, two, three and four would be simultaneously open. Additionally, pump pressure variation above a minimum necessary, can be used to provide further adjustment of water flow rate through use of a variable speed, variable pressure pump. In this way flow rates between the percentages listed above could be provided.

These various states and the amount of flow provided are sequentially illustrated in FIGS. 6-16. Each circle represents a separate nozzle 60 and the nozzles 60 are arrayed upon bars 50 with separate lines 42 located within each bar 50, as shown in the detail of FIG. 5. In this preferred embodiment, each bar 50 has an inlet 52 (FIGS. 2 and 3) at one end through which each of the lines 42 can enter the bar 50. An end 54 opposite the inlet 52 allows for attachment of the bar 50 within the housing 20, preferably adjacent the outlet and oriented with a long axis thereof extending substantially vertically. A face 56 of each bar 50 includes the nozzles 60 extending therefrom and faces toward the inlet 26 of the housing 20.

Each nozzle 60 preferably has a small orifice 64 within a cap 62 on a side of each nozzle 60 facing toward the inlet 26 of the housing 20. The size of the orifice 64 is carefully selected and shaped to maximize atomization of water spray passing therethrough. Pressure within each stage is maintained sufficiently high, and orifice 64 size is sufficiently small so that the nozzles 60 maintain their optimal performance providing a fine nebulized spray from each nozzle 60.

Because the flow rate is not controlled by a variable flow rate valve, which inherently also effects pressure, but rather by having separate stages which can be selectively added together or subtracted therefrom to provide the desired flow rate, flow rate adjustment is provided independent of pressure. Thus, the high pressure required for optimal performance of the nozzles 60 is not degraded as the flow rates are decreased by throttling a valve. Rather, even flow rates as low as ten percent of maximum can be achieved with the stage one valve 30 wide open and all of the other valves 30 closed. No pressure-controlling valve is in a partially open and pressure reducing state, but rather the nozzles 60 receive full pressure at all times. Thus, the nozzles 60 which are receiving water flow provide a fine nebulized mist of water (arrow B of FIG. 2) which forms a cloud within the housing 20. The airflow A entering the housing 20 readily evaporates this fine mist of water, in turn reducing the temperature of the air and increasing the humidity of the air before exiting the housing 20 along arrow C.

Preferably, the housing 20 includes a drift eliminator 70 adjacent the outlet 28. Due to the relatively laminar flow nature of the air entering each individual cell, some of the droplets can become entrapped in a band of saturated air and not be able to complete the evaporation process. For this reason, an absorptive media drift eliminator 70 is provided in the air stream downstream from the nozzles 60. The drift eliminator 70 causes the air to make rapid turns before entering the conditioned device, such as the heat exchanger HX (FIG. 1). Due to their greater mass, the water droplets are not able to make those turns as rapidly, thus resulting in impact with the drift eliminator 70. The drift eliminator 70 is preferably formed of a material which is somewhat absorbent and is readily thus wetted. This wetted surface can give rise to additional moisture to drier portions of the airflow A. If the wetted portions are over-saturated, gravity pulls the excess water down through the drift eliminator 70 down to the floor 21 of the housing 20 for excess water collection, as described in detail below.

The drift eliminator 70 thus acts differently from a fully irrigated media pre-cooler pad constructed of similar material. First, as a drift eliminator 70, the amount of water that impacts the drift eliminator 70 causes it to become damp, whereas a pad in a traditionally fully irrigated pre-cooler is typically completely wetten, with rivulets of liquid water flowing down both faces. This is important because typically completely wetten pads are much more likely to have droplet carryover. When droplet carryover occurs, these droplets of water usually containing levels of dissolved solids, impinge upon the conditioned device. In most cases this will result in significant scale buildup and has been the principle barrier to market penetration of pre-coolers utilizing fully irrigated evaporation pad technology.

Secondly, since the drift eliminator 70 is only being used for drift elimination, the absorptive material used can be significantly thinner. Typical absorptive media pads for fully
irrigated pre-cooler systems are from six inches to twelve inches in thickness, whereas the drift eliminator 70 of this invention can be from one to six inches in depth. The combination of reduced thickness and reduced water loading substantially reduces both the operational weight and airflow resistance of the described device when compared to fully irrigated pre-coolers.

Finally, the surface area of the droplets is larger by an order of magnitude or more than the surface area of the largest fully irrigated evaporative pre-coolers. Greater surface area results in superior cooling performance at a lower weight while the reduced water load on the material largely eliminates carryover based equipment degradation effects. Edges 74 of the drift eliminator 70 reside against the sides 25, floor 21 and cap 22, so that the airflow A passes through the cells 72 within the drift eliminator 70. If the air A has water droplets entrained therein they will be deposited upon the surfaces of the drift eliminator 70. If the air A is not yet fully saturated, the wet surfaces of the drift eliminator 70 provide a source of water for further evaporation towards saturation of the air A.

With particular reference to FIGS. 17 and 18, the operation of the cells 10 within an overall system 100 for pre-cooling with water reclamation are described. The system 100 includes a series of pre-coolers 10 fed by the high pressure water line 32. This water line 32 is in turn fed from a pump package 106 if necessary to raise the pressure to the required level. Most preferably, at least two separate feed valves 104 or a single valve which can switch from different sources is provided upstream of the pump package 106 or otherwise upstream of the high pressure main line 32. The main line 32 can thus be fed either from a primary source of water, such as a municipal water supply 102, or from a secondary source of water such as a collection tank and associated booster pump 110 which receives recycled water from drains of the pre-coolers 10, along a drain line 108.

An ambient calculator 120 receives as input information related to humidity of the surrounding air, such as wet bulb and dry bulb temperatures. Airflow rates can also be part of the ambient calculator 120, such as through use of the anemometer 90. This anemometer is shown as a fan blade impeller that rotates about an axis aligned with the direction of flow. Alternatively, the anemometer could have an impeller mounted to an axis transverse to the air flow. As another alternative, an air flow rate signal can be provided from a fan associated with the heat exchanger HX (FIG. 1) or other equipment adjacent the cell 10. The signal could be a variable fan speed control signal or a master controller signal that correlates to the speed desired for the fan, or could be a tachometer coupled to the fan itself. With these sensor readings, desired airflow rates can be calculated and in turn specific controls for the valves 30 (FIGS. 1, 3 and 4) can be chosen for operation of the system 100.

In particular, the calculator or other controller can receive the dry bulb temperature, ambient relative humidity, wet bulb temperature, either calculated or measured, to calculate absolute humidity in grains per pound of dry air. This absolute humidity is defined as one hundred percent relative humidity at ambient wet bulb temperature in grains per pound of dry air. The absolute humidity in grains per pound of dry air can then be subtracted from the relative humidity in grains per pound of dry air to determine how much water in terms of grains per pound of dry air can be added to the air.

This amount is then divided by the maximum mass of water that can be delivered to a pound of dry air, measured in grains. Ten percent of this amount (rounded down), equals a flow rate for stage one. Twenty percent of this amount (rounded down), equals a flow rate for stage two. Third and fourth stages can in turn be twenty and thirty percent of this amount (rounded down). This criteria can then be used for sizing of the nozzles 60 when initially configuring the system. Thereafter, upon sensing airflow in ambient conditions, the local controller can set the proper mass of water flow actuating one or more of the several valves 30 either individually or in concert to achieve the percentage desired of maximum airflow.

While this preferred algorithm can be executed by this invention, other algorithms could similarly be utilized. For instance, taking into account known typical environmental conditions and the typical availability of air to receive additional humidity, before saturation, a typical maximum rate can be identified. This maximum amount can then be divided into subparts to be provided by each of the stages in the initial design.

In an embodiment typical for this invention, four stages are provided, but different numbers of stages could be provided in the alternative. In one embodiment, stage one is provided which is controlled by a valve which feeds eight separate nozzles 60 which total 0.1 gallons per minute in flow rate. Stage two includes sixteen nozzles 60 totaling 0.2 gallons per minute. Stage three has twenty-four nozzles 60 totaling 0.3 gallons per minute and stage four has thirty-two nozzles 60 totaling 0.4 gallons per minute. Different combinations of the stages yield to different mass of water as is needed to saturate the air down to wet bulb temperature. For example, if the control calculates that 0.7 gallons per minute are needed to achieve saturation, then stages three and four can be operated in conjunction. In this way, a variable mass of water can be admitted to the air stream (0.1 gallons per minute, 0.2 gallons per minute, etc.) without dropping below the minimum operating pressure at the nozzle 60.

Maintaining minimum operating pressure at the nozzle 60 is critical for flash evaporative cooling operation. Evaporative performance is linked to droplet size, and droplet size in turn linked to pressure at the nozzle. However, a need for variable mass water flow conflicts with this need for constant pressure at the nozzle. A staged nozzle 60 system as described herein avoids the problems inherent with current control methodologies as the pressure remains constant and flexibility of flow rate is still provided. The addition of a variable speed/pump junction allows a virtually limitless number of flow rates, all in pursuit of providing a proper mass of water to saturate the air without producing carryover. For instance, in addition to the stages, some small amount of pressure regulation and/or speed of an associated pump can be controlled to fine tune the system while still maintaining minimum pressure required for nozzle 60 performance. Such a staged system is thus able to provide variable and precise flow control without the problems associated with previous examples of pressure variation.

While the vast majority of water emitted from the nozzle 60 within the pre-coolers 10 immediately convert to vapor, nozzle type cells 10 also may have a small amount of unevaporated water that collects on surfaces of the housing 20 due to impact with walls of the housing 20 itself. In the preferred embodiment of the system 100, such non-evaporated excess water is conducted away by way of collection...
drains along drain line 108 and routed to a collection tank 110. Condensate drains from evaporator coils can also be routed to a common collection tank or to a separate condensate only collection tank.

[0078] When the collection tank 110 is full, controllers shut the valve coming from a primary water source, such as the municipal water supply 102 and open valves from the collection tank system 110. When the high pressure pumps are next engaged, an optional booster pump associated with the collection tank 110 goes into operation to supply inlet water to the high pressure pump package 106. When the collection tank empties, controls close the valve from the outlet of the booster pump associated with the collection tank 110 and turn off the booster pump. The valve from the primary water source is simultaneously opened.

[0079] Use of a collection tank 110 in conjunction with the flash evaporative system delivers many benefits. First, condensate from evaporator coils (alone or mixed with the non-evaporated excess water from the drain line 108) can be utilized as feed water for the pre-coolers 10. Use of condensate in this matter not only reduces overall water consumption by the system, but also reduces the volume of water which is discharged to waste water treatment plants. Additionally, because of the extremely low levels of dissolved solids in condensate drain water, a periodic flushing of the pump and pre-cooler condensate acts as a solvent removing any potential buildup of dissolved solids before they can form performance degrading scale. While a small amount of water will be returned to the cells 10 for reutilization, the binary nature of water that is admitted to the pump system either the primary water source such as the municipal water supply 102, or water from the collector tank 110 in the form of excess non-evaporated water and/or condensate water, means that the system as a whole remains essentially single pass in nature. A single pass system has several benefits. First, a single pass system will not increase the concentration of dissolved solids in the recirculating water in the way that a recirculating system would. This reduces the opportunity for scale formation that has proven to be a challenge for previous evaporative pre-cooler technologies. Additionally, a single pass system does not need to periodically discharge saturated water solutions into the waste water treatment system.

[0080] An alternative embodiment of the cells 10 disclosed herein is to utilize ultrasonic nebulizers in place of the nozzles 60 for the injection of water vapor into the air stream A. Multiple nebulizers can be used in a cell 10, with the same type of proportional flow control as in the preferred embodiment through multiple separate stages. Thus, the precise amount of water is provided as directed by the controller and as indicated by ambient conditions to provide saturated water without excess condensing water flow leaving the cells 10.

[0081] This disclosure is provided to reveal a preferred embodiment of the invention and a best mode for practicing the invention. Having thus described the invention in this way, it should be apparent that various different modifications can be made to the preferred embodiment without departing from the scope and spirit of this invention disclosure. When structures are identified as a means to perform a function, the identification is intended to include all structures which can perform the function specified. When structures of this invention are identified as being coupled together, such language should be interpreted broadly to include the structures being coupled directly together or coupled together through intervening structures. Such coupling could be permanent or temporary and either in a rigid fashion or in a fashion which allows pivoting, sliding or other relative motion while still providing some form of attachment, unless specifically restricted.

What is claimed is:
1. An evaporative pre-cooler with variable water flow, comprising in combination:
   a support interposed within an air stream to be cooled;
   a plurality of water outlets coupled to said support and oriented to discharge water into the air stream;
   said plurality of water outlets each including a nebulizer, such that the water is discharged as a fine spray;
   a source of water coupled to said plurality of water outlets and upstream of said plurality of water outlets;
   each of said plurality of water outlets coupled to one of at least two valves downstream of said source of water, with each said water outlet that is coupled to a common valve discharging water from said source of water when said common valve is open; and
   a controller adapted to operate said at least two valves to cause a water flow rate into the air stream to be varied.
2. The evaporative pre-cooler of claim 1 wherein said nebulizer includes an ultrasonic nebulizer.
3. The evaporative pre-cooler of claim 1 wherein said nebulizer includes a sufficiently small hole in each of said plurality of water outlets, in conjunction with a sufficiently high pressure of water upstream of said plurality of water outlets that water exiting said hole is atomized into a fine spray.
4. The evaporative pre-cooler of claim 3 wherein said valves and lines coupling said source of water to said water outlets through said valves are each sized to facilitate a greater flow rate of water than a sum of water outlet flow rates for water outlets associated with each said valve, such that pressure upstream of said water outlets is maintained.
5. The evaporative pre-cooler of claim 4 wherein a pump is interposed between said source of water and said at least two valves, said pump pressurizing water upstream of said valves to a pressure greater than a minimum pressure required to maintain nebulizer fine spray performance at said water outlets.
6. The evaporative pre-cooler of claim 1 wherein said water outlets coupled to said common valve of said at least two valves define a stage, with a number of said valves equal to a number of said valves downstream of said source of water, each of said stages having at least two water outlets therein, and wherein said water outlets of each said stage are spaced apart to decrease concentration of water within the air stream when said valve associated with said stage is open and each of said water outlets associated with said valve is discharging water.
7. The evaporative pre-cooler of claim 6 wherein a plurality of bars are oriented extending transverse to the air stream, said bars supporting a plurality of said water outlets thereon, said water outlets of each said bar coupled to at least two separate stages.
8. The evaporative pre-cooler of claim 1 wherein said support includes a partial enclosure surrounding the air stream on lateral sides of the air stream, and with an open front and rear, with the air stream entering said front of said enclosure and exiting said rear of said enclosure, said enclosure having a depth between said front and said rear at least as great as a majority of spray distance of said fine spray of water discharged from said plurality of water outlets.
9. The evaporative pre-cooler of claim 8 wherein said water outlets are located closer to said rear than to said front and with said water outlets facing at least partially toward said front of said enclosure.

10. The evaporative pre-cooler of claim 8 wherein a drift eliminator is located adjacent said rear of said enclosure, said drift eliminator having a plurality of open cells passing entirely therethrough and adapted to allow the air stream to pass through said cells in said drift eliminator, said cells having an at least somewhat curving path such that the air stream is required to curve while passing through said cells of said drift eliminator.

11. The evaporative pre-cooler of claim 10 wherein said water outlets are located adjacent said drift eliminator and facing away from said drift eliminator.

12. The evaporative pre-cooler of claim 11 wherein a drain is located below said drift eliminator, said drain adapted to collect water condensing on said drift eliminator and falling down off of said drift eliminator, said drain coupled to said plurality of water outlets through a pump upstream of said water outlets, such that water condensing on said drift eliminator is at least partially recycled back to said water outlets.

13. The evaporative pre-cooler of claim 1 wherein an anemometer is coupled to said support and oriented to measure a flow rate of the air stream to be cooled, said anemometer coupled to said controller to supply a signal related to speed of the air stream to be cooled.

14. The evaporative pre-cooler of claim 13 wherein a humidity sensor is coupled to said support and positioned to measure humidity of the air stream to be cooled, said humidity sensor adapted to send a signal to said controller indicative of humidity of the air stream to be cooled.

15. The evaporative pre-cooler of claim 1 wherein a sensor is located downstream of said water outlets, said sensor adapted to measure humidity of the air stream after the air stream has been cooled by evaporation of the fine spray of water discharged by said plurality of said water outlets, said sensor supplying a signal in the form of feedback to the controller to adjust a water flow rate from said plurality of water outlets responsive to humidity sensed by said humidity sensor downstream from said water outlets.

16. The evaporative pre-cooler of claim 1 wherein said support is located adjacent an inlet of an air receiving mechanical device with a fan therein, said fan generating the airflow, a signal associated with speed of said fan coupled to said controller to supply a signal related to speed of the air stream to be cooled.

17. A water evaporation pre-cooler, comprising in combination:

a plurality of water outlets oriented to discharge water into an air stream;

said plurality of water outlets each including a nebulizer, such that the water is discharged as a fine spray;

a primary source of water coupled to said plurality of water outlets upstream of said plurality of water outlets;

drain below said plurality of water outlets, said drain adapted to collect condensed water from said water outlets;

said drain routed to a secondary source of water coupled to said plurality of water outlets upstream of said plurality of water outlets; and

at least one feed valve upstream of said plurality of water outlets, said at least one feed valve adapted to control which of said primary source of water and said secondary source of water supplies water to said plurality of water outlets.

18. The water evaporation pre-cooler of claim 17 wherein said primary source of water has a greater water capacity than said secondary source of water.

19. The water evaporation pre-cooler of claim 18 wherein said primary source of water has a water capacity greater than twice a capacity of water in said secondary source of water.

20. The water evaporation pre-cooler of claim 19 wherein said primary source of water has a water capacity at least ten times greater than a water capacity of said secondary source of water.

21. The water evaporation pre-cooler of claim 17 wherein said secondary source of water has a lesser amount of dissolved solids contained therein than said primary source of water.

22. The water evaporation pre-cooler of claim 17 wherein a drift eliminator is located downstream of said water outlets, said drift eliminator having a plurality of open cells passing entirely therethrough and adapted to allow the air stream to pass through said cells in said drift eliminator, said cells having an at least somewhat curving path such that the air stream is required to curve while passing through said cells of said drift eliminator.

23. The water evaporation pre-cooler of claim 22 wherein an enclosure surrounds at least portions of the air stream to be cooled, said enclosure including an entrance opposite an exit with said entrance adapted to receive said air stream therein and said exit adapted to discharge said air stream therefrom, said enclosure including a floor on one lateral side of the air stream extending between said entrance and said exit, said floor having said drain therein, said floor located beneath said drift eliminator, said drift eliminator located adjacent said exit of said enclosure.

24. The water evaporation pre-cooler of claim 23 wherein said water outlets are located adjacent said drift eliminator and oriented to spray said fine spray of water at least partially toward said entrance of said enclosure.

25. The water evaporation pre-cooler of claim 24 wherein each of said plurality of water outlets is coupled to one of at least two valves downstream of both said primary source of water and said secondary source of water, with each said water outlet that is coupled to a common valve discharging water when said common valve is open.

26. The water evaporation pre-cooler of claim 25 wherein said water outlets coupled to said common valve of said at least two valves define a stage, with a number of said stages equal to a number of said valves downstream of said source of water, each of said stages having at least two water outlets therein, and wherein said water outlets of each said stage are spaced apart to decrease concentration of water within the air stream when said valve associated with said stage is open and each of said water outlets associated with said valve is discharging water.

27. The water evaporation pre-cooler of claim 26 wherein a plurality of bars are oriented extending transverse to the air stream, said bars supporting a plurality of said water outlets thereon, said water outlets of each said bar coupled to at least two separate stages.

28. A method for cooling an air stream, including the steps of:

providing a plurality of water outlets oriented to discharge water into the air stream, the plurality of water outlets
each including a nebulizer, such that the water is dis-
charged as a fine spray, a source of water coupled to the
plurality of water outlets and upstream of the plurality of
water outlets, each of the plurality of water outlets
coupled to one of at least two valves downstream of the
source of water, with each water outlet that is coupled to
a common valve discharging water from the source of
water when the common valve is open, and a flow rate
controller coupled to the water outlets and adapted to
control a rate of flow out of the water outlets;
determining an amount of water flow needed to cool the air
stream a desired amount by evaporation of the water into
the air stream; and
adjusting the at least two valves to adjust a number of water
outlets discharging water to more closely match the
needed amount of water flow.
29. The method of claim 28 including the further step of
defining water outlets coupled to a common valve as being
associated with a common stage, with a number of stages
equaling a number of valves, with each stage having a corre-
sponding water flow rate when open; and
selecting stages to be open as needed to total the desired
amount of water flow.
30. The method of claim 29 including the further step of
spacing water outlets within common stages so that when a
stage is operating water outlets associated with the operating
stage are spaced apart to distribute water evenly within the
air stream.
31. The method of claim 30 including the further step of
dividing the air stream into separate portions and providing
separate cells associated with each portion of the air stream to
be cooled, the separate cells each including a separate enclo-
sure which surrounds at least portions of the air stream to be
cooled, said enclosure including an entrance opposite an exit
with the entrance adapted to receive the air stream therein and
the exit adapted to discharge the air stream therefrom, the
enclosure including a floor on one lateral side of the air stream
extending between the entrance and the exit.
32. The method of claim 31 including the further step of
collecting unevaporated water from the air stream by provid-
ing a drift eliminator adjacent each exit, the drift eliminator
having a plurality of open cells passing entirely therethrough
and adapted to allow the air stream to pass through the cells in
the drift eliminator, the cells having an at least somewhat
curving path such that the air stream is required to curve while
passing through the cells of the drift eliminator.
33. The method of claim 31 wherein said dividing step
includes the step of configuring each cell to have the floor
thereof located beneath the drift eliminator and adjacent the
exit of the enclosure.
34. The method of claim 33 including the further step of
configuring each cell to have a separate controller and sepa-
rate valves for independent operation of the separate cells on
an associated portion of the air stream.
35. The method of claim 33 wherein the separate cells
include a common controller and common valves with each
stage having at least one water outlet associated with each
cell.
36. The method of claim 28 including the further step of
locating a drain below said plurality of water outlets, the drain
adapted to collect condensed water from the water outlets, the
drain routed to a secondary source of water coupled to the
plurality of water outlets upstream of the plurality of water
outlets, and locating at least one feed valve upstream of the
plurality of water outlets, the at least one feed valve adapted
to control which of the source of water and the secondary
source of water supplies water to the plurality of water outlets.
37. The method of claim 36 wherein the secondary source
of water has a capacity less than a capacity of the source of
water.
38. The method of claim 37 including the further step of
cycling the feed valve to cause the water outlets to periodically
receive water from the secondary source of water, the
secondary source of water having a lesser amount of dis-
solved solids therein, such that said cycling step purges dis-
solved solids from water lines upstream of the plurality of
water outlets.

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