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Open Cooling Tower Design Considerations

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The design decisions made in selecting and sizing cooling towers and their components has a direct impact on the performance of the overall chiller water plant. A cooling tower's long-term performance is a function of the details of design for the cooling tower and its supporting components.

This month, I point out some common problems that must be addressed in cooling tower selection and the design of condenser water systems. These problems can impede the system's ability to perform reliably and efficiently. These are all examples from actual facilities that I have designed, peer reviews I have performed on designs by others, or retrofits of systems designed by others.

Principle of Operation

Evaporation is a cooling process. Cooling towers use the internal heat from water to vaporize the water thus removing heat from the water. Sensible heat that changes temperature is also responsible for a small part of the cooling tower's operation. A cooling tower's purpose is to expose as much water surface area to air as possible to promote the evaporation of the water. In a cooling tower, approximately 1% of the total flow is evaporated for each 10°F (6.9°C) temperature change. Range and approach are two important terms used in the discussion of cooling towers (see sidebar, *Cooling Tower Terminology*, Page 53).

The performance of a cooling tower is a function of the ambient wet-bulb temperature, entering water temperature, airflow, and water flow. The dry-bulb temperature has an insignificant effect on the performance of a cooling tower. Performance also is a function of the physical design of the tower.

Design Considerations

Selection Criteria

ASHRAE/IES Standard 90.1 and California's Title 24 use minimum gpm/hp (L/s·kW) to specify minimum tower performance. These minimums are based on a tower selection with 95°F/85°F (35°C/29.4°C) hot/cold water temperatures with an entering wet-bulb temperature of 75°F (23.9°C). The cooling tower horsepower is the fan motor nameplate power.

There are five parameters that define the performance of a cooling tower: hot water temperature, cold water temperature, wet-bulb temperature, water-flow rate, and airflow rate. The first four items are usually provided by the designer while the fifth is selected by the cooling tower manufacturer. Taylor has provided excellent guidance on selecting tower approach and efficiency using life-cycle cost based selection.[1] A narrower approach will provide a lower cooling tower leaving water temperature resulting in higher chiller efficiency due to reduced lift on the chiller. The narrower approach temperature will typically require a larger cooling tower with more fill.

The location of the cooling tower should be selected to minimize recirculation by following the manufacturer's layout guidelines. Forced draft towers are characterized by high air entrance velocities and low exit velocities. Accordingly, they are extremely susceptible to recirculation and are considered to have less performance stability than the induced draft type. The author has successfully used an allowance of 1 to 2°F (0.6 to 1.1°C) wet-bulb margin of safety added to the ambient wet-bulb temperature when recirculation cannot be avoided. The designer should increase the entering wet-bulb temperature when some recirculation is anticipated.

There are a variety of cooling tower material choices available to construct a cooling tower. Cooling towers and

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the areas around them are typically in a continuous corrosive environment. Stainless steel, fiberglass and concrete will outlast galvanized steel towers. It is always important to ensure the water treatment program is compatible with the materials used in the cooling tower. An example would be using soft water with low dissolved ion content in a concrete cooling tower. Control and power wiring in PVC coated galvanized rigid steel conduit provides excellent service life. Thin walled EMT should be avoided around cooling towers.

Open Piping System Problems to Avoid

Cooling tower hydronic problems can occur when working with open towers. These problems are generally related to one or several of the following issues and can be avoided:

Pump cavitation is the flashing of water into a vapor due to excessively low suction pressure. Cavitation sounds like the pump is pumping gravel and can cause severe damage to the impeller. Net positive suction head (NPSH) is the measure of suction pressure. The suction pressure required to prevent cavitation for a particular pump is indicated as NPSHR and is published on the pump curve. The NPSH available (NPSHA) must be calculated by the designer to confirm that the NPSHA > NPSHR or pump cavitation will occur.

NPSHA (in feet) is calculated using *Equation 1*:

$$NPSHA = \frac{2.31}{s}\left(P_a - P_{vp}\right) + \frac{\left(V_a^2 - V_s^2\right)}{61.3} + \left(Z_a - Z_s\right) - H_{a\rightarrow s} \quad (1)$$

where s is the specific gravity of the fluid (= 1 for water), P is absolute pressure (psia), v is velocity (fpm), and H is the head loss (feet) due to piping, fittings, valves etc. These are defined at two points: Point a, which is a reference point in the system where conditions are known, and Point s, which is the pump suction. For open systems such as cooling towers, point a is the top of the tower cold water basin. P_{vp} is the vapor pressure of the fluid at the pump suction, which is a function of fluid temperature. For a typical condenser water supply of 80°F (26.6°C), P_{vp} is 0.5 psia (3.45 kPa).

Many engineers get concerned about maintaining NPSHA in open cooling tower systems and consequently insist on elevating the tower basin well above the pump suction. But this is in fact not necessary because atmospheric pressure (P_a) is so high (14.7 psia [101.4 kPa] at sea level). For instance, assuming the suction line pressure drop (H_f) between the basin and the pump suction is 2 feet and the pump suction elevation is the same as the basin elevation, the NPSHA is:

$$NPSHA = \frac{2.31}{1}\left(14.7 - 0.5\right) + \frac{\left(0^2 - 12^2\right)}{61.3}\left(0\right) - 2 = 28.5 \text{ ft} \quad (2)$$

This is well above NPSHR for common pumps. So cavitation is seldom an issue as long as the pressure drop between the basin and the pump suction H_f is reasonable. Accordingly, avoid fine mesh, high pressure drop strainers in the suction line when the pump elevation is near that of the basin. Fine mesh strainers in this case should be installed on the pump discharge or at the inlet to the condensers when the pump suction is under negative pressure. Install a compound pressure gauge on the pump suction when anticipating zero to slightly negative suction pressure.

What is often mistaken as cavitation is another phenomenon that occurs when the pump is not located well below the basin: air that is dissolved in the water in the tower basin comes out of solution as the pressure drops when water flows into the pump suction. These air bubbles can make a gurgling sound that is similar to (but not as loud as) the sound of cavitation. It is generally harmless to the pump, although the pump flow and head will suffer and efficiency will be reduced. To completely prevent this from occurring, the pump must be below the tower basin by an elevation equal to or larger than the NPSHR plus the pressure drop of the inlet piping H_f.

Air traps in the piping between the collection basin and pump suction can lead to improper pump operation. The collection basin water is full of entrained air, so air in the piping should be assumed. The author has witnessed pumps located too close to the basin (less than 10 pipe diameters) draw entrained air from the cooling tower collection basin into the pump suction. Remember, air vents will not remove air trapped in a negative pressure suction line. It is important to slope piping up toward the tower collection basin and avoid any vertical piping traps that would collect air in the pump suction line. Design for eccentric reducers located top side flat, so as not to trap air at the pump suction.

Cooling tower overflow on shutdown is typically caused by draining back water to the basin upon shutdown. The collection basin is designed to hold the pull down volume of the tower that includes the full volume of water in the distribution basin, fill, and overhead supply piping from

FIGURE 1 Incorrect cooling tower bypass.

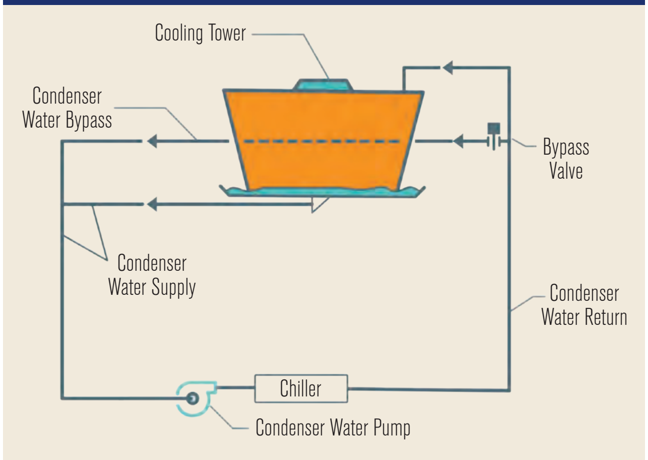
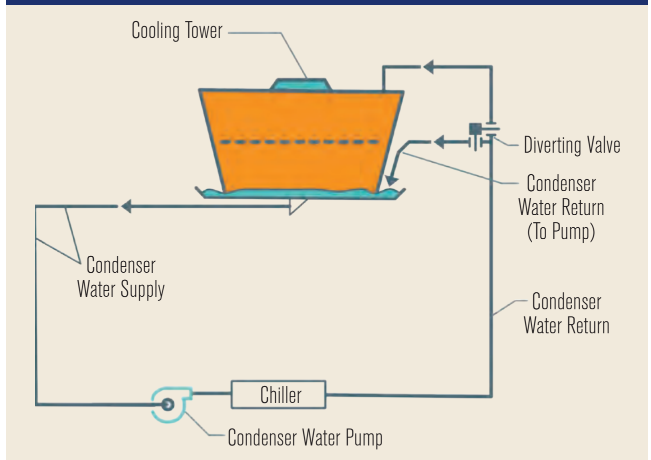


FIGURE 2 Correct cooling tower bypass.



the tower. It is preferred to minimize the amount of horizontal pipe above the distribution basin. Where that cannot be avoided, an inverted water trap on the hot water pipe at the inlet to the distribution basin will limit the pull down volume. A functioning check valve on the condenser water pump will restrict water from falling back to the collection basin through the tower discharge pipe.

Air introduction to pump suction can be caused by tower pan vortexing, tower pan drain down, or the pumps located too close to the collection basin. Vortexing usually occurs with excessive collection basin discharge pipe velocities. Vortexing can be avoided by maintaining the tower exit pipe diameter for a minimum of 10 pipe diameters, installing a vortex breaker in the tower pan where the cold water exits (standard on most towers), and not exceeding manufacturer's stated maximum flow rate. Tower pan drain down is when the tower draws air into the pump suction upon startup. This is a consequence of the tower collection basin overflowing on shutdown. When the tower starts, the water in overhead supply piping needs to fill the pipe prior to reaching the collection basin. This can typically be avoided with proper attention to the piping design mentioned previously to minimize overflow at shutdown.

Improper equalizing line sizing on multiple towers piped in parallel can cause unbalanced water flow through the tower. If the collection basin water levels are not equal, one tower could draw air into the outlet while the other tower overflows. All connected towers should be installed to have their overflow levels at the same elevation. Isolation valves at the inlet and outlet of each tower can also assist in final balancing of water flow. An equalizing line with isolation valves should be adequately sized so that minimal water level differential exists between operating collection basins. The isolation valves should allow for one tower to be taken out of service while the others remain active. This situation can usually be avoided by paying attention to the design and sizing of the equalizing line. Follow the tower manufacturer's recommended guideline for sizing. A means of cleaning the equalizer line should be designed if the equalizer is below the collection basin since it will collect particulate matter.

Improper bypass configuration can sometimes cause air introduction into the pump inlet. The author has witnessed tower bypasses as shown in *Figure 1* where a two-way valve was used between the cooling tower inlet pipe above the collection basin and pump suction without automatic isolation on the cooling tower inlet. This type of bypass can lead to air introduction from the cooling tower return pipe located above the collection basin when in full bypass. Three-way mixing valves on the pump suction should also be avoided since this can cause additional pump suction pressure drop. These problems can be avoided by piping the bypass directly to the collection basin, not to the suction piping as shown in *Figure 2*.

Modulating Flow

All cooling towers have a minimum flow requirement that is defined as the allowable turndown. Most energy codes (such as Standard 90.1) require a minimum turndown of 50%; in a two-chiller plant, this allows one condenser water pump and one chiller to operate with both cooling towers enabled. With variable speed drives on the tower fans (also required by most energy codes), efficiency is always improved by running as many towers as allowed by the minimum flow rate. For instance, operating two

Cooling Tower Terminology

Ambient Wet-Bulb Temperature. The wet-bulb temperature of the air encompassing a cooling tower, not including any temperature contribution by the tower. Generally measured upwind of a tower, in a number of locations sufficient to account for all extraneous sources of heat.

Approach. Difference between the cold water temperature and either the ambient or entering wet-bulb temperature.

Atmospheric. Refers to the movement of air through a cooling tower purely by natural means, or by the aspirating effect of water flow.

Blowdown. Water discharged from the system to control concentrations of salts and other impurities in the circulating water.

Capacity. The amount of water (gpm) that a cooling tower will cool through a specified range, at a specified approach and wet-bulb temperature.

Casing. Exterior enclosing wall of a tower, exclusive of the louvers.

Cell. Smallest tower subdivision, which can function as an independent unit with regard to air and water flow; it is bounded by either exterior walls or partition walls. Each cell may have one or more fans and distribution systems.

Circulating Water Rate. Quantity of hot water entering the cooling tower.

Cold Water Temperature. Temperature of the water leaving the collection basin, exclusive of any temperature effects incurred by the addition of makeup and/or the removal blowdown.

Collection Basin. Vessel below and integral with the tower where water is transiently collected and directed to the sump or pump suction line.

Counterflow. Airflow direction through the fill is counter-current to that of the falling water.

Crossflow. Airflow direction through the fill is essentially perpendicular to that of the falling water.

Cycles of Concentration (C.O.C). The ratio of dissolved solids in circulating water to the dissolved solids in makeup water.

Distribution Basin. Shallow pan-type elevated basin used to distribute hot water over the tower fill by means of orifices in the basin floor. Application is normally limited to crossflow towers.

Distribution System. Those parts of a tower, beginning with the inlet connection, which distributes the hot circulating water within the tower to the points where it contacts the air for effective cooling. May include headers, laterals, branch arms, nozzles, distribution basins and flow-regulating devices.

Drift. Circulating water lost from the tower as liquid droplets entrained in the exhausted airstream.

Drift Eliminator. An assembly of baffles or labyrinth passage through which the air passes prior to its exit from the tower for the purpose of removing entrained water droplets from the exhaust air.

Entering Wet-Bulb Temperature. The wet-bulb temperature of the air actually entering the tower, including any effects of recirculation. In testing, the average of multiple readings taken at the air inlets to establish a true entering wet-bulb temperature.

Evaporation Loss. Water evaporated from the circulating water into the airstream in the cooling process.

Fill. That portion of a cooling tower, which constitutes its primary heat transfer surface.

Forced Draft. Refers to the movement of air under pressure through a cooling tower. Fans of forced draft towers are located at the air inlets to force air through the tower.

Hot Water Temperature. Temperature of circulating water entering the cooling tower by means of an induced partial vacuum. Fans of induced draft towers are located at the air discharges to "draw" air through the tower.

Makeup Water. Water added to the circulating water system to replace water lost by evaporation, drift, windage, blowdown, and leakage.

Mechanical Draft. Refers to the movement of air through a cooling tower by means of a fan or other mechanical devices.

Natural Draft. Refers to the movement of air through a cooling tower purely by natural means. Typically, by the driving force of a density differential.

Nozzle. A device used for controlled distribution of water in a cooling tower. Nozzles are designed to deliver water in a spray pattern either by pressure or gravity flow.

Plume. The effluent mixture of heated air and water vapor (usually visible) discharge from a cooling tower.

Range. Difference between the hot water temperature and the cold water temperature (HW-CW).

Recirculation. Describes a condition in which a portion of the tower's discharge air re-enters the air inlets along with the fresh air. Its effect is an elevation of the average entering wet-bulb temperature compared to the ambient.

Windage. Water lost from the tower because of the effects of wind.

Note: Terminology compiled from various manufacturers and the Cooling Tower Institute.

towers at 50% speed uses half the energy of running one tower at 100% speed. Operating the tower below its minimum flow turndown can result in the eventual buildup of mineral deposits (scale) on the cooling tower fill. The purpose of maintaining the minimum flow is to ensure the fill remains sufficiently wet to provide consistent heat transfer.

Water Treatment

Cooling towers are notorious for requiring high maintenance. By their design, open cooling towers are prime candidates for contamination issues since they are very effective air scrubbers removing particulate matter from the air. Because they are open to the atmosphere, the water is oxygen-saturated, which can cause corrosion in the tower and associated piping. Towers evaporate water, leaving behind calcium carbonate (hardness) that can precipitate out on the tubes of the condensers and decrease heat transfer and energy efficiency.[2]

Towers must be cleaned and inspected regularly. Well-maintained and regularly cleaned cooling towers have generally not been associated with outbreaks of Legionellosis. It is best to contract with an experienced cooling tower water treatment specialist. Corrosion can be caused by high oxygen content, carbon dioxide (carbonic acid), low pH, or high dissolved solids.

Mineral scale is the silent threat to plant efficiency due to loss of heat transfer efficiency. Scale is mainly composed of inorganic mineral compounds such as calcium carbonate, magnesium silicate, calcium phosphate and iron oxide. These minerals will tend to precipitate in warmer condensers if left to concentrate without control. It is necessary to continuously blow down a portion of circulating water to maintain a proper total dissolved solids content level in a cooling tower. This loss of water from the system is necessary and cannot be avoided for the successful operation of the cooling tower. A rule of thumb is that for a buildup of no more than two to four concentrations of hardness, the blowdown rate should be about 0.5 to 1.0% of the total flow rate.

Control of the pH (acid levels) is also important for scale control. Acids, inorganic phosphates, or similar compounds are commonly used to control pH. Slime and algae are handled with shock treatments of chlorine or chlorine compounds. It is best to alternate between two different compounds so that organisms do not develop a tolerance to the chemicals. Foam and scum in the cooling tower basin is usually caused by excess organic material. Cleaning the basin is the best remedy. Side stream filters with basin-sweep eductors should be considered for removing solids from the basin and recirculating water. These filters generally include high pressure drop, high energy use pumps so their use is recommended only where there are high concentrations of airborne particles, such as near farming, freeways, and airports. To limit energy use, filters should be operated on a time schedule for a few hours per day on days when the tower has operated, preferably during off-peak energy rate periods; the exact time period required must be determined empirically by the plant operator.

PHOTO 1 SDSU cooling tower.

Non-chemical technologies are available for the treatment and cleaning of cooling towers. The design engineer should carefully review all proposed chemical treatment and alternate technologies for each specific application. Makeup water chemistry can vary significantly from location to location and what works in one facility may not work in other facilities. The *ASHRAE Handbook—HVAC Applications*[3] provides good guidance on cooling tower water treatment.

Conclusion

Cooling tower performance and operation are a function of both good tower selection and system design for the condenser water system. Poor cooling tower selection or implementation can have significant long-term problems and costs on chiller plants. Hopefully, these tips can help designers and chilled water plant operators improve cooling tower and condenser water system performance.

References

1. Taylor, S. 2012. "Optimizing Design & Control of Chilled Water Plants—Part 4: Chiller & Cooling Tower Selection." *ASHRAE Journal* 54(3).

2. Peterson, K. 2009. "Cooling Systems and Thermal Energy Storage." APPA Body of Knowledge Section III-B: District Energy Systems.

3. *2015 ASHRAE Handbook—HVAC Applications*, Chap. 49. ■