Practical Methods for Achieving Cooling Tower Water Savings

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Cooling towers are routinely used in the utility and manufacturing industry for removing waste heat from utility and process applications. These include turbine condensers, comfort cooling, temperature and humidity control, and process cooling.

From the mechanical engineer's perspective, the purpose of a cooling tower is to reject waste heat to the atmosphere by evaporative and sensible heat transfer. The environmental engineer's stance is slightly different. Cooling towers are water conservation devices. From this view,the purpose of a cooling tower is to conserve water. It fulfills it's purpose by rejecting unwanted heat to the atmosphere so that the cooler water can be recycled back to the point of heat exchange. From this perspective one can argue that the operation of a cooling tower is best measured in terms of how efficiently it reduces freshwater withdrawals and wastewater discharge and not just by how efficiently it rejects heat, although that is an important consideration and should not be ignored.

In a study performed by the California Utilities Statewide Codes and Standards Team (October 2011) and adopted in the 2013 California Building Energy Efficiency Standards, they conclude that "most towers are not operated in such a manner as to maximize cycles of concentration and minimize water losses." They further conclude that because of the diversity and complexity of water treatment technology most cooling tower operations adopt an "overly conservative approach to tower bleed frequency."

That said, it is well accepted that cooling tower efficiency can be improved by increasing the cycles of concentration. How this is best achieved requires a practical understanding of the various water quality and treatment technology options.

CYCLES OF CONCENTRATION

Cooling towers achieve their purpose by rejecting waste heat to the atmosphere by latent and sensible heat transfer. Approximately 0.1% of the water that flows through the cooling tower is evaporated for every 1 degree temperature drop across the tower.

The water that is evaporated is pure. That is, it does not contain any of the dissolved solids (minerals) contained in the cooling tower makeup. As a result, the dissolved solids concentrate in the cooling water over time. If this is allowed to continue without limit, eventually the dissolved solids reach their solubility limit and precipitate as an insoluble scale or sludge in the heat exchangers, tower fill and basin.

As shown in Figure 1, cooling towers are designed with a bleed line that sends a flow of concentrated cooling water to drain. The bleed (also know as blowdown) controls the concentration of dissolved solids to keep them below their solubility limit. This prevents the formation of unwanted scale deposits. In order to prevent the tower from running dry, water that is lost by evaporation and bleed must be replaced by fresh makeup. From this, it follows that the makeup rate equals the evaporation rate plus the bleed rate.

A fundamental measure of cooling tower efficiency is cycles of concentration (also known as concentration ratio). Cycles of concentration (COC) is defined by the ratio of the dissolved solids in the tower water to the dissolved solids in the makeup. This is easily and commonly determined by taking the specific conductance of the cooling water and dividing it by the conductance of the makeup.

An alternate, equally accurate method, of calculating cycles of concentration is to take the makeup volume and divide it by the bleed volume. This is easily done if the tower is equipped with water meters on the makeup and bleed lines, a practice that is highly recommended.

Defining COC is easy. Determining the optimum COC that yields maximum water efficiency without producing energy-robbing scale deposits in the heat transfer areas of the process is more difficult.

Referring again to the California Building Energy Efficiency Standards, the investigative team found that the typical cooling tower operates between 3 and 4 cycles of concentration. They adopted 3.5 cycles for their water and energy saving calculations. The study further concluded that because of the variability of local water quality and the inherent complexity of water treatment technology, 3.5 cycles tends to be overly conservative and below the average permissible COC, which the studied indicates is 4.9.

This begs the question, is 4.9 cycles of concentration a realistic and practical target for cooling tower COC?

Figure 2 illustrates the relationship between cooling tower makeup and cycles of concentration. This is a diminishing returns curve in that the makeup rate decreases significantly if one goes from 2 cycles to 5 cycles, for example. At about 10 cycles of concentration,however, the curve begins to "flatten out". Further increases in cycles yields minimal reduction in makeup water rates. From this, towers that operate in the 10 to 12 COC range have achieved a reasonable and practical limit for water efficiency. The makeup rate decreases by 21% when cycles are increased from 3.5 to 10, for example, as compared to a 11% decrease when cycles are increased to 4.9.

All of this begs a second question, if 10 to 12 cycles of concentration represents an optimum water efficiency standard, why are most towers operated at 3.5 COC and should we be satisfied if we increase that to 4.9 COC?

FACTORS THAT LIMIT CYCLES OF CONCENTRATION

Maximum cycles of concentration are determined by the local makeup water quality. Since water sources vary significantly from location to location, it is necessary to determine the local water quality by laboratory analysis. This should include calcium hardness, magnesium hardness, total alkalinity, sulfate, silica, pH and specific conductance. These parameters can then be used to determine the limitations on COC imposed by the solubility of calcium carbonate, calcium sulfate, and silica, since these are the primary contributors to mineral scale and sludge deposits. Some times calcium phosphate is a concern especially if water treatment chemicals containing phosphate-based corrosion inhibitors are used. In this case, the water chemistry is controlled to minimize the deposition of calcium phosphate.

Since calcium carbonate is the primary scale-forming impurity in a majority of water supplies, the Langelier Saturation Index (LSI) is often used to determine the maximum permissible COC based on calcium carbonate solubility. This index is computed from the cooling water pH, total dissolved solids, temperature, calcium hardness and total alkalinity. An LSI index value of 0 indicates the water is neutral; neither scale-forming nor scale-dissolving with respect to calcium carbonate. A positive value indicates the water is scale-forming. A negative value suggests the water is scale-dissolving or corrosive. Cooling tower concentration ratios are set to maintain the LSI of the recirculated cooling water in the +2.0 to +2.5 range. The LSI, however, only applies to calcium carbonate solubility and says nothing about the tendency to form other deposits such as calcium sulfate, calcium phosphate or silica.

It should be noted that calcium plays a dominate role in causing scale deposits and therefore, poses the primary limitation in achieving maximum COC. In general, cooling towers that operate on makeup that is low in calcium hardness achieve higher COC than towers that use high hardness/high alkalinity makeup.

WATER TREATMENT OPTIONS THAT INCREASE COC

Traditional water treatment programs are designed to prevent mineral scale deposits, inhibit corrosion, minimize suspended solids fouling and control the growth of bacteria and other microorganisms. Various treatment formulations and methods have been used in cooling tower operations with considerable success. The main objective is to prolong the useful life of plant equipment and maintain efficient heat transfer.

As indicated in the California report, 3.5 COC is typical of most conventional chemical treatment programs. In order to increase COC, it is necessary to pretreat the cooling tower makeup to adjust the impurities that limit the cycles of concentration. This is done by (1) injecting mineral acid to reduce the carbonate alkalinity and maintain a near-neutral pH in the cooling water; (2) softening the makeup to remove calcium and magnesium hardness (the primary scale-forming impurities); and/or (3) installing a non-chemical water treatment device.

Acid Injection: Mineral acid, such as sulfuric or hydrochloric, neutralizes carbonate alkalinity resulting in a decrease in pH. Reducing the carbonate alkalinity increases the solubility of calcium salts such as calcium carbonate by preventing the formation of carbonate ($CO3$)alkalinity and its subsequent reaction with calcium hardness to form lime scale.

Traditional cooling water programs use acid to control the recirculating water pH within a narrow range of 7.0 to 7.5. Because the acid makes the water more corrosive, a corrosion inhibitor such as chromate (no longer allowed in the US), zinc and/or phosphate are used in conjunction with the acid to protect system metals from corrosive attack.

This approach works as long as the acid feed and pH are controlled within recommended limits. Upsets such as over- or under- feed conditions, however, cause either an unacceptable scaling condition (high pH) or a serious corrosive environment (low pH).

Further, maintaining the pH within 7.0 to 7.5 creates a very favorable environment for the growth of bacteria and algae. This requires the diligent application of oxidizing and non-oxidizing biocides to keep bacteria populations in check.

Water Softening is used to remove or reduce calcium hardness from the makeup. Large installations may use precipitation units such as lime or lime-soda softeners. These reduce carbonate hardness and alkalinity by reaction with hydrated lime (calcium hydroxide, $Ca(OH)_2$). If removal of non-carbonate hardness is required, soda ash (Na_2CO_3) is added in conjunction with lime.

For smaller cooling towers, it is more practical to use an ion exchange (also known as a sodium zeolite) softener to reduce the calcium and magnesium hardness to zero. Sodium ion exchange softeners do not reduce carbonate alkalinity, however, as in the case of lime softening or pH control.

A softener has a limited exchange capacity, which requires that the unit be periodically regenerated with salt ($NaCl$). Since cooling towers require a continuous supply of makeup, pretreatment softeners are designed with multiple exchange beds so that one vessel is always in service while the other is in regeneration.

Softening cooling tower makeup has the advantage of removing calcium which is the primary limiting factor for achieving optimum cycles of concentration. This produces a secondary, but equally important, benefit of allowing the cooling tower to operate at higher carbonate alkalinity and pH levels. Cooling towers operating on soft water makeup may have a total alkalinity over 2000 ppm and a corresponding pH of 9.2 to 9.6. Carbonate alkalinity is a natural corrosion inhibitor. Independent studies confirm that the solubility of iron, copper and zinc are at a minimum under high pH/alkalinity conditions, which suggests that the driving force for corrosion is greatly reduced.

High pH/alkalinity serves as a natural bacteriostat by creating an environment that is outside the amplification range of most bacteria and algae. Using soft water makeup enables this by permitting the operation of the cooling tower at 10 cycles of concentration or above. Under these conditions, the need for biocides is greatly reduced. If an oxidizing biocide is used such as chlorine or bromine, the high pH tends to stabilize the oxidizer and the higher COC extends the retention time of the biocide in the cooling tower for enhanced contact with the bacteria.

Non-Chemical Water Treatment Technology

A variety of non-chemical water treatment equipment is marketed for use in protecting cooling systems from scale deposition, corrosion and microbiological growths. These devices employ a variety of chemical and physical properties such as magnetic, electromagnetic, and electrostatic fields; electro-deposition, electrolysis, membrane separation, ultrasonic and pulsed-power technology, to name a few. Some applications require the use of traditional water treatment chemicals in addition to the non-chemical equipment, which adds complexity to the problem.

Considerable debate surrounds the efficacy and performance of non-chemical water treatment equipment. The fundamental question is whether the technology has the capability to produce the intended effect as claimed in the manufacturer's advertising. In the absence of independent, 3rd party evaluations, the manufacturers strive to silence skeptics by offering case studies and testimonials from satisfied customers. Some of these studies suggest that cooling towers can be operated with minimal bleed at very high cycles of concentration. This has considerable appeal for owner/operators who would like to eliminate the purchase, shipping, handling and storage of traditional water treatment chemicals.

Summary

Cooling towers are water conservation devices. They fulfill their purpose by the rejection of waste heat to the atmosphere by evaporative and latent heat transfer.

To achieve optimum efficiency, cooling towers should be operated at maximum cycles of concentration. Studies suggest that the typical cooling tower is operated at 3 to 4 cycles of concentration, which is very conservative. Water treatment technology exists that permits cooling towers to achieve 10 to 12 cycles of concentration while still maintaining clean, corrosion-free heat transfer surfaces. Applying these methods results in a significant reduction in fresh water withdrawals, chemical consumption, energy and waste.