Plume Abatement and Water Conservation with the Wet/Dry Cooling Tower

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The studies and conclusions reported in this paper are the results of the author’s own work. The paper has been presented before, and reviewed by the Cooling Tower Institute, and approved as a valuable contribution to cooling tower literature.

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Background

Wet/dry cooling towers, sometimes referred to in Europe as hybrid cooling towers, evolved beginning about 1970 due to concerns regarding the environment. The United States Environmental Protection Agency classified the visible discharge plume from evaporative or wet cooling towers as visual pollution. Tower designs evolved which incorporated readily available air-cooled or dry heat exchangers to introduce a non-evaporative air heating process. The combination of evaporative and non-evaporative heating results in reduction of the relative humidity of the air leaving these wet/dry cooling towers. For a period of time, environmental impact statement requirements required review of the plume abatement option on most large industrial and power sites. A result was construction of some large industrial and power plant sized wet/dry cooling towers for plume abatement. Higher capital cost and operating power consumption than that of wet towers was typical of this generation of wet/dry towers. The higher off-design cold water temperatures of wet-dry towers resulted in higher heat rates and fuel costs for power plants. By the end of the decade, economic influences led to diminished pressure from the EPA. For these reasons, the number of wet/dry towers studied and purchased subsided drastically during the late 1970’s.

At about the same time, interest in cooling towers with lower evaporative water consumption was also rising. One cause for this interest was the consideration of nuclear power plants in remote sites with limited water resources. A result of this interest was a tower design with the same general concept of combining wet and dry heat exchangers as used for plume reduction. This type of tower dissipates a portion of the heat load by non-evaporative heat transfer in the dry section to reduce water consumption.

Some construction of water conservation cooling towers and fully dry installations occurred. The largest in the United States was a 70% water saver, compared to a conventional wet tower, on a 550 MW mine-mouth coal-fired power plant which began operation in 1977. The cost, power consumption and operating temperature factors mentioned above were even more significant in the case of water conservation and dry cooling. The purchase of water or water rights at high prices and even the pumping of water over significant distances optimized in nearly all cases over the use of water conservation or dry cooling tower technology. The market for water conservation and all dry cooling towers essentially vanished, particularly in the United States by 1980. Some exceptions occurred on small urban sites, and in isolated cases such as in South Africa where political influences have led to the construction of all dry installations.

Recently, the rapid growth of cogeneration, refuse recovery, independent power projects, and repowering of older power plants have led to a resurgence of interest in plume abatement and water conservation. The primary cause is the typically urban project sites chosen for these types of projects. Often, the value of successfully gaining approval by regulatory bodies and avoiding impact on neighbors outweighs the negatives of plume abatement or water conservation listed above. A new factor in this product market today is that nearly 20 years of operating experience exists on a number of installations, giving the wet/dry concept a level of credibility that did not exist when it was introduced in the early 1970’s.
Cooling Tower Plume

WET COOLING TOWER PLUME

Visible plume from a cooling tower is not an air pollutant. The plume is essentially pure water vapor made visible as the moist heated air mass leaving the tower is cooled below its dew point. Another plume constituent, cooling tower drift, is drops of circulating water carried out of the tower along with the airflow through the tower. The very small amount of drift that leaves a modern tower has the potential of containing polluting elements if they are present in the circulating water. A typical drift rate with modern eliminators is less than 0.005% of the circulating water rate. The cooling tower adds heat and moisture to the surrounding environment in the discharged plume. It also performs a secondary service of washing out many of the solid dust particles contained in the incoming air. Several factors affect the amount of moisture evaporated into the air and the percentages of sensible (dry) and latent (evaporative) heat absorbed by the air. These are the heat rejection rate from the waste heat source, the ambient wet and dry bulb temperatures, and to a lesser extent the mass of air circulated per unit mass of water circulated for a certain tower design.

Visible plume formation from an evaporative, or wet, cooling tower is most prevalent during the cooler months when warmer, moist air mixes with colder ambient air. The mixing of warm, moist tower discharge air with cooler ambient air may result in condensation of water droplets that are the visible. Referring to the Psychrometric Chart shown in Figure 1, for typical winter operation, cold ambient air at condition (1) flows into the wet cooling tower. As evaporation occurs, air moisture content increases on the vertical axis while air dry bulb temperature increases along the horizontal axis. Experience shows that the discharge at any point at the eliminators is at or slightly below a saturated condition.

In the mixing process of Figure 1 of the tower effluent air (2) with ambient air (1) occurs on a straight line. The saturated effluent air gradually dilutes in the larger ambient air mass above the cooling tower. The portion of the mix line that crosses the saturation curve into the supersaturated, or fog, region represents the potential to produce visible plume. As the dilution process passes out of the supersaturated area, the visible plume vanishes, while continuing the dilution in an invisible state. Similarly, the line from (3) to (4) represents effluent to ambient mixing under normal summer operating conditions. Note that there is no theoretical tendency for plume generation in this summer case, since the mixing-line shown is entirely below the saturation curve on the Psychrometric Chart.

A source of possible confusion is that the mixing of saturated air at different temperatures from point to point across the eliminator exit plane sometimes results in slightly supersaturated average conditions. Supersaturation in such case results from condensation of drops during cooling of the warmest portion of the saturated air down toward the average effluent condition. Uneven air distribution across the fill face area results in increased differences in effluent air temperature from point to point at the eliminators, exaggerating any tendency toward mixing to supersaturation. It is also important to separate the quantity of drift in consideration of effluent moisture content. Drift is predominantly well above the fog range in drop size, and as a result has no effect on the extent to which a plume is visible. Drift is mechanical entrainment of water into the saturated effluent, and could be interpreted as supersaturation if using techniques for measurement of effluent moisture content which cannot segregate drift. Depending upon the design of any test chamber or instrumentation, the influences of uneven air distribution and drift elimination could significantly distort any conclusions regarding the moisture content of cooling tower effluent air.

With low inlet air relative humidity or low heat loads, the average effluent air condition from the eliminators may be slightly below saturation. A slight variation in degree of effluent air saturation explains why under more humid inlet conditions there is visible fog inside the plenum of a cooling tower, while under less humid conditions there is no visible fog inside the tower plenum. Another factor affecting the conditions in a cooling tower plenum is whether the tower is heating up or cooling down. The surfaces in the plenum will be cooler than the air when a tower is heating up, such as in rising wet bulb conditions. With a sufficient temperature difference, condensation in the plenum results, contributing to slight supersaturation due to slight cooling of the air. Extensive experience in the laboratory and over 20 years of experience in the field have shown that wet section effluent is best assumed at saturation for plume abatement purposes.

AIR COOLED HEAT EXCHANGER

Since dry air-cooled heat transfer systems do not add moisture to the air, mixing does not occur in the supersaturated area and no visible plume occurs. Referring to Figure 2, the ambient air at (1) passing through a dry air cooled heat exchanger discharges at
condition (2). Note that heat content of the air increases at constant moisture content as the dry bulb increases horizontally along the x-axis. As the heat content of the air increases, the further the discharged air condition moves away from the saturation curve. Winter operation along line 3-4 also produces invisible effluent air.

Wet/Dry Tower Configurations for Plume Abatement

Most wet/dry cooling towers combine finned tube heat exchangers, or dry sections and conventional evaporatively cooling, or wet sections into configurations that utilize common air moving equipment. Other wet/dry configurations utilize separate fans for wet and dry sections. The nomenclature as a wet/dry tower addresses configurations that utilize a surface condenser or other process heat exchanger circulating water as the source of heat dissipated in both the wet and the dry sections. Classification of wet/dry towers is generally according to their air side design. Two such classifications are parallel path air flow and series path air flow.

SERIES PATH AIR FLOW

Series flow arrangements employ dry sections either preceding or following the wet section. Figure 3 is a schematic description of a dry section following the wet section and a psychrometric representation. This arrangement has several disadvantages: 1) Deposition of dissolved solids contained in drift from the wet section occurs on the dry sections. 2) A full time increase in fan pressure occurs due to the added air-side resistance of the dry sections in the air stream. 3) Except at low relative humidities, a reduced driving force for heat rejection in the dry sections exists due to the increase in dry bulb temperature of the air stream leaving the wet sections.

Another series air flow possibility is the placement of dry sections ahead of the wet sections. Figure 4 presents this concept and its psychrometric representation. The ambient air first contacts the dry section, providing it with cooler, drier air for that component than would occur in the series path arrangement in Figure 3. The air exiting the dry section undergoes an increase in dry bulb, an increase in wet bulb, and thus, a decrease in relative humidity. This system will theoretically function according to the psychrometrics illustrated only under certain conditions. The heat load for the wet section to dissipate must be small to prevent saturation of the effluent air. The configuration of the wet section must also allow effluent conditions far enough below saturation to avoid visible plume. Only a prototype installation of this type is known to exist.

PARALLEL PATH AIR FLOW

Parallel air path configurations separate into parallel, integral and series water path designs. All three configurations have separate wet and dry streams.

Parallel Path Water Flow. In a parallel path air flow, parallel path water flow design, the dry sections and the wet sections both receive hot water from the process and deliver it to mix in the cold water basin. Since the dry sections are inefficient in comparison to the wet sections, the relatively high cold water temperature leaving dry sections impairs overall thermal performance. This configuration is not commonly used.

Integral Designs. Parallel air flow, integral water flow designs are a special case of the parallel water flow designs that utilize plume reducing fill instead of a separate dry section. This modification of low cost PVC crossflow film fill has roughly parallel sheets with water delivered to every other passage in the plume reducing mode. In some designs water can also be delivered to all passages for an optional non-plume-reducing mode. Air flows through all passages, so that only the passages receiving water act as cooling tower wet sections. The alternate passages without water act as dry sections which heat the air flowing through them by conduction through the fill sheets from the warm water in the adjacent wet passages.

The water on the fill sheets in the wet passages is at temperatures ranging from the hot water temperature at the top to the cold water temperature at the bottom. The mean temperature difference between the fill sheets and air in the dry passage drives the heat transfer. The heat transfer in the dry passages is thus a function of the mean temperature of the water films on the fill sheets in the wet passages. This temperature is about halfway between hot and cold water temperatures and is significantly lower than in the series water path arrangement described in the next section. A lower temperature difference as a driving force for the integral design results in a lower exit dry bulb temperature. A lower exit dry bulb temperature results in a requirement for greater air flow (and accompanying fan power) to mix with and reduce the relative humidity of the wet section effluent air. The heat transfer in the dry sections
is also impaired by relatively low heat transfer coefficient and surface area per unit face area as compared to finned tube heat exchangers.

The integral design has the main advantages of low cost, and near design summer thermal performance with water flowing in all passages. Due to its low dry passage thermal efficiency in the plume reducing mode, the integral design is practical only for minimal to moderate reduction of plumes and not for plume elimination for a significant percentage of the year. The design does not lend itself to wet or dry section dampering for air-side control purposes. The integral design is most practical for clean water applications, particularly HVAC using potable water, due to the small orifice sizes typically used for water distribution. In the plume reducing mode, the wet passages receive much higher water flow rate, as well as reduced air flow due to increased air bypass through the dry passages. This results in a much greater reduction of tower thermal performance, or higher cold water temperatures, in the plume reducing mode for the integral design than for a comparable series water path design. Installations are predominantly in small cooling towers, although some larger integral design, plume reducing cooling towers have been built in the United Kingdom.

Series Path Water Flow. In the parallel air flow, series path water flow arrangement, the hot water passes first through the dry section, is cooled some portion of the total cooling range, and then passes through the wet section. The average water temperature inside the dry section is relatively nearer to the hot water temperature than in the integral design described above, since the water passages in the integral design are actually the wet sections which see the total cooling range. The larger mean temperature difference, better heat transfer coefficient, and larger surface area per unit face area all contribute to a lower dry section air flow requirement, with correspondingly lower fan power requirement than for the integral design.

The most common type of the series water path design has dry sections located physically above the wet sections. Either doubleflow crossflow or counter flow cooling tower designs with opposing face air inlets are typically used. The water leaving the dry sections typically flows by gravity into the wet section below. This type of series path arrangement has been commonly referred to as a parallel path wet/dry or PPWD tower. A variant of this design is application of a dry section on the backwall of a single flow crossflow tower. In this case the hot water enters the base of the dry section, rises through the dry section, crosses the tower plenum in piping, and falls through the wet section. This variant of the series water path design is commonly referred to as an opposed path wet/dry, or OPWD.

External Heat Source. An additional variant of the series water path arrangements is similar only in general configuration. Dry sections are located as in the PPWD or OPWD, but are supplied with an external heat source such as steam. This provides the opportunity to reduce the size of the dry section and air flow required due to higher dry side fluid temperature. In practice, the design optimization process in nearly all cases rules out this design due to the cost of the additional energy, the cost of delivering the external heat to the dry section, and providing a flow control system. Since fans are used to control the cooling tower, flow control is the only process control available for the external heat source. The total cost for the external heat system exceed the savings in dry section size.

The PPWD Tower

PSYCHROMETRIC OPERATION

Figure 5 illustrates air flow through a series water path, parallel air path design with finned tube dry sections, commonly referred to as a parallel path wet/dry (PPWD), cooling tower. The tower shown has crossflow wet sections, but either crossflow or counterflow wet sections may be employed.

In Figure 5, ambient air is at condition (1). The portion of the air that passes through the dry sections is sensibly heated along line 1-3. A small dry section cooling range, generally less than 20% of the total tower heat load, is sufficient to adequately heat the amount of air passing through the dry sections.

Line 1-2 in Figure 5 represents the portion of air that passes through the wet section of the tower. Before discharging from the tower the two air streams from dry and wet sections mix along line 2-3. For equal dry air mass flows through each portion, the average effluent mixture condition is the midway point (4), along line 2-3. The effluent air then mixes with ambient air at condition (1) represented by the line 4-1. Since this line falls below the saturation curve, the result will be little or no visible plume. The further below the saturation line, the less tendency will exist for visible plume to occur.
PLUME CHARACTERISTICS

In the crossflow configuration shown in Figure 6, the essentially saturated wet air leaving the wet sections flows to the center of the cooling tower plenum, then turns vertically to enter the plenum between dry sections at about twice the velocity of the air leaving the dry sections. Slower moving dry air from the dry sections flows around the wet air from either side, resulting in a dry air envelope around the moist air. The mixing process after leaving the fan stack involves wet air mixing through dry air before reaching the ambient air. At zero theoretical visible plume conditions, the resulting stratified wet/dry plume due to incomplete mixing has a distinctive translucent, but visible cone shape. At zero theoretical visible plume conditions, the effluent air continues mixing to invisibility within 2-3 fan stack exit diameters after leaving the fan stack. This assumes moderate to light winds, and otherwise normal atmospheric conditions. It is obvious that high winds accelerate mixing and bend the plume, and that low level inversions or other abnormal atmospheric conditions affect the length of any plume. Mixing devices are not known to have been used in full scale crossflow towers, but may be used to provide more complete mixing if appropriate. It is common to oversize dry sections to provide fan to ambient mix line tangency to a relative humidity below 100% as a conservatism to offset incomplete mixing.

In a counterflow configuration, the two low velocity air streams intermingle less predictably since the wet section effluent air is not concentrated at the center of the cell and is at about the same velocity as the dry section effluent air. It is not necessarily assured that a dry envelope will occur or that the mixture leaving the tower will continue to mix predictably after leaving the tower. As a result, mixing devices are more commonly used in counterflow to promote mixing as well as possible before leaving the fan stack. The more effective mixing devices are, the more pressure drop they tend to add and the more additional fan power they tend to consume.

The economic choice between counterflow and crossflow wet section designs varies with differences in design thermal duty, site limitations and power evaluation. Properly designed towers of either type are functionally equivalent.

WATER SAVINGS

In addition to plume abatement, operation of a PPWD tower also results in a reduction of water consumption by evaporation. Any portion of the heat load, or cooling range, dissipated in the dry sections reduces the wet section’s cooling range and accompanying evaporation. Since wet sections respond to wet bulb and dry sections respond to dry bulb, the effects of changing weather on the portions of heat dissipated in the wet and dry sections in a parallel path tower are complex. The percentage of heat rejected by the dry sections of the tower changes through the year with dry bulb, wet bulb, and heat load on the tower. Statistical weather data, heat load profiles and water availability data enable proper design for both plume abatement and water savings.

PPWD DRY SECTION DESIGN

Description/Construction. The dry sections used on PPWD’s are basically conventional air-cooled heat exchangers, such as are used in the petrochemical industry. The dry sections are commonly vertical in tube orientation, although some horizontal tube arrangements with vertical headers have been used. The tube bundle designs are commonly triangular pitch with extended surface, or fins. Tubes are usually expanded (“rolled”) into holes drilled into tube sheets of the headers. Hydraulically, the bundles are usually one or two pass design. The finned tube bundle side frames, tube supports, headers, and piping are carbon steel, hot dip galvanized after fabrication to extend longevity.

Tubes. Typical tube materials are copper-nickel or stainless steel. Tube diameters are typically greater than or equal to the tube size in other portions of the same cooling system, such as the surface condenser tubing. Smaller tube diameters can result in the tubes acting as a filter for the circulating water, trapping contaminants or cleaning balls in the dry section headers. One inch outside diameter tubing is most common.

Fins. Use of 5/8 inch high, spiral tension wound, footed, 1100 series aluminum fins, at about 10 fins per inch, is typical for normal cooling water service. For intermittent operation, exposure to seacoast or to other very corrosive environments may warrant consideration of alternative fin materials, fin coatings or extruded fins.

Headers. Adequate access to keep the tubes and headers clean enhances operation. Removable plugs opposite each tube, removable covers or other means avoid the breaking of piping connections when conducting repair and maintenance.

Corrosion/Fouling. The warm, moist environment inside a cooling tower is corrosive for many metallic
components. Corrosion warrants careful consideration in selection of the dry section and dry section damper materials. The PPWD tower design has the advantage over some series air path designs of providing ambient air to the dry sections. This minimizes the likelihood of fin surface corrosion or constriction of air passages due to deposition of solids. To avoid deposition of drift on the plenum side of the dry sections, the dry section air flow control dampers are best designed to allow a small amount of air flow across the finned tubes when closed.

**PPWD OPERATIONAL FEATURES**

**Pump Head Considerations.** The normal pump head for a wet tower has two components. One is the friction loss through the piping system to the tower. The other is the vertical distance, or static lift, between the cold water basin water level and the hot water discharge to atmosphere. The PPWD tower, when arranged with a crossflow wet section configuration, utilizes finned-tube dry sections located on the sides of an elevated plenum above the water distribution basins for the wet sections as shown in Figure 6. As shown in Figure 7, water from the dry sections in the crossflow wet section configuration discharges into an open connecting flume elevated above the spray system to provide pressurization, or into a closed piping connection to the spray system.

For a single water pass design with vented piping to an inlet or open headers at the top of each coil, the pump head would include the full coil height as an additional static lift. For a PPWD tower with two pass vertical tube heat exchangers closed at the top header or single pass vertical tube heat exchangers with unvented unvented at the top, minimal additional static lift occurs in comparison to an all wet tower. The dry section in this case is actually in the loop of a siphon which causes the top headers to be in a partial vacuum condition. The only additional pump head losses compared to an all wet tower, are the head lost to friction within the dry sections plus any small elevation increase to the coil inlet connection.

**Freeze Protection of Coils.** The example of flowing streams in freezing weather is a good analogy for freeze protection of dry sections. The risk of freezing exists when water stands still or flows very slowly in any tubes during freezing weather. Water flow distribution within large cooling tower inlet piping systems requires careful analysis to assure parallel siphon loops are all started properly.

**Vent Manifold System.** A vent manifold piping system is one option (See Figures 6 and 7), using a main pipe to interconnect with smaller lines to the top headers of all the coils on each side of the tower. The vent manifold piping system provides the capability to vent all the coils to atmosphere simultaneously using multiple remotely actuated valves located along the main vent manifold pipes. Pumps start with these vents open to provide atmosphere pressure in all of the top headers. This allows water to start flowing in all dry sections against the full static lift before any siphon loops initiate. After a short delay to assure full flow on all dry sections, the vent valves close and all dry sections initiate siphon operation together.

Without the vent manifold system, any coils that begin to flow first will start to operate as a siphon. Any localized siphon operation decreases the pump head and increases the flow rate. The head delivered by the pump can fall below the elevation of the top of the coils before water flows in all coils. This could leave standing water in unstarted tubes or coils, creating a freezing risk in cold weather. Since a higher pump head mode occurs at start-up, pump selection criteria should include start-up head capability with at least half of design flow rate, and a minimum of about 2 feet per second tube velocity.

In operation of a PPWD tower with the vent manifold system, water always flows initially through the dry sections, above the wet sections. For PPWDs in freezing climates, a full time “freeze protection bypass” is necessary. This consists of a small drain that is open from the inlet header of each dry section to the wet section water distribution system, allowing a small percentage of the circulating water flow to bypass the coils. This fail safe bypass will allow the first pass of dry sections always to drain quickly when the pumps are off and the vents are open. The shut off sequence in PPWDs is to first open the vents and then shut off the pumps. The last pass of tubes always drains directly into the water basin water level and the hot water discharge to atmosphere pressure in all of the top headers. Pumps start with these vents open to provide atmosphere pressure in all of the top headers.

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**Vacuum Pumps.** A variant vent manifold design used with two pass coils utilizes a vacuum pump connected to the vent manifold system. This allows start-up at reduced head and requires maintenance of the vacuum pump in full time operation. The system must still be vented to atmosphere at shutdown to allow the coils to drain quickly. The intent of a vacuum pump is to provide removal of any trapped gasses, or of any gasses flashing in the top header.

The need for vacuum pumps on two pass PPWD
return headers has improperly been considered analogous to the need for vacuum pumps on the discharge side water boxes of power plant surface condensers in once through service. Once-through surface condensers also operate at a vacuum condition due to the elevation difference between the surface condenser and the discharge to the river or lake. There is a fundamental difference from dry sections in a PPWD in that water is heated while going through the tubes in a surface condenser, and cooled in a PPWD dry section. The solubility of air in water strongly decreases with increased temperature, so that dissolved air flashes in the outlet chamber of the once through surface condenser and vacuum pumps are required for removal.

In a PPWD coil, the water is cooled, which strongly increases the solubility, and actually tends to rapidly dissolve any trapped gasses or leaked air in the water. Experience confirms the efficiency of this characteristic of the system, making vacuum pumps unnecessary.

**Air Flow Control. Wet Section Dampers.** A control device to regulate air flow through the evaporative section is sometimes necessary to allow plume abatement during start-up and during reduced heat load operation. Dampering the wet section air passage and diverting air flow and heat rejection to the dry section reduces air flow and heat transfer in the wet section of the tower. Reducing heat transfer in the wet sections results in higher hot and cold water temperatures at the tower by forcing a larger portion of the tower heat load to the less efficient dry sections. It is important to note that plume abatement requires that the fans be in operation to pull air through the dry sections. Wet section dampering facilitates more hours per year of fan operation at low ambient temperatures and low heat load conditions. It is also important to note that wet section dampering will not always improve plume reduction. As air flow is reduced to the wet sections, the saturated air temperature leaving the wet sections increases, causing an increase in plume abatement difficulty. Generally the diversion of heat load to the dry sections is sufficient to abate the plume. If, however, the dry section size is insufficient to supply enough dry air as the plume abatement difficulty increases, wet section dampering may not improve the plume abatement.

**Dry Section Dampers.** A key design feature that permits economic application of the PPWD tower is the dry section damper component shown in Figures 6 and 7. This is sometimes a door-like air flow restrictor located in the heated dry air stream between the air cooled heat exchangers and the fan, a conventional metallic air cooled heat exchanger face damper or other device such as a rolling door located on the outside of the dry section. The cooling tower environment requires suitable materials and design for any such device.

The purpose of the dry section damper is to reduce the air flow through the dry sections and increase the air flow rate through the wet sections. Closing the dry section dampers during summer periods when plume abatement requirements are minimal increases the wet section thermal performance capability when peak performance is needed. The fan power requirement to achieve summer design performance with dry section dampers reduces to within about 10% of that for a conventional wet tower in most cases. This additional fan power requirement is for the small amount of leakage air flow through the dry sections with dampers closed as discussed under PPWD dry section design.

The size of the dry sections on PPWDs is a variable, allowing designs for the elimination of visible plume during cold weather on most sites. The PPWD tower, with dry section dampers closed, provides essentially the same economic advantages as a wet tower in the summer in terms of cold water temperature and fan power. This is not possible with totally dry cooled systems selected for dry operations throughout the year, without benefit of efficient evaporative cooling.

If the damper doors completely close, the air flow to the dry stream would be zero. The evaporative performance level would be equivalent to that of a wet cooling tower. The PPWD would lack the capability to reduce visible plume in mornings and evenings or other high relative humidity periods in the summer. An intentional leakage allowance through the dry dampers permits some summer plume abatement capacity, adds only a small amount of fan power, and protects the coils from drift deposition. Dry section dampers are operated with seasonal manual adjustment, remote adjustment, or automatic remote control to provide optimum system operation.

**OPPOSED PATH WET/DRY**

A variant of the PPWD design is the opposed path wet/dry (OPWD) as shown in Figure 8. In this configuration, instead of a typical doubleflow crossflow configuration, a single flow wet section is utilized with a dry section on what would otherwise be the backwall of the tower. The airstreams leaving the dry and wet sections are directly opposite to one another. The water circuit is again series path, with water entering the bottom headers of a single water pass dry sections, leaving the top headers of the dry sections and flowing through cross-over piping to the distribution basins of the wet sections. Wet and dry section dampering is similar to that of PPWDs. This arrangement is low in
capital cost, but results in longer towers than with the PPWD. With lower efficiency single water pass dry sections and the additional siting requirements, the OPWD is somewhat more limited than the PPWD in flexibility to suit plume abatement needs.

CONVERSION OF EXISTING TOWERS TO PPWD OR OPWD TOWERS

Backfitting to include dry sections is possible for existing wet cooling tower installations that are experiencing undesirable plume discharge. An increase in the existing tower size or fan power may be necessary to accommodate present heat loads at current water temperature levels. Conversely, maintaining the tower size and fan power sacrifices slight increases in water temperature levels. Some increase in pump head and decrease in circulating water flow rate will also occur without pump modification. The fan power and pump head impact is minimized by use of dry sections in a siphon loop and by dry section dampering. The tower structure is generally modified to support the dry sections. A significant capital cost for such a conversion is typical and is not always economical in comparison to replacement with a new wet/dry tower. Careful consideration of the economics of conversion vs. replacement is particularly important for older towers.

PPWD APPLICATIONS

PPWD FIELD EXPERIENCE

Prototype. By 1970, a prototype PPWD installation provided an opportunity to confirm laboratory experience with the plume abatement concept in the field. Visible plume photography along with concurrent thermal performance tests at various weather and heat load conditions for the prototype test cell allowed correlation of the visual results to theoretical psychrometrics. This test data provided information for substantiation of mathematical modeling methods utilized in computerized performance programs. These rating programs define the average temperature condition end points of the four “flow stream” line segments needed for psychrometric analysis of plume abatement (see Figure 9). These four air flow streams are: the wet stream, the dry stream, the plenum stream and the fan discharge or fan to ambient mix-line stream. The actual position of the fan to ambient mix-line is defined by the ambient wet and dry bulb temperature at the lower end and by the average air wet and dry bulb temperature condition leaving the fan at the upper end.

The psychrometric chart example in Figure 9 illustrates an ambient condition of 37 wet bulb, 42 dry bulb at the lower end of the fan to ambient mix-line and an 80.1 dry bulb, 86% relative humidity average air condition at the top end of the fan to ambient mix-line, with the fan to ambient mix-line tangent to the saturation curve. This particular fan to ambient mix-line location represents a specific thermal performance test correlation to zero theoretical visible plume abatement capability on the prototype installation shown in Figure 10. Only the end cell of the prototype tower was backfit with dry sections as a PPWD.

Plume abatement observations and tests occurred for a variety of ambient conditions, heat loads, water loads and wet/dry face area ratios on the prototype and later commercial installations. Experience on the prototype and later crossflow towers confirmed the tendency for dry air to envelop the wet air at the center of the cell that results in the cone shaped residual visible plume as seen in Figure 10. Again, this is representative of the residual plume appearance of a crossflow PPWD at zero theoretical plume. The mixing continues after leaving the fan stack, as wet air mixes through the dry, and no plume is visible beyond 2-3 fan stack exit diameters.

Example PPWD Towers for Plume Abatement and Water Conservation. Figure 11 shows a production model PPWD tower designed for reduced water consumption. The wide design latitude available with the PPWD tower permits the tailoring of the tower selection to accommodate a wide range of plume abatement levels or water consumption requirements. Figure 12 shows a PPWD tower designed for visible plume control. Both of these towers utilize wet section damper operation to maintain a constant cold water temperature, in the one case to maximize water savings and in the other to minimize plume.

Example PPWD with Simultaneous Modes of Abatement. Figure 13 shows a large PPWD on a 330 MW fossil fueled power plant. This tower design was for only moderate plume abatement capability on 5 of the 7 cells in each tower. The photograph depicts conditions for slight plume producing psychrometrics (fan to ambient mix-line slightly crossing the saturation curve) on the third and fourth cells from the left, which have dry section dampers open. The first two cells on the left have no dry sections for plume abatement, and would normally not be operated in the winter at this plant. The fifth, sixth and seventh cells from the left have dry section dampers closed so that about 20% of the face area is open to air flow over the coils. The contrast between the all wet plume behavior and the
plume abated cell effluent characteristics with two damper positions makes this an interesting photograph.

Summary. Up to 20 years of successful operating life on the earliest installations confirm the theoretical performance for the Parallel Path Wet-Dry tower concept and the technical soundness of the design from a practical standpoint. More recent designs have evolved with changes in wet section technology, to include film type fill in both crossflow and counterflow for reduced power consumption and tower size requirements.

SELECTION OF DESIGN POINTS

Plume Abatement (Winter) Design Point. As an approach to selecting a plume abatement, or winter design point, consider a curve of ambient temperatures plotted on a psychrometric chart, for which a given piece of equipment will produce fan to ambient mix lines are exactly tangent to the saturation curve, or have zero theoretical visible plume. The curve is typically generated for operation of the equipment at various ambient temperatures and full design heat load, unless a profile of tower heat load versus wet bulb temperature is available. Figure 14 shows the method of generating this theoretical curve of ambient at which visible plume formation begins. This curve, known as a fogging frequency curve, is a tool to determine fogging frequency at a given site for a particular PPWD.

The fogging frequency curve divides the psychrometric chart into fog producing and non-fog producing conditions. The visible plume intensity increases as the ambient conditions represented on the psychrometric chart move to the left of the theoretical line, since the corresponding effluent-ambient mix lines move further into the supersaturated region. Site weather characteristics utilized with the fogging frequency curve allow determination of the fogging frequency, expressed as a number of hours per year or percentage of total hours for which visible fog may occur.

Figure 15 graphically shows a typical study showing a standard mechanical draft tower and a wet-dry tower with representative annual ambient weather occurrences superimposed. In practice, use a tabulation of coincident ambient wet bulb and dry bulb temperatures and the number of hours per year for which they occur. Check each point against the fogging frequency curve on an psychrometric chart. To allow approximation of the number of fog producing hours per year, sum the hours for points on the fogging side (left of the fogging frequency curve) typical for weather on the site.

For selection of a suitable winter design point, the nature of the visible plume concern is important. If the site location is in a well lighted and high traffic area with 24 hour a day visibility, or if the proximity of visible plume to a road or other icing or visibility risk area is a constraint, then all hours per year are important. If no plume is acceptable under any circumstances, the selected winter design point is near the lowest dry bulb, highest relative humidity point within the weather data. Such a severe plume abatement requirement is seldom the case.

The difficulty of the selected winter plume abatement design point drastically affects the cost of the dry section required to accomplish plume abatement. The specifying engineer and owner should consider the significant reduction in visible plume length and opacity from a plume abatement tower even when visible at a condition more severe than the design point. In some actual cases, use of 15% to 20% of the hours per year with theoretically visible plume is an acceptable criterion. In such a case, selection of a winter design point is along the upper edge of the typical weather data (as in Figure 15) at the point for which 15% to 20% of the hours per year are above and to the left of the fogging frequency curve and produce theoretical visible plume. The frequency of weather points above and to the left of the PPWD fogging frequency curve in Figure 15 represents about 20% of the hours per year. Note that a fogging frequency curve cuts across the weather data at a diagonal. Counting the hours below a particular dry bulb temperature, as some have tended to do, would incorrectly appear to about double the estimated number of hours of visible plume production.

In some cases, the visibility constraint does not apply to the late night time period when few if any observers will be around to see the plume. In this situation, many of the severest hours of the year in low temperature and higher night-time relative humidity are not relevant in determining the plume abatement design point. This can potentially have a very significant effect on the difficulty of the winter plume abatement design point, the size of the dry section, and the cost of the PPWD.

It is appropriate to specify a zero theoretical plume guarantee requirement for the manufacturer at a specified winter wet bulb and dry bulb condition, circulating water flow rate, cooling range and maximum concurrent cold water temperature. The specification should reference independent third party thermal testing of the overall tower according to the specific provisions of CTI ATC-105 for the thermal performance testing of wet/dry cooling towers, for both the summer and winter design operational modes.
For an integral film type design, separate dry performance measurements are not possible. In this case a complete set of effluent air wet bulb and dry bulb curves at varying water flows, ranges, and entering wet and dry bulb temperatures should be guaranteed. A complete thermal test, in conjunction with a detailed wet bulb, dry bulb and velocity traverse at tower discharge should be conducted to validate the guaranteed effluent air condition curves. This methodology can be used for any plume abatement tower design. It should be noted, however, that this type of test is about as difficult and complex as an isokinetic drift test which will make it impractical in cost for all but the very largest (and most expensive) plume abatement towers.

**Plume Abatement Tower Summer Design Point.**
Consideration of the economic effects of summer design point on plume abatement requirements requires a means of comparing the relative plume abatement capability of very different towers. If towers of varying configuration and design selection conditions produce fan-to-ambient mix lines that superimpose on one another for a specific ambient condition, the plume abatement performance of each is psychrometrically equivalent. One method to describe such psychrometrically equivalent mix lines is by the angle of the lines from the horizontal on a specific psychrometric chart at that ambient condition. The numerical value of the plume abatement angle will actually vary depending on the particular psychrometric chart used, as it is a function of the scale used in construction of the chart. The concept of psychrometric equivalence, in conjunction with the plume abatement angle at a reference ambient condition, allows description of relative levels of plume abatement capability.

Figure 16 is a chart showing the relative impact of difficulty of the summer thermal design point on the degree of difficulty of plume abatement duty for a family of crossflow splash-filled PPWD towers. Similar trends exist for other tower types. The plume abatement angle at a 37 wet bulb / 42 dry bulb reference temperature is shown versus the approach to a design wet bulb of 76 at 50% relative humidity for various cooling ranges and actual equipment configurations.

The graph includes a representative standard mechanical draft wet tower along with three ratios of dry to wet section (D/W) face areas of the PPWD design. There are many possible D/W’s due to the flexibility of the components and their arrangements. The D/W ratio is valid only for comparison of towers of very similar type, but is significant in that it relates to the relative ratio of dry and wet section air flow which, in turn, strongly affects plume abatement capability.

Figure 16 shows that for the same plume abatement capability, a tower designed for a closer, or more difficult, summer design approach requires less dry section than for one at a longer, or less difficult, summer design approach. This is a result of the fact that more difficult summer design duties require greater air flow rates through the wet sections. Higher air flow rates result in a lower amount of heat added per pound of air, or lower wet section effluent temperatures. Lower wet section exit air temperatures require much less dry section air flow, or dry air at lower temperatures, to pull the effluent to ambient mix line below the saturation curve.

Since the cost of the dry sections of a PPWD will often exceed the cost of the wet sections of the tower, a close approach PPWD may cost less than a PPWD with a longer approach for the same plume abatement design point. This is the opposite of the case for a conventional cooling tower. The strong message for the specifying engineer from this analysis is that a circulating water system with a plume abatement tower may optimize differently from a conventional cooling tower, particularly if the fan power evaluation is low. One may expect optimization at a different circulating water flow rate, cooling range, and approach temperature at the summer design point than a conventional cooling tower will have. In evaluating bids, specifiers should compare off-design cold water temperatures, as use of extensive wet section dampering will raise off-design cold water temperatures. In other words, the process may be hurt more by a design with smaller dry section requiring wet section dampering at the winter design point than by one not using dampering.

**Wet/Dry Towers for Water Conservation**

**PPWD FOR WATER SAVINGS**

One of the most significant aspects of wet-dry cooling towers is that they fill the void between an all wet system and an all dry system, with respect to their costs and water requirements. In a wet system, there are essentially two types of heat transfer that occur. The majority of the heat transferred from the water is through the latent process, or cooling the water by evaporating a small portion of the circulating water. The remaining heat is transferred by the sensible, or non-evaporative process, from the hot circulating water to the cooler air passing through the wet sections. The PPWD tower heat transfer process is more complex...
than all wet heat transfer due to the addition of the dry section. A continually changing balance occurs between the heat transfer in the wet and dry portions of a particular PPWD due to changes in the ambient conditions and heat load. When throttling the air mass flow through the wet section to minimize evaporation, the process becomes more complex to analyze due to varying air mass flow rates.

A cooling tower operating in a closed loop will dissipate all of the heat directed to it at some equilibrium hot and cold water temperatures that are appropriate to the tower characteristics, ambient conditions, and heat load. For a given wet bulb and dry bulb condition, the amount of evaporation that occurs in the evaporative process is primarily a function of the amount of heat dissipated and, secondarily, a function of the air rate and the water loading. Thus, the amount of evaporation in a parallel path wet/dry tower is possible from knowing the amount of heat rejected by the wet section.

While PPWD towers offer some reduction in water consumption over that of an all wet cooling tower, their water savings potential is limited. The obvious change in a plume abatement tower for reduction of water consumption is to increase the size of the dry sections to carry more of the tower heat load. This, in turn, leaves less evaporative heat transfer in the wet section. Since most PPWD towers use a common fan for the wet and dry sections, the dry side air rate is reduced as the physical size of the dry section increases, reducing the effectiveness of the dry section surface area. PPWD towers using siphon loops in the hydraulic circuit with vertical dry sections have a practical limitation in dry section height. For tubes installed vertically, the gauge pressure in the top header of such a dry section is approximately equal to the vertical elevation difference between the top of the dry section and the discharge to atmosphere less the friction loss in the second pass of the dry section. The absolute pressure in the top header is the site atmospheric pressure plus the (negative) gauge pressure in the top header. If this absolute pressure is below the saturation pressure of the water at the temperature of the water in the top header, boiling will occur. At sea level, and about 110°F, water temperature, the maximum practical vertical height between upper and lower headers in a two pass dry section is 32 feet. For those conditions a slight margin prevents boiling of water at the vacuum conditions in the upper headers. In the case of finned tube dry sections installed with horizontal tubes along the side wall of the tower, this limitation applies to the total height of the stacked headers. When the requirements are to dissipate greater cooling ranges than possible with vertical dry sections, dry sections can slope outward from vertical, and/or the number of fans per cell can be increased. Use of sloped tubes avoids exceeding the maximum allowable vertical siphon heights.

**DESIGN FOR LARGE SCALE WATER CONSERVATION**

**Description.** As the water saving requirement becomes more severe in comparison to all wet operation, the overall plan area and fan power requirement of the air cooled portion of the tower becomes much larger than required for the wet section. The largest wet/dry installation for water conservation at the present time has operated for about 15 years on a 550 MW mine-mouth coal-fired power plant as shown in Figure 17. The two 480 foot long towers have dry sections with 48 foot long tubes and a 24 foot high wet sections, for 70% water savings compared to an all wet tower. The dry sections are sloped so that the siphon loop in this tower is 20 foot high, allowing a comfortable margin to prevent boiling in the upper headers as the tower is at about 5000 ft elevation and the design hot water temperature is about 125 °F. The arrangement shown has 96 foot long cells for the dry section, with four 10 meter diameter fans at 200 BHP in a common plenum for each cell. The wet sections are only 32 foot long, and each has a single 24 foot diameter fan at 75 BHP. This leaves a 64 foot open area between wet sections, under the dry portion of the tower. (See Figure 18.)

This open area between wet sections, below the dry sections, allows ventilation of the leeward wake that would normally occur downwind of such a large structure. The configuration for this tower had extensive modelling in the water flume at the Iowa Institute of Hydraulics Research to determine its recirculation characteristics. The recirculation of heated air from the fans into downwind air inlets for this configuration is very low. Without the ventilation feature, the dry sections would have to be significantly oversized to account for recirculation. (See Figure 19.)

**Water Conservation Tower Operation.** When the allowable water consumption is very small as compared to an all wet tower, it becomes necessary to isolate the airflow from the wet sections with separate fan control. (See Figure 20.) Modulation of wet section performance is, in this case, accomplished by shutting off wet section fans progressively to keep the cold water temperature within a pre-set band. The water from dry sections collects in a flume that carries it to the wet section centered under the dry sections for each cell. Bypass lines from these flumes can divert water leaving the coils directly into the cold water basin. Using these bypass lines to shut off the water to the wet sections at
the same time as fans are shut off maintains positive control over evaporation. If the water were not off in this mode, the natural draft due to heat load would result in undesired air flow and evaporation in the wet sections.

This large water conservation tower utilizes the same vent manifold system as described for PPWDs to protect the parallel siphon loops operating in the tower during start-up and shut-down. For this site, multiple pump and multiple tower operation require an additional feature in concert with the vent system to allow shut-down and draining of one tower while the other remains operating at reduced total flow. This feature is a draining system in the risers of each tower. The riser drains open along with the vent manifold valves in that tower when tower isolation valves close and a circulating pump is shut off. Both passes of the dry sections and the distribution piping can drain into the cold water basin, while the other tower continues operating.

Summary. A water conservation tower of the general configuration shown in Figures 17-20, having either crossflow or counterflow wet sections, allows tuning of the dry/wet percentage to suit virtually any water consumption requirement. Even in cases where water consumption is a severe constraint, it is most economical to use the maximum possible amount of water that is available. Evaporative heat transfer is more cost effective than dry cooling so that the use of the maximum amount of available water in wet sections for the peak summer conditions will optimize relative to an all dry tower. The water conservation tower concept shown allows a flexible, highly controllable, integrated design with the ability to operate over a wide variation in water consumption requirements.

Split Condenser Systems

Another wet/dry configuration recently employed for power plants uses a split steam duct from the turbine. One branch leads to an air-cooled condenser and the other to a surface condenser connected to a wet tower as shown in Figure 21. This system is not properly a wet/dry tower design, but warrants discussion as an alternative for plume abatement and water conservation.

This combination uses the maximum available amount of water with a separate wet tower to reduce the size and cost of the air-cooled condenser. This system can also be used to accomplish severe plume abatement requirements by using a wet/dry tower designed for plume abatement in place of the wet tower. In either case, the system diverts as much load as economically possible to the air-cooled condenser and operates all dry under some conditions. Obviously, a very carefully designed air-cooled condenser is required in freezing climates. Several installations are operating or are under construction using this concept.

Summary

An overview has been presented of the wet/dry concepts which are available. Some of the concepts have established as much as 20 years of operating experience. The established record of some of these designs should be timely and reassuring for potential users in a marketplace with increasing environmental sensitivity.
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