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Basic Calculations Necessary to Survive in the Field—Part I: Cooling Water

By Chris Golden, CWT, Taylor Technologies, Inc.

Knowing the proper calculations to use in the field is critical to the professional water treater. With this knowledge in hand, and a proper diagnosis, the correct treatment of a system can be determined. These essential calculations can be grouped into four applications: cooling water, boiler water, pretreatment, and wastewater. Part I of this series addresses cooling water systems.

Mass Balances

Whatever substances (mass) enter a system must either leave the system or accumulate. In other words, "the books must balance" — everything should be accounted for. Here are the most frequently used equations for performing mass balance evaluations in cooling water systems.

In an open recirculating cooling water system with a heat load, water is constantly leaving the system through evaporation, and intermittently (sometimes continuously) leaving the system through blowdown. In general, 1 % of water is lost through evaporation for every 10 °F temperature drop across the tower. A simplification of this relationship is:

$$ER \text{ (gpm)} = F \times \Delta T \text{ (°F)} \times RR \text{ (gpm)} / 1000 \qquad (1)$$

Where:

ER = evaporation rate
F a factor accounting for heat absorption through sensible heat
ΔT is the temperature difference across the cooling tower in °F and
RR = recirculation rate

The factor F can vary from 0.75 through 1. The average value is 0.8. The factor reflects the relative humidity in the vicinity of the tower. The lower values are used in areas of high humidity or warmer weather, whereas higher values are used for areas of low humidity or colder weather. ER represents, on average, how much pure water is leaving the system through evaporation from the cooling tower. Here are short-cuts to determine ER based on system type.

On a centrifugal chiller, the generally accepted calculation is:

$$ER \text{ (gph)} \cong 1.8 \times \text{Chiller Capacity (tons)} \times \% \text{ Load} \qquad (2)$$

On an absorption chiller, the generally accepted calculation is:

$$ER \text{ (gph)} \cong 3.2 \times \text{Chiller Capacity (tons)} \times \% \text{ Load} \qquad (3)$$

Another way to calculate the evaporation rate is:

$$ER = \frac{\text{(Heat Load in BTU/hr} \times 24 \text{ hr/day} \times 0.8)}{(1{,}040 \text{ BTU/lb} \times 8.345 \text{ lb/gal})} = \text{gal/day} \qquad (4)$$
$$ER = 0.0022 \times \text{(Heat Load in BTU)/hr} = \text{gal/day}$$

The recirculation rate can be found by referring to a system's engineering drawings, control screens, a pump's nameplate, or by estimating the number using:

$$RR \text{ (gpm)} \cong 3 \times \text{Tower Tonnage} \qquad (5)$$

As pure water evaporates from the cooling system, dissolved solids left behind concentrate in the bulk cooling water. The degree of the concentration of these solids is referred to as the concentration ratio (CR), also called the cycles of concentration. There are various ways to determine this value. The best practice is:

$$CR = \text{(Make-up Rate) / (Blowdown Rate)} = MU/BD \qquad (6)$$

where the BD also includes tower water lost due to drift. Water meters can determine MU and BD, and drift or windage (which is often negligible) can be calculated:

$$\text{Drift} = F_D \times RR \qquad (7)$$

where F_D (a drift factor) ranges from 0.05 % to 0.2 %. The higher values pertain to older towers. Newer towers are guaranteed at least 0.05 % of the recirculating rate. The most common value for F_D is 0.1 %.

If the water has been tested, then a comparison of the chemistries of the cooling water to the make-up water can be made.

$$CR \cong \text{(Cooling Water Conductivity) /}$$
$$\text{(Make-up Water Conductivity)} \qquad (8)$$

Although this simplification will be close, the result is affected by chemical additions (such as acid, chlorination, and other treatments) which, themselves, add conductivity to the tower water. A better method to determine the concentration ratio is:

$$CR \cong \text{(Ionic Species in the Cooling Water) /}$$
$$\text{(Same Ionic Species in the Make-up Water)} \qquad (9)$$

where the ionic species can be any analyte, which is highly soluble in most systems. As shown in equation 8, conductivity provides a close approximation to cycles of concentration. Other substances that will cycle are total hardness, calcium hardness, and total alkalinity. Very soluble ions (i.e., chloride from oxidizing biocides) are not normally used to represent cycles of concentration due to their ubiquitous nature. Note that any precipitation of a hardness salt will reduce the calculated cycles, especially in poorly treated systems. McCoy[1] goes to great lengths in developing an equation to calculate cycles of concentration. His equation is more cumbersome to use and provides no significant improvement in calculating cycles of concentration compared to using equation 9.

Total water loss (W) is the sum total of blow down (BD), drift (D), and any leakage (L) for the system.

$$W = BD + D + L \qquad (10)$$

In the best case scenario L is zero, but its value is always undetermined. Drift usually has an insignificant impact on overall water loss. Thus, overall wastage is essentially blowdown.

Blowdown (BD) can be calculated from evaporation and concentration ratio:

$$BD \text{ (gpm)} = ER \text{ (gpm) / (CR} - 1) \qquad (11)$$

Finally, for mass balance of cooling tower water, the make-up rate (MU) must be known.

$$MU = ER + W \cong ER + BD \qquad (12)$$

$$MU = ER \times CR / (CR - 1) \qquad (13)$$

Knowing the ER, CR, BD, and MU allows us to determine the treatment chemicals needed.

Half-life or Holding Time Index (HTI)

The half-life of the cooling water system is commonly referred to as the "Holding Time Index." It is a measure of time at which the rate of an analyte in the cooling water system decreases to 50% of its original value through the process of wastage (blowdown and drift) of tower water from the system, plus addition of make-up water to the system. A typical value for HTI is approximately 24 hours. High HTI levels (>48 hours) can result in chemical treatment degradation.

Holding Time Index is dependent on the system volume (V):

$$HTI = ln2 \times V / BD \tag{14}$$

where ln2 is the natural logarithm of 2 = 0.693. The time unit of HTI is the unit of the BD time value: gpm, gph, etc.

For example: If a system has a volume of 1,000 gallons and a BD = 5 gpm, then:

$$HTI = 0.693 \times (1{,}000 \text{ gal}) /$$
$$(5 \text{ gal/min} \times 60 \text{ min/hr}) = 2.3 \text{ hr} \tag{15}$$

The dosage of a slow-acting, non-oxidizing biocide would not function well in this system with an HTI of 2.3 hours. DBNPA, or another fast-acting biocide, should be considered. However, if system volume was 10,000 gallons, then HTI would be 23 hours. In this case, non-oxidizing biocides are more likely to be effective, and a wider selection is available.

Additionally, if a non-oxidizing biocide needs 24 hours to function at a minimum dosage rate of 100 mg/L, then in the last example, a dose of approximately 200 mg/L of product into the system would be necessary to ensure the optimum kill rate. After 24 hours, about 100 mg/L of product would still be in the system, making the program more effective.

To determine system volume (V), a common method is to add salt (NaCl). Prior to the salt addition, the water is tested for chloride ions. After the addition of the salt (W = pounds of salt added) and when the system has reached steady-state (after a few hours) with the blow down closed, then the water is again tested for chloride ions to determine the increase in chloride ions (ΔCl).

$$V = W \times (120,000) / (\Delta Cl \times 1.65) \qquad (16)$$

The multiplier 120,000 is the conversion factor of 1,000,000 lb of water divided by 8.3 lb per gallon of water. The multiplier 1.65 converts chloride ion to sodium chloride.

If using any other chemical:

$$V \text{ (gal)} = \frac{\text{(lb Product Added)} \times 120,000 \times \text{(\% Actives mg/L of Product Increase)}}{\Delta \text{Product (mg/L)}} \qquad (17)$$

Equations 16 and 17 can also be used to calculate the volume of a closed cooling water system.

Remember: When calculating a system volume from the dimensions of a system, there are 7.48 gallons of water in each cubic foot of water.

Calculating Product Usage Rates

To slug feed any product, the amount of product needed is:

$$\text{Product Usage (lb/dose)} = \text{mg/L Product Desired} \times V \text{ (gal)} / 120,000 \qquad (18)$$

Therefore, if feeding a treatment product to maintain a desired dosage level in a cooling tower, the following is needed:

$$\text{Product Usage (lb/day)} = \text{mg/L Product Desired} \times \text{BD (gpd)} / 120,000 \qquad (19)$$

To convert product usage rates into pounds per day to a draw-down on a chemical metering pump:

$$\text{Feed Rate (mL/min)} = \frac{[\text{Product Usage (lb/day)}] \times (3,785 \text{ mL/gal})}{[\text{Product Density (lb/gal)}] \times (1,440 \text{ min/day})} \qquad (20)$$

When faced with a system that requires acid feed to control pH, calculating the theoretical amount of sulfuric acid required might be needed. This is particularly valuable when sizing storage tanks or negotiating contracts with commodity suppliers.

$$66^{\circ} \text{ Baumé } H_2SO_4 \text{ (lb/day)} = \frac{[(CR \times \text{Make-up MAlk}) - \text{Desired Cooling Water MAlk}] \times \text{BD (gpd)}}{\{120,000 \times [(1 \text{ lb MAlk Reduction})/(1.05 \text{ lb } H_2SO_4)]\}} \qquad (21)$$

where MAlk is the total alkalinity level (in mg/L as $CaCO_3$) in make-up and cooling water, respectively. Each 1.05 lb of H_2SO_4 neutralizes 1 lb of alkalinity.

To convert sulfuric acid from pounds to gallons, divide pounds 66° Baumé H_2SO_4 by 15.3 lb/gal.

Performance of Program

There are several ways to determine how a treatment program is performing. Corrosion coupons provide feedback on the effectiveness of corrosion inhibitors for different metallurgies. Microbiological tests (such as dip slides, ATP, etc.) indicate the performance of the biocide programs. These methods have been discussed in past issues of *The Analyst*.

A method often used to provide feedback on scaling is to evaluate hardness balance in the cooling waters. This relates to CR calculations in equation 8.

A hardness balance involves testing make-up water and cooling tower water for total hardness (TH) and calcium hardness (CaH). The difference between the TH and CaH is equal to magnesium hardness (MgH). (Ed. Be careful in subtracting CaH from TH to obtain MgH. Manipulation of small values can produce large errors.)

Make-up magnesium hardness multiplied by the system's concentration ratio should be equal to cooling water

magnesium hardness for most systems. Because magnesium is generally soluble in most cooling water systems, it is usually safe to assume that:

> Cooling Water MgH / Make-up MgH =
> CR(MgH) ≅ CRSystem   (22)

A hardness balance compares the same ratio applied to the calcium hardness (CaH) levels in both the make-up and cooling water system:

> Cooling Water CaH / Make-up CaH =
> CR(CaH) ≅ CRSystem   (23)

If CR(CaH) is less than CR(MgH), then calcium scale could be forming in the system. This is an easy test to perform, but each titration must be done carefully for accuracy.

Also note that cooling water total hardness (TH) ratio to make-up total hardness should provide cycles of concentration.

> Cooling Water TH / Make-up TH =
> CR (TH) ≅ CRSystem   (24)

Complete material balance is observed when the cycles of concentration obtained from total hardness, calcium hardness, magnesium hardness, total alkalinity (as long as acid is not fed), and conductivity are essentially the same value.

The Langelier Saturation Index (LSI) calculation will indicate the calcium carbonate scaling tendency of the water. This information is important when designing a cooling water chemical treatment program, especially in waters that have a tendency to form calcium carbonate scale. If tests indicate a system is losing calcium, then one potential explanation for the loss is the formation of calcium carbonate. Calculating an LSI for the cooling water is in order. Treatment programs have different abilities to prevent calcium carbonate scale at different LSI levels. (Ed. The Langelier Saturation Index was developed by Langelier in 1936 as a guide to develop a thin eggshell coating of calcium carbonate on municipal distribution piping to prevent attack on the internal surface of the piping. Using the LSI under cooling water conditions is an unrealestic extension of the index.)

Exceeding a treatment program's LSI limit will likely lead to the formation of a calcium carbonate deposit.

A procedure[2] for calculating LSI in the field is as follows:

> P1 = $\log_{10}$ [Calcium (as $CaCO_3$) mg/L x Total Alkalinity (as $CaCO_3$)]
> P2 = [(Highest Expected Temperature °F) x 0.00912)] + P1
> P3 = [$\log_{10}$ (Total Dissolved Solids mg/L) x 0.10] + 12.27
> pH Saturation (pHs) = P3 – P2
> Langelier Saturation Index (LSI) = Actual pH of Cycled Water – pHs

For example: Calculate the LSI from the cooling water analysis shown in Table 1:

Table 1: Cooling Water Analysis

Species	Value
Calcium as $CaCO_3$	250 mg/L
Total Alkalinity as $CaCO_3$	155 mg/L
Total Dissolved Solids	475 mg/L
pH of the Cooling Water	7.8
Temperature °F	125°F

Calculated values are shown in Table 2.

Table 2: Langelier Saturation Index

Parameter	Value
P1	4.588
P2	5.728
P3	12.538
P4	6.8
LSI	1.0

Table 3 interprets the LSI values:

Table 3: Key to Indices

LSI	Potential for $CaCO_3$ Deposition
3.0	Extremely Severe
2.0	Very Severe
1.0	Severe
0.5	Moderate
0.2	Slight
0.0	Stable Water
-0.0	Non-scaling, very slight tendency to dissolve $CaCO_3$ scale
-0.5	Non-scaling, slight tendency to dissolve $CaCO_3$ scale
-1.0	Non-scaling, moderate tendency to dissolve $CaCO_3$ scale
-2.0	Non-scaling, strong tendency to dissolve $CaCO_3$ scale
-3.0	Non-scaling, very strong tendency to dissolve $CaCO_3$ scale

Performance of Heat Exchangers

While system monitoring is important, it is sometimes advantageous to monitor heat exchanger performance. This can be done several ways.

Log Mean Temperature Difference (LMTD or ΔTlm): This calculates average temperature differential across heat exchangers. It compares the difference between temperatures of the "hot" and "cold" fluids in heat exchangers. The larger temperature difference between two fluids at either the exit or the entrance of the heat exchanger is designated as ΔT_2 and the smaller temperature difference is designated as ΔT_1.[3]

$$LMTD = (\Delta T_2 - \Delta T_1) / [\ln(\Delta T_2 / \Delta T_1)] \qquad (25)$$

In a heat exchanger with countercurrent flow (where hot fluid enters the exchanger on the opposite end as cooling fluid), the LMTD is calculated as:

$$LMTD = [(T_1 - t_2) - (T_2 - t_1)] / \ln[(T_1 - t_2) / (T_2 - t_1)] \qquad (26)$$

In a heat exchanger with parallel flow (where hot and cold fluids enter on the same side of the heat exchanger), the LMTD is calculated as:

$$LMTD = [(T_1 - t_1) - (T_2 - t_2)] / \ln[(T_1 - t_1) / (T_2 - t_2)] \qquad (27)$$

where:

T_1 = hot fluid inlet temperature
T_2 = hot fluid outlet temperature
t_1 = cold fluid inlet temperature
t_2 = cold fluid outlet temperature

Increasing LMTD means there is reduced heat transfer occurring, and the system might be fouling on the process side or the cooling water side.

Approach Temperature (TA): This is the difference between the temperatures of hot fluid exiting (T hot-out) and cold fluid entering (T cold-in) the heat exchanger.

$$TA = T_{hot\text{-}out} - T_{cold\text{-}in} \qquad (28)$$

An increasing TA also means there is reduced heat transfer occurring, and the system might be fouling on the process side or the cooling water side.

Terminal Temperature Difference (TTD): Similar to approach temperature, TTD is the difference in temperatures of hot fluid exiting ($T_{\text{hot-out}}$) and cold fluid exiting ($T_{\text{cold-out}}$) the heat exchanger.

$$\text{TTD} = T_{\text{hot-out}} - T_{\text{cold-out}} \qquad (29)$$

An increasing TTD also means that reduced heat transfer is occurring, and the system might be fouling on the process side or the cooling water side.

Miscellaneous Calculations

Fluid Velocity (v): When evaluating a heat exchanger, knowing fluid velocity is always helpful. The procedure for calculating v is:

$$v = \frac{(F / 7.48 \text{ gal/ft}^3)}{(\text{Number of Tubes} \times \pi \times r^2 \times 60 \text{ sec/min})} \qquad (30)$$

or

$$v = F / (\text{Number of Tubes} \times r^2 \times 1{,}409) \qquad (31)$$

where: F is the flow rate (gpm)

$\pi = 3.14$ (pi)
$r = $ radius of tubes (in feet)

Cooling water velocities should be maintained between 4-6 ft/sec (fps) to keep heat exchangers from fouling. Velocities over 6 fps have a tendency to erode the tubes.

Convert Conductivity to Total Dissolved Solids (TDS):

$$\text{TDS (mg/L)} \cong 0.8 \times \text{Conductivity}$$
$$(\mu\text{mhos or in } \mu\text{S/cm}) \qquad (32)$$

Summary

Keeping these calculations handy will enable a water treater to develop accurate treatment proposals for current customers' cooling water systems as well as those at prospective accounts. For water treaters pursuing CWT certification, these calculations are indispensable. ✂

References

1. McCoy, James, "The Chemical Treatment of Cooling Water," Chemical Publishing Co., New York, 1974

2. Tim Keister, ProChemTech International, Inc., Product Application Guide - Cooling Water, 1987.

3. http://www.engineersedge.com/heat_transfer/log_mean_temp_diff.htm

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CEU Quiz on Article "Basic Calculations Necessary to Survive in the Field – Part 1: Cooling Water" published in the Spring 2010 "The Analyst"

1. A standard 200-ton cooling tower at 100% load has a ΔT of 18 degrees F. Assuming an "F" factor of 0.8, what is the evaporation rate?
   a. 0.9 gpm
   b. 10.8 gpm
   c. 8.6 gpm
   d. 9 gpd

2. A cooling tower with an evaporation rate of 20 gpm runs at a concentration ratio (CR, or cycles of concentration) of 4.5. What is its blow down rate?
   a. 5.7 gpm
   b. 4.4 gpm
   c. 0.6 gpm
   d. 11 gpm

3. A cooling tower with a recirc rate (RR) of 1,000 gpm is at 100% load has a ΔT of 18 degrees F and a CR of 5. Assume the "F" factor is 0.8. Its volume is 7,000 gallons. What is the system's Holding Time Index (HTI)?
   a. 1,348 hours
   b. 22 hours

c. 32 hours

d. 1.5 days

4. If the above cooling tower's load is decreased to 50%, then the HTI will
   a. Decrease
   b. Stay the same
   c. Double
   d. Increase four-fold

5. A cooling water non-oxidizing biocide requires a dosage rate of 150 ppm and 8 hours of contact time to work. The HTI of the system is 16 hours. How many gallons of a biocide that weighs 10 pounds per gallon would you need to add to a system with a volume of 10,000 gallons?
   a. 1.3 gallons
   b. 0.15 gallons
   c. 2.6 gallons
   d. 26 gallons

6. You are commissioning a new closed cooling water loop and no one knows the system volume. You add 10 pounds of sodium chloride and later find the chloride level is 280 ppm (as Cl⁻). The original chloride level was 20 ppm. What is the system volume?
   a. 2,800 gallons
   b. 3,200 gallons
   c. 4,600 gallons
   d. 2,600 gallons

7. You are starting up a new system and have just filled the 10,000 gallon system with fresh water. You would like to "shock-dose" the system with 100 ppm of your treatment chemical, which weighs 10.3 pounds per gallon. How much chemical do you add?
   a. 80 gallons
   b. 0.8 gallons
   c. 8 gallons
   d. 4 gallons

8. After starting up a new system and getting all of the chemistries correct, you need to maintain a 150 ppm treatment chemical level in a system with a continuous blowdown (BD) rate of 30 gpm. The treatment chemical weighs 10.3 pounds per gallon. What is the treatment chemical feed rate in mL/min?
   a. 14 mL/min
   b. 5 mL/min

c. 17 mL/min

d. 7 mL/min

9. A competitor's cooling tower has the following chemistry, while the make-up water chemistry is also shown:

Analyte	Tower Water	Make-up water	units
Sodium	120	20	as Na
Calcium	450	110	as $CaCO_3$
Total Hardness	600	140	as $CaCO_3$
Magnesium	150	30	as $CaCO_3$
Total Alkalinity	380	80	as $CaCO_3$
Chloride	92	16	as Cl^-
Silica	60	12	as SiO_2
Conductivity	2,400	450	as µS

If the system is being treated with an all-organic program and sodium hypochlorite (NaOCl), then what are the cycles of concentration?

a. 6

b. 4

c. 5

d. 5.3

10. If the pH of the above water is 8.8 and the hottest water temperature is 115 degrees F, then what is the approximate LSI for this water?

a. 1.3

b. 1.8

c. 2

d. 2.5