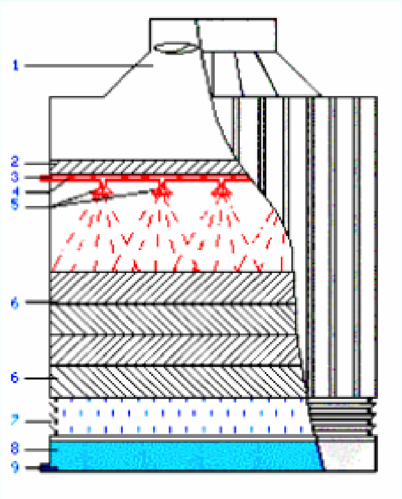
Cooling Tower Operation

Forced draught cooling towers use the evaporation of a liquid (often water) into air to achieve cooling. The tower often consists of a sprinkler system which wets a high-surface-area substrate (plates) continuously, while air flow through the chamber converts liquid to vapor. The decrease in temperature of the liquid is due to the heat of vaporization.



1. Fan; 2. Drift eliminator; 3. Warm water; 4. Water distribution; 5. Water sprinkling nozle; 6. Fill packing; 7. Air inlet; 8. Water pool; 9. Cooled water

Images from http://www.coolingtowers-bg.com/st.htm

An example of a reason for installing a cooling tower might be that your plant produces a stream of hot water (from a heat exchanger, for example) that is too warm to discharge into a river or stream. The water may be clean, but "heat pollution" is detrimental to waterways due to its ecological effects.

Experiment Objectives

Our lab-scale cooling tower is designed to mimic an industrial operation, except it recycles and re-heats the water as it is cooled.

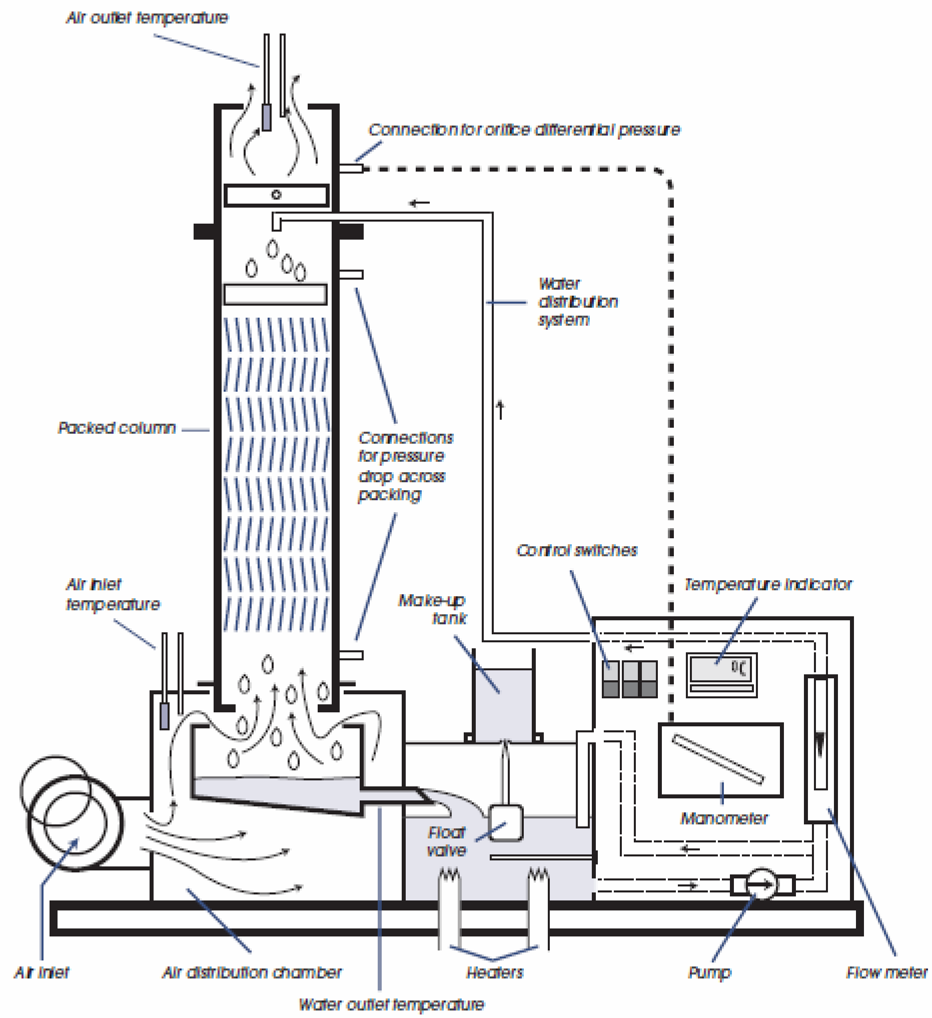
The goals of the experiment are:

1). To perform mass and energy balances on the system.

2). To observe the effects of process variables on the exit temperature of the water.

- air flow rate
- water flow rate (cooling load)
- inlet water temperature
- packing density

UOP6: Basic water cooling tower flow diagram



Types of Cooling Towers

Cooling towers fall into two main sub-divisions: natural draft and mechanical draft. Natural draft designs use very large concrete chimneys to introduce air through the media. Due to the tremendous size of these towers (500 ft high and 400 ft in diameter at the base) they are generally used for water flowrates above 200,000 gal/min. Usually these types of towers are only used by utility power stations in the United States. Mechanical draft cooling towers are much more widely used. These towers utilize large fans to force air through circulated water. The water falls downward over fill surfaces which help increase the contact time between the water and the air. This helps maximize heat transfer between the two.

Types of Mechanical Draft Towers

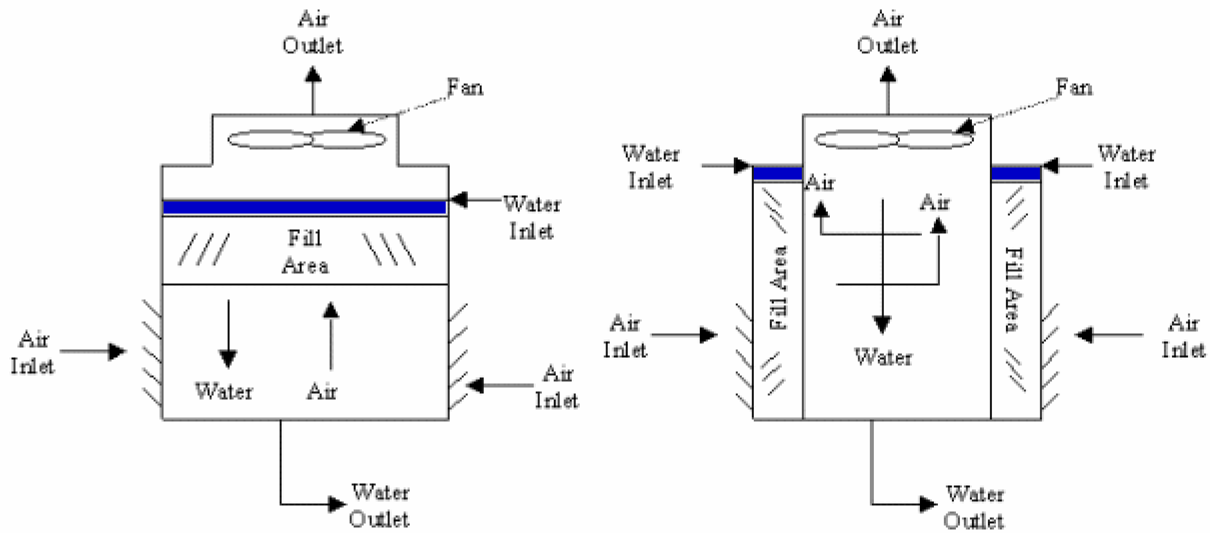
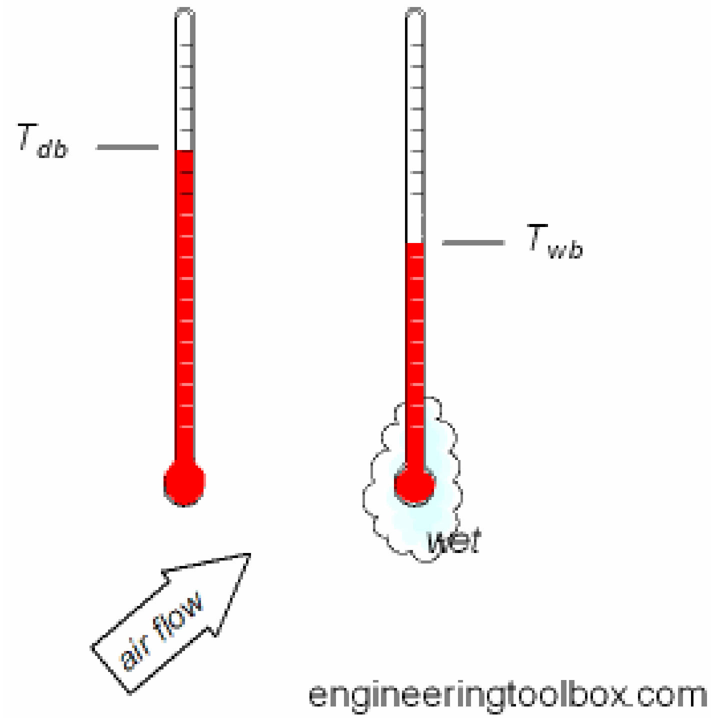


Figure 2: Mechanical Draft Counterflow Tower *Figure 3: Mechanical Draft Crossflow Tower*

Mechanical draft towers offer control of cooling rates in their fan diameter and speed of operation. These towers often contain several areas (each with their own fan) called cells.

Source: Ch.E. resources.com

Background: Wet Bulb vs. Dry Bulb Temperatures



Temperature can be measured with two thermometers simultaneously - one with a wet bulb and one with a dry bulb- in order to determine the relative humidity of the surrounding air. This method was used historically by meteorologists, but we will use it extensively in this experiment to measure the water concentration in the air.

If the air is saturated with water vapor (100% relative humidity), then the wet bulb and dry bulb temperatures will be equal.

If the relative humidity is less than 100%, then the wet bulb temperature will be lower due to evaporation of water from the surrounding wrap.

To obtain an accurate wet bulb temperature, it is important to make sure that the wet bulb reaches steady state under the conditions of air flow and relative humidity.

The relative humidity is determined by looking at wet-bulb and dry-bulb temperatures on a psycrometric chart.

Basic Principles: Evaporation from a Wet Surface

Mechanisms of cooling at work:

1) Evaporation. As water molecules leave the liquid phase, the enthalpy change of vaporization results in cooling. The specific enthalpy of saturated vapor is significantly higher than that of liquid water at the same temperature, so ΔH of vaporization is positive. The result is a lowering of the temperature of the liquid. The enthalpy change associated with vaporization is the dominant mechanism of cooling.

2) Conduction and convection. Loss of heat to the surrounding air and the chamber walls could cause some cooling to occur, but it should be negligible compared to the effects of evaporation.

3) Radiation. A very minor contribution to the cooling occurs as the water loses energy by radiation. We will ignore radiation.

Therefore, the rate of evaporation of water from the liquid surface essentially determines the effectiveness of the cooling tower. Factors that increase the rate of evaporation will help cooling-

a.) The difference between the partial pressure of water in the air (p_w) and the saturation vapor pressure (p^*) should be kept as large as possible. In other words, passing dry air into the cooling tower is a good idea, but humid air will be less effective.

b.) Increasing the surface area available for mass transfer is a good idea- so we use a system of plates that spread the water out over a large area.

c.) Increasing the air flow rate is a good idea because it will increase the rate of evaporation.

If we ran an infinitely tall cooling tower under *adiabatic conditions*, meaning that no heat was transferred from the tower to its surroundings, with adequate air flow, we expect that the temperature of the exiting liquid reached at steady state would be equal to the wet bulb temperature of the incoming air.

Therefore, the cooling tower is working optimally if the temperature of the exiting water (T_o) is close to the wet bulb temperature of the air outside the tower (T_{air}^w).

The difference (T_o-T_{air}^w) is therefore a measure of how well the cooling tower is functioning. The smaller this difference, the better.

Specific Enthalpy

To perform the calculations in this experiment, we'll need to know the change in specific enthalpy of the water during vaporization (Δh_f). "Specific" enthalpy means enthalpy per unit mass.

Appendix 7 (p. 1094) gives the enthalpy of water and steam (saturated vapor) at different temperatures. Δh_f is slightly temperature-dependent over the range of temperatures we'll be studying. Some useful conversion factors are given below:

1,000 BTU ≈ 1,055 kJ
1,000 kg ≈ 2204.6 lb (It's easier to work in SI units)

If we were working at high pressure, we would also have to apply a correction factor to calculate the enthalpy of compressed liquid. However, this correction is negligible in our experiment, so you can safely use the values directly from Appendix 7.

Humidity Definitions

There is more than one way of reporting the water vapor content in air: partial pressure (p_w), absolute (specific) humidity, percentage saturation, and relative humidity.

Absolute (specific) humidity (ω) $= \dfrac{\text{mass of water vapor}}{\text{mass of dry air}}$

Relative humidity (ϕ) $= \dfrac{\text{partial pressure of water vapor}}{\text{saturation pressure of water vapor}} = \dfrac{p_w}{p^*}$

Percentage Saturation $= \dfrac{\text{mass of water vapor in air}}{\text{mass of water vapor at saturation}} \times 100\% \approx \phi \times 100\%$

Regnault, August, & Apjohn Equation

Instead of using a psychrometric chart, we can obtain relative humidity by the following eqn.:

$$p_w = p^* - 6.666 \times 10^{-4} P(T_d - T_w)$$

T_d = dry bulb temperature
T_w = wet bulb temperature
P = total air pressure in mbar
p* is the saturation pressure **at T_w**

Note: atmospheric pressure ≈ 101,325 Pa ≈ 1,013 mbar

Heat Capacity & Specific Enthalpy Calculations

We will occasionally need to know the (constant pressure) heat capacity of the water for our calculations. The heat capacity is the amount of energy needed to raise the temperature of 1 kg of the material by 1 °C.

Values of C_p (and p* as well) are tabulated for *liquid* water in the handout posted on the course website (water properties.pdf). Over the operating temperature range of the cooling tower, C_p is almost constant at 4.2 kJ/kg·K. More precise values can be obtained by looking at the charts. For water vapor, take $C_p \approx 1.9$ kJ/kg·K at 20 °C and 2.08 kJ/kg·K at 100 °C.

The specific enthalpy of saturated water vapor (steam) can just be looked up in a chart. However, we often want to calculate the specific enthalpy of **superheated water vapor**, meaning it is *not* saturated vapor. The partial pressure is p_w, which is less than the value of p* at T_d. The specific enthalpy is found from the following approximate equation:

$$h \approx h_o + C_p^{\,steam}(T_d - T_o)$$

where T_o is the temperature at which the saturation pressure would be equal to p_w

C_p^{steam} is the constant-pressure heat capacity of steam at a temperature halfway between T_o and T_d

h_o is the specific enthalpy of steam at $T=T_o$

Energy Balance on the Cooling Tower

- Heat transfer is occurring primarily in the load tank, where the water is brought up to the feed temperature.
- A small amount of heat is also lost to the surroundings by radiation/conduction/convection.
- Work is done on the water by the pump.
- Energy is transferred along with mass loss, because dry air enters, and humid air leaves.

Now let's set up the energy equation for the portion of the process illustrated at the right:

$\dot{Q}$ = the rate of heating added to the system

$\dot{P}$ = rate of work done by the pump on the water

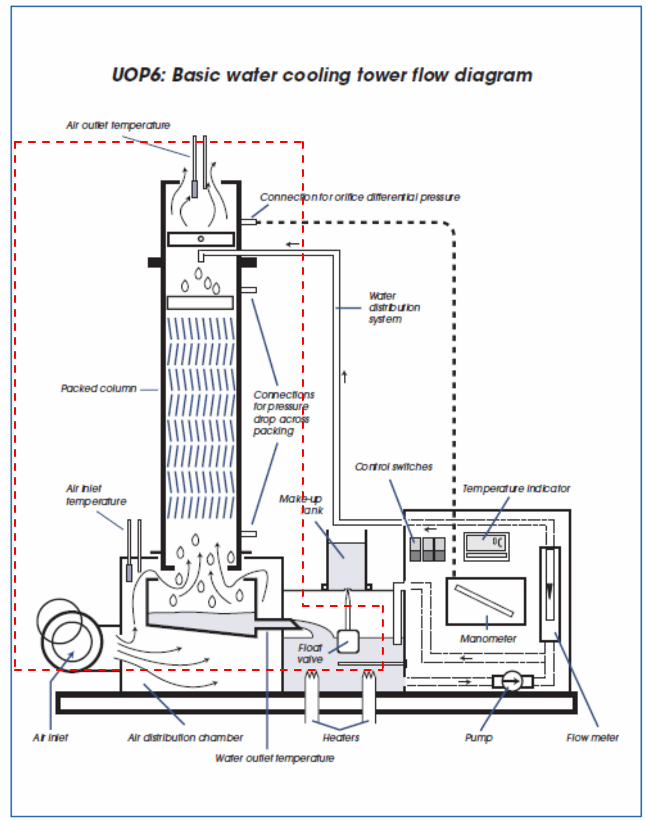
$\dot{H}_{exit}$ = rate of enthalpy loss in exiting vapor

$\dot{H}_{entry}$ = rate of enthalpy gain due to entering air and entering water from make-up tank

$$\dot{Q} + \dot{P} = \dot{H}_{exit} - \dot{H}_{entry}$$ at steady state

[work done on system] = [energy loss due to enthalpy change]

$\dot{P} = 100 \text{ Watts}$ $\quad\quad\quad$ $\dot{Q} = 1000 \text{ Watts or } 500 \text{ Watts}$



Now let's define some mass flow rates and enthalpies:

$\dot{m}_E$ the rate of (liquid) water addition from the "make-up" tank

$\dot{m}_a$ the mass flow rate of air h_{da} the specific enthalpy of (dry) air

$\dot{m}_s$ the mass flow rate of steam h_s the specific enthalpy of steam

subscript *A* -------- entering the chamber
subscript *B* -------- leaving the chamber

The energy balance equation is now written:

$$\dot{Q} + \dot{P} = \left(\dot{m}_a h_{da} + \dot{m}_s h_s\right)_B - \left(\dot{m}_a h_{da} + \dot{m}_s h_s\right)_A - \dot{m}_E h_E$$

- $\left(\dot{m}_a h_{da} + \dot{m}_s h_s\right)_B$ → steam/air leaving
- $\left(\dot{m}_a h_{da} + \dot{m}_s h_s\right)_A$ → steam/air entering
- $\dot{m}_E h_E$ → water entering from make-up tank

Note that there are no terms for the water stream that is circulating through the system. It is being heated and cooled, but no energy is leaving the system through this stream because it circulates.

Mass Balance on the Cooling Tower

Conservation of mass gives us the following simple equations at steady state:

Air in = air out

$$(\dot{m}_a)_A = (\dot{m}_a)_B$$

Water in = water out

$$(\dot{m}_s)_A + \dot{m}_E = (\dot{m}_s)_B$$

This equation simply says that the mass flow rate of water entering the system (because the entering air is humid) plus the mass flow rate of water entering from the make-up tank equals the mass flow rate of water leaving the system as vapor/steam.

The ratio of water vapor to air can be determined if the humidity is known.

$$\frac{(\dot{m}_s)_A}{(\dot{m}_a)_A} = \omega_A \quad \text{and} \quad \frac{(\dot{m}_s)_B}{(\dot{m}_a)_B} = \omega_B$$

Inserting these equations into the mass balance and solving for $\dot{m}_E$

$$\dot{m}_E = \dot{m}_a(\omega_a - \omega_b)$$

We will need to figure out how to convert between ω and ϕ to verify the mass balance (homework exercise).

Adapted from *Rules of Thumb for Chemical Engineers* by K. Branan.

Transfer Units

The section on Performance provides a handy nomograph for quick cooling tower evaluation. More detailed analysis requires the use of transfer units. The performance analysis then asks two questions:

1. How many transfer units correspond to the process requirement?
2. How many transfer units can the actual cooling tower or proposed new cooling tower actually perform?

The number of transfer units is given by:

$$N_{tog} = \int_{H_1}^{H_2} dH/(H_{sat} - H) \quad (1)$$

where

H = Enthalpy of air, BTU/lb dry air
H_1 = Enthalpy of entering air, BTU/lb dry air
H_2 = Enthalpy of exit air, BTU/lb dry air
H_{sat} = Enthalpy of saturated air, BTU/lb

Equation 1 is normally integrated by graphical or numerical means utilizing the overall material balance and the saturated air enthalpy curve.

Khodaparast has provided an equation for H_{sat} that allows simpler evaluation of Equation 1:

$$H_{sat} = (-665.432 + 13.4608t - 0.784152t^2)/(t - 212) \quad (2)$$

This equation is good if the air temperature is 50°F or above, the cooling tower's approach to the wet bulb temperature is 5°F or above, and N_{tog} is within a range of about 0.1 to 8.

t = temperature in degrees F.

Cooling Tower Theory

Source: Ch.E. resources.com

Heat is transferred from water drops to the surrounding air by the transfer of sensible and latent heat.

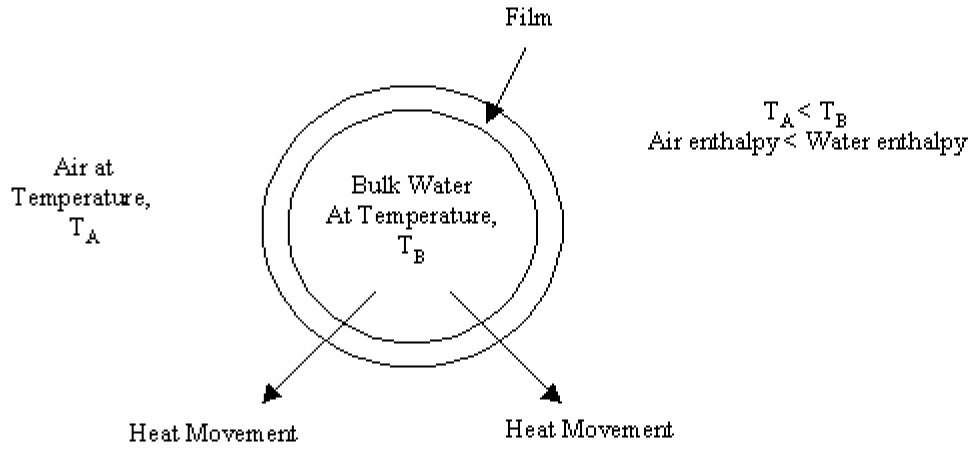


Figure 4: Water Drop with Interfacial Film

This movement of heat can be modeled with a relation known as the Merkel Equation:

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h_w - h_a} \qquad (1)$$

KaV/L = tower characteristic

K = mass transfer coefficient (lb water/h ft^2)

a = contact area/tower volume

V = active cooling volume/plan area

L = water rate (lb/h ft^2)

T_1 = hot water temperature (^{0}F or ^{0}C)

T_2 = cold water temperature (^{0}F or ^{0}C)

T = bulk water temperature (^{0}F or ^{0}C)

h_w = enthalpy of air-water vapor mixture at bulk water temperature (J/kg dry air or Btu/lb dry air)

h_a = enthalpy of air-water vapor mixture at wet bulb temperature (J/kg dry air or Btu/lb dry air)

Thermodynamics also dictate that the heat removed from the water must be equal to the heat absorbed by the surrounding air:

$$L(T_1 - T_2) = G(h_2 - h_1) \qquad (2)$$

$$\frac{L}{G} = \frac{h_2 - h_1}{T_1 - T_2} \qquad (3)$$

where:

L/G = liquid to gas mass flow ratio (lb/lb or kg/kg)

T_1 = hot water temperature (^{0}F or ^{0}C)

T_2 = cold water temperature (^{0}F or ^{0}C)

h_2 = enthalpy of air-water vapor mixture at exhaust wet-bulb temperature (same units as above)

h_1 = enthalpy of air-water vapor mixture at inlet wet-bulb temperature (same units as above)

The tower characteristic value can be calculated by solving Equation 1 with the Chebyshev numberical method:

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h_w - h_a} = \frac{T_1 - T_2}{4}\left(\frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4}\right) \qquad (4)$$

Where:

Δh_1 = **value of $h_w - h_a$ at $T_2 + 0.1(T_1 - T_2)$**

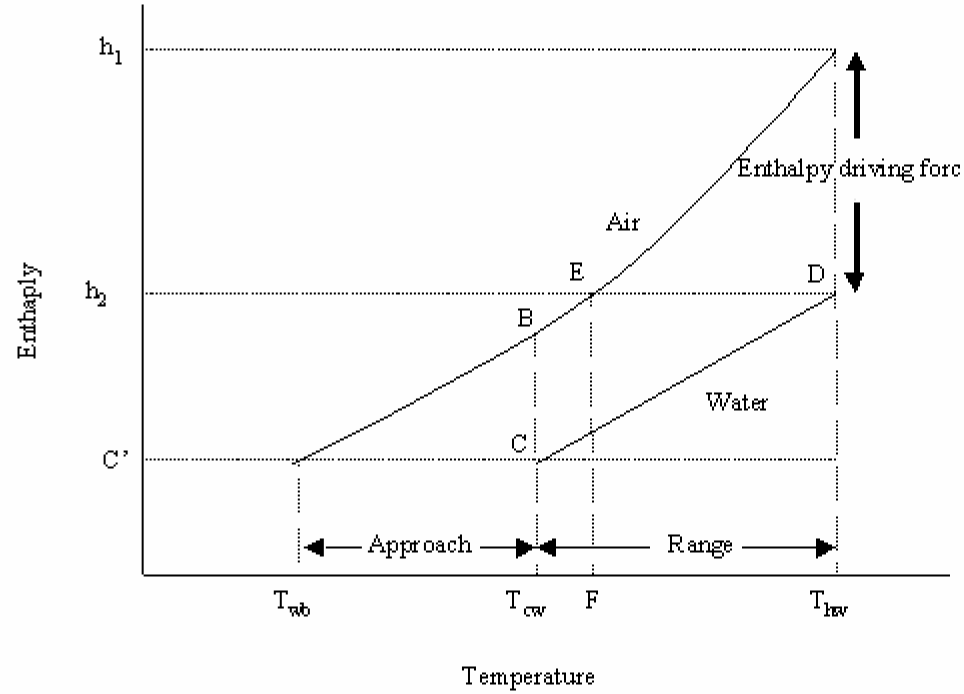
Δh_2 = **value of $h_w - h_a$ at $T_2 + 0.4(T_1 - T_2)$**

Δh_3 = **value of $h_w - h_a$ at $T_1 - 0.4(T_1 - T_2)$**

Δh_4 = **value of $h_w - h_a$ at $T_1 - 0.1(T_1 - T_2)$**

Source: Ch.E. resources.com

Figure 5: Graphical Representation of Tower Characteristic



The following represents a key to Figure 5:

C' = Entering air enthalpy at wet-bulb temperature, T_{wb}

BC = Initial enthalpy driving force

CD = Air operating line with slope L/G

DEF = Projecting the exiting air point onto the water operating line and then onto the temperature axis shows the outlet air web-bulb temperature

As shown by Equation 1, by finding the area between ABCD in Figure 5, one can find the tower characteristic. An increase in heat load would have the following effects on the diagram in Figure 5:

1. Increase in the length of line CD, and a CD line shift to the right
2. Increases in hot and cold water temperatures
3. Increases in range and approach areas

The increased heat load causes the hot water temperature to increase considerably faster than does the cold water temperature. Although the area ABCD should remain constant, it actually decreases about 2% for every 10 ^{0}F increase in hot water temperature above 100 ^{0}F. To account for this decrease, an "adjusted hot water temperature" is usd in cooling tower design.

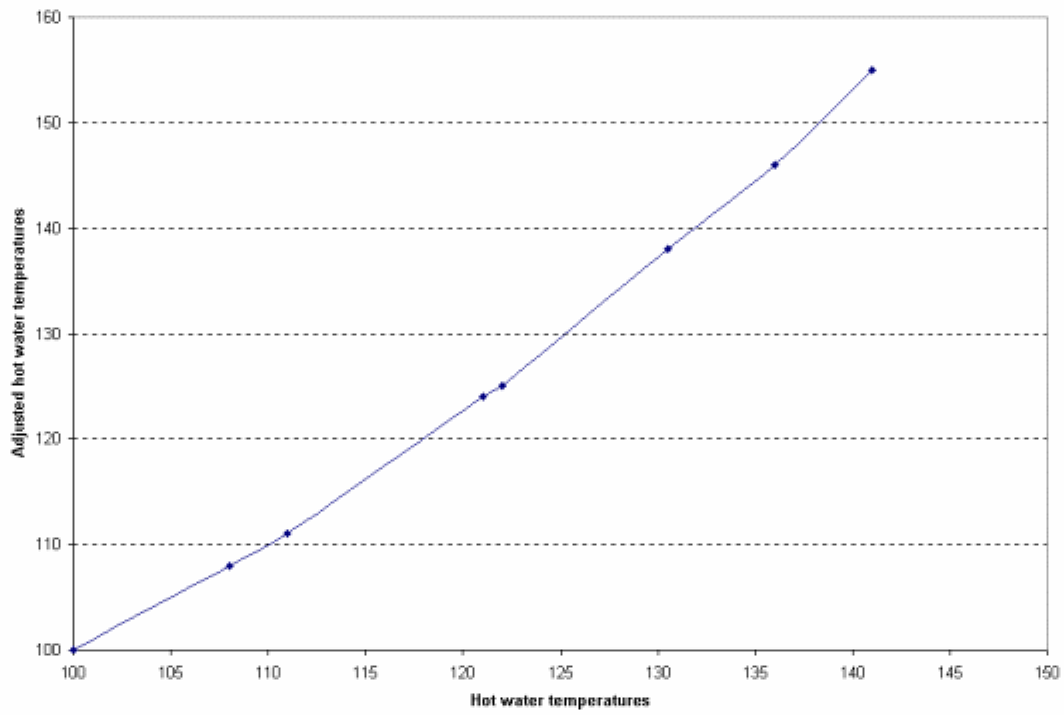


Figure 6: Graph of Adjusted Hot Water Temperatures

The area ABCD is expected to change with a change in L/G, this is very key in the design of cooling towers.

Cooling Tower Design

Although KaV/L can be calculated, designers typically use charts found in the Cooling Tower Institute Blue Book to estimate KaV/L for given design conditions. It is important to recall three key points in cooling tower design:

1. A change in wet bulb temperature (due to atmospheric conditions) will not change the tower characteristic (KaV/L)

2. A change in the cooling range will not change KaV/L

3. Only a change in the L/G ratio will change KaV/L

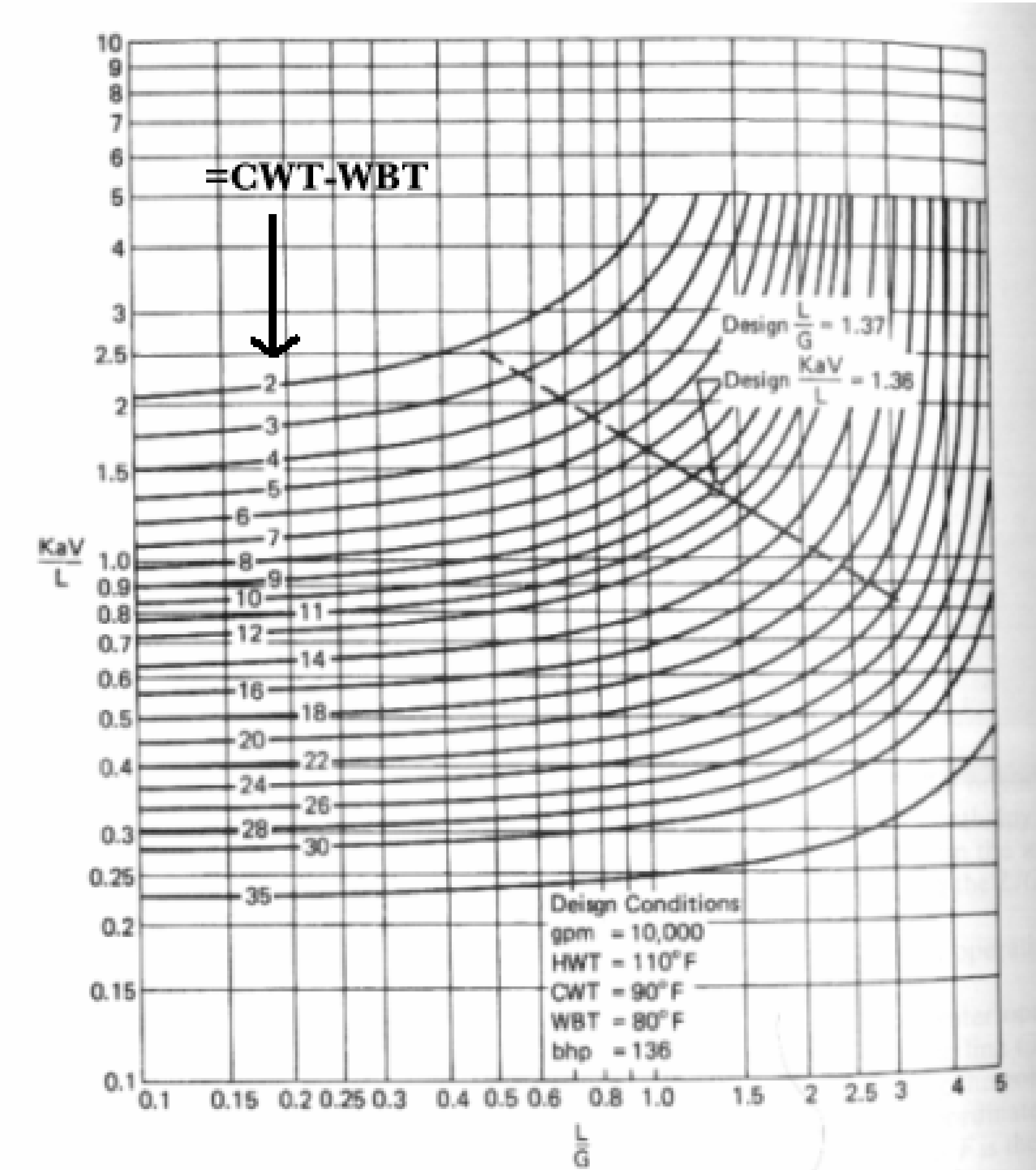


Figure 7: A Typical Set of Tower Characteristic Curves

The straight line shown in Figure 7 is a plot of L/G vs KaV/L at a constant airflow. The slope of this line is dependent on the tower packing, but can often be assumed to be -0.60. Figure 7 represents a typical graph supplied by a manufacturer to the purchasing company. From this graph, the plant engineer can see that the proposed tower will be capable of cooling the water to a temperature that is 10 ^{0}F above the wet-bulb temperature. This is another key point in cooling tower design.

Cooling towers are designed according to the highest geographic wet bulb temperatures. This temperature will dictate the minimum performance available by the tower. As the wet bulb temperature decreases, so will the available cooling water temperature. For example, in the cooling tower represented by Figure 7, if the wet bulb temperature dropped to 75 ^{0}F, the cooling water would still be exiting 10 ^{0}F above this temperature (85 ^{0}F) due to the tower design.

Below is the summary of steps in the cooling tower design process in industry. More detail on these steps will be given later.

1. Plant engineer defines the cooling water flowrate, and the inlet and outlet water temperatures for the tower.
2. Manufacturer designs the tower to be able to meet this criteria on a "worst case scenario" (ie. during the hottest months). The tower characteristic curves and the estimate is given to the plant engineer.
3. Plant engineer reviews bids and makes a selection

Design Considerations

Once a tower characteristic has been established between the plant engineer and the manufacturer, the manufacturer must design a tower that matches this value. The required tower size will be a function of:

1. Cooling range
2. Approach to wet bulb temperature
3. Mass flowrate of water
4. Web bulb temperature
5. Air velocity through tower or individual tower cell
6. Tower height

In short, nomographs such as the one shown on page 12-15 of Perry's Chemical Engineers' Handbook 6th Ed. utilize the cold water temperature, wet bulb temperature, and hot water temperature to find the water concentration in gal/min ft^2. The tower area can then be calculated by dividing the water circulated by the water concentration. General rules are usually used to determine tower height depending on the necessary time of contact:

Approach to Wet Bulb (^{0}F)	Cooling Range (^{0}F)	Tower Height (ft)
15-20	25-35	15-20
10-15	25-35	25-30
5-10	25-35	35-40

Other design characteristics to consider are fan horsepower, pump horsepower, make-up water source, fogging abatement, and drift eliminators.

Operation Considerations

Water Make-up

Water losses include evaporation, drift (water entrained in discharge vapor), and blowdown (water released to discard solids). Drift losses are estimated to be between 0.1 and 0.2% of water supply.

Evaporation Loss = 0.00085 * water flowrate(T_1-T_2) (5)

Blowdown Loss = Evaporation Loss/(cycles-1) (6)

where cycles is the ratio of solids in the circulating water to the solids in the make-up water

Total Losses = Drift Losses + Evaporation Losses + Blowdown Losses (7)

Cold Weather Operation

Even during cold weather months, the plant engineer should maintain the design water flowrate and heat load in each cell of the cooling tower. If less water is needed due to temperature changes (ie. the water is colder), one or more cells should be turned off to maintain the design flow in the other cells. The water in the base of the tower should be maintained between 60 and 70 ^{0}F by adjusting air volume if necessary. Usual practice is to run the fans at half speed or turn them off during colder months to maintain this temperature range.

References:

1. The Standard Handbook of Plant Engineering, 2nd Edition, Rosaler, Robert C., McGraw-Hill, New York, 1995

2. Perry's Chemical Engineers' Handbook, 6th Edition, Green, Don W. et al, McGraw-Hill, New York, 1984