Cooling Tower Performance

BASIC THEORY AND PRACTICE

Total Heat Exchange

An open-circuit cooling tower, commonly called a cooling tower, is a specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to affect the transfer of heat. In a "spray-type" cooling tower shown in **Figure 1**, this is accomplished by spraying a flowing mass of water into a rain-like pattern, through which an upward moving mass flow of cool air induced by the action of a fan.
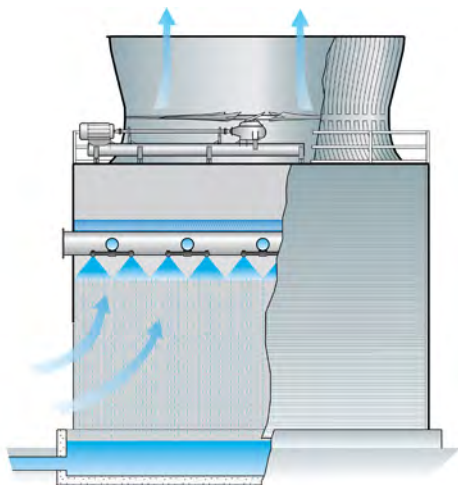

FIGURE 1

Ignoring any negligible amount of sensible heat exchange that may occur through the walls (casing) of the cooling tower, the heat gained by the air must equal the heat lost by the water. Within the air stream, the rate of heat gain is identified by the expression G $(h_2 - h_1)$, where:

$G =$ mass flow of dry air through the cooling tower – lb/min
$h_1 =$ enthalpy (total heat content) of entering air – Btu/lb of dry air
$h_2 =$ enthalpy of leaving air – Btu/lb of dry air

Within the water stream, the rate of heat loss would appear to be L $(t_1 - t_2)$, where:

$L =$ Mass flow of water entering the cooling tower – lb/min
$t_1 =$ Hot water temperature entering the cooling tower – °F
$w =$ Cold water temperature leaving the cooling tower – °F

This derives from the fact that a Btu (British thermal unit) is the amount of heat gain or loss necessary to change the temperature of 1 pound of water by 1°F.

However, because of the evaporation that takes place within the cooling tower, the mass flow of water leaving the cooling tower is less than that entering it, and a proper heat balance must account for this slight difference. Since the rate of evaporation must equal the rate of change in the humidity ratio (absolute humidity) of the air stream, the rate of heat loss represented by this change in humidity ratio can be expressed as G $(H_2 - H_1)$ $(t_2 - 32)$, where:

$H_1 =$ humidity ratio of entering air – lb vapor/lb dry air
$H_2 =$ humidity ratio of leaving air – lb vapor/lb dry air
$(t_2 - 32) =$ an expression of water enthalpy at the cold water temperature – Btu/lb (the enthalpy of water is zero at 32°F)

Including this loss of heat through evaporation, the total heat balance between air and water, expressed as a differential equation, is:

$$Gdh = Ldt + GdH (t_2 - 3_2) \qquad (1)$$

The total derivation of equation (1) can be found in *A Comprehensive Approach to the Analysis of Cooling Tower Performance* available from SPX Cooling Technologies.

Heat Load, Range and Gallons per Minute

The expression "Ldt" in equation (1) represents the heat load imposed on the cooling tower by whatever process it is serving. However, because pounds of water per unit time are not easily measured, heat load is usually expressed as:

$$\text{Heat Load} = \text{gpm} \times R \times 8\tfrac{1}{3} = \text{Btu/min} \qquad (2)$$

Where:
gpm = water flow rate through process and over tower – gal/min
R = "range" = the difference between the hot and cold water temperatures – °F (see Figure 3)
$8\tfrac{1}{3}$ = pounds per gallon of water
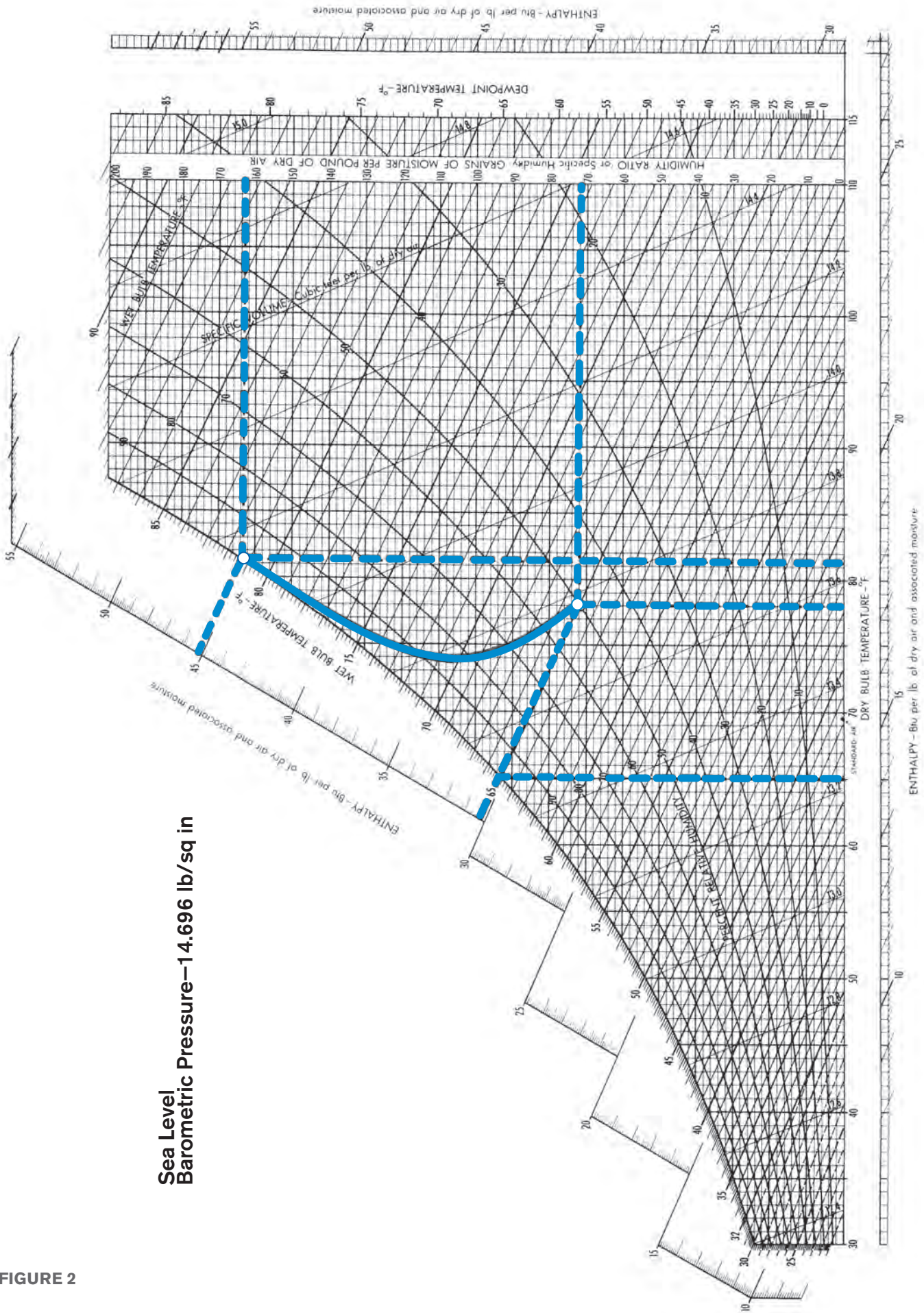
**Sea Level
Barometric Pressure—14.696 lb/sq in**

FIGURE 2

Temperature | Water Flow

Hot Water °F

L lb/min of water

Range R °F

Heat Load = L × R

Load

Cold Water °F

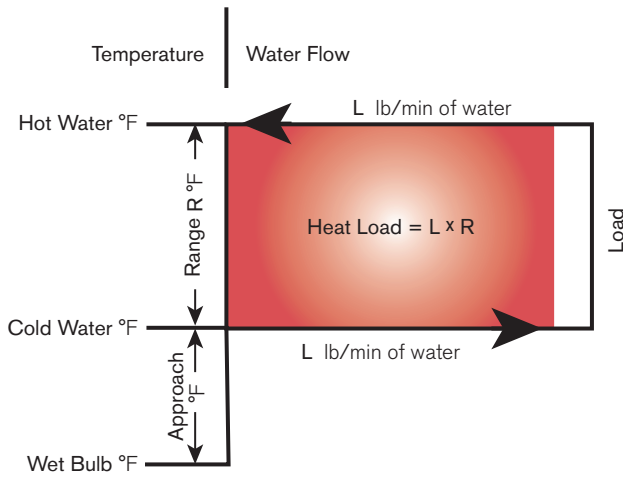Approach °F

L lb/min of water

Wet Bulb °F

FIGURE 3

Note from formula (2) that heat load establishes only a required temperature differential in the process water and is unconcerned with the actual hot and cold-water temperatures themselves. Therefore, the mere indication of a heat load is meaningless to the application engineer attempting to properly size a cooling tower. More information of a specific nature is required.

Optimum operation of a process usually occurs within a relatively narrow band of flow rates and cold-water temperatures, which establishes two of the parameters required to size a cooling tower — gpm and cold-water temperature. The heat load developed by the process establishes a third parameter — hot-water temperature coming to the cooling tower. For example, let's assume that a process developing a heat load of 125,000 Btu/min performs best if supplied with 1,000 gpm of water at 85°F. With a slight transformation of formula (2) we can determine the water temperature elevation through the process as:

$$R = \frac{125,000}{1,000 \times 8\frac{1}{3}} = 15°F$$

Therefore, the hot water temperature coming to the cooling tower would be 85°F + 15°F = 100°F.
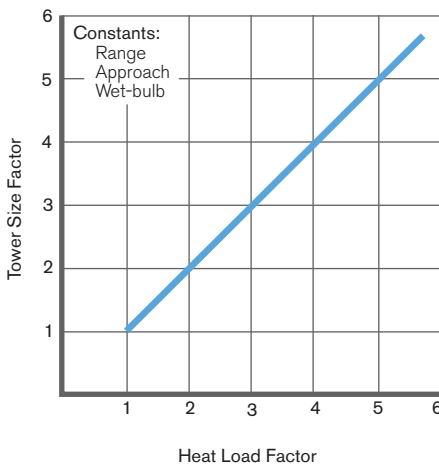
Wet-Bulb Temperature

Having determined that the cooling tower must be able to cool 1,000 gpm of water from 100°F to 85°F, what parameters of the entering air must be known? Equation (1) would identify enthalpy to be of prime concern, but air enthalpy is not something that is routinely measured and recorded at any geographic location. However, wet-bulb and dry-bulb temperatures are values easily measured, and a glance at **Figure 2** (psychrometric chart) shows that lines of constant wet-bulb are parallel to lines of constant enthalpy, whereas lines of constant dry-bulb have no fixed relationship to enthalpy. Therefore wet-bulb temperature is the air parameter needed to properly size a cooling tower and its relationship to other parameters as shown in **Figure 3**.

Effects of Variables

Although several parameters are defined in **Figure 3**, each of which will affect the size of a cooling tower, understanding their effect is simplified if one thinks only in terms of 1) heat load, 2) range, 3) approach and 4) wet-bulb temperature. If three of these parameters are held constant, changing the fourth will affect the cooling tower size as follows:

1　Cooling tower size varies directly and linearly with heat load. See **Figure 4**.

2　Cooling tower size varies inversely with range. See **Figure 5**. Two primary factors account for this. First; increasing the range — **Figure 3** — also increases the ITD (driving force) between the incoming hot-water temperature and the entering wet-bulb temperature. Second, increasing the range (at a constant heat load) requires that the water flow rate be decreased — **formula (2)** — which reduces the static pressure opposing the flow of air.

3　Cooling tower size varies inversely with approach. A longer approach requires a smaller cooing tower. See **Figure 6**. Conversely, a smaller approach requires an increasingly larger cooling tower and, at 5°F approach, the effect upon the cooling tower size begins to become asymptotic. For that reason, it is not customary in the cooling tower industry to guarantee any approach less than 5°F.
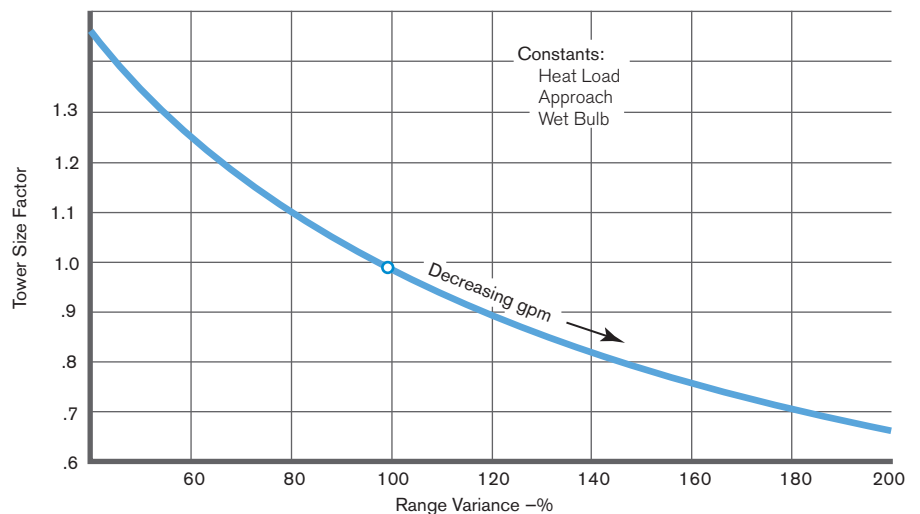

Constants:
Range
Approach
Wet-bulb

Tower Size Factor

Heat Load Factor

FIGURE 4

Constants:
Heat Load
Approach
Wet Bulb

Tower Size Factor

Decreasing gpm

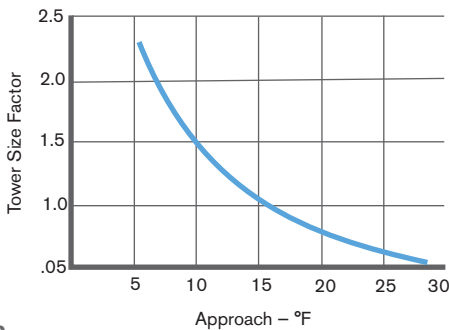Range Variance —%

FIGURE 5

FIGURE 6

FIGURE 7

4 Cooling tower size varies inversely with wet-bulb temperature. When heat load, range, and approach values are fixed, reducing the design wet-bulb temperature increases the size of the cooling tower — see **Figure 7**. This is because most of the heat transfer in a cooling tower occurs by virtue of evaporation (which extracts approximately 1000 Btus for every pound of water evaporated), and air's ability to absorb moisture reduces with temperature.

Enthalpy Exchange Visualized

To understand the exchange of total heat that takes place in a cooling tower, let's assume a cooling tower designed to cool 120 gpm (1000 lb/min) of water from 85°F to 70°F at a design wet-bulb temperature of 65°F and (for purposes of illustration only) a coincident dry-bulb temperature of 78°F. (These air conditions are defined as point 1 on **Figure 2**) Let's also assume that air is caused to move through the cooling tower at the rate of 1000 lb/min (approximately 13,500 cfm). Since the mass flows of air and water are equal, one pound of air can be said to contact one pound of water and the psychrometric path of one such pound of air has been traced on **Figure 2** as it moves through the cooling tower.

Air enters the cooling tower at condition 1 (65°F wet-bulb and 78°F dry-bulb) and begins to gain enthalpy (total heat) and moisture content in an effort to achieve equilibrium with the water. This pursuit of equilibrium (solid line) continues until the air exits the cooling tower at condition 2. The dashed lines identify the following changes in the psychrometric properties of this pound of air due to its contact with the water:

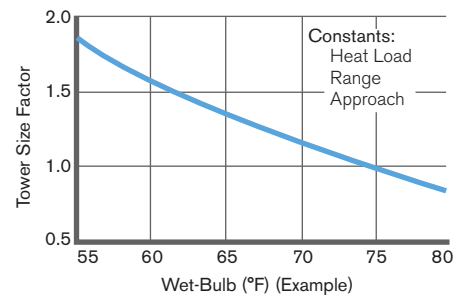• Total heat content (enthalpy) increased from 30.1 Btus to 45.1 Btus. This enthalpy increase of 15 Btus was gained from the water. Therefore, one pound of water was reduced in temperature by the required amount of 15°F (85-70) — see page 1.

• The air's moisture content increased from 72 grains to 163 grains (7000 grains = 1 lb). These 91 grains of moisture (0.013 lb of water) were evaporated from the water at a latent heat of vaporization of about 1000 Btu/lb. This means that about 13 of the 15 Btus removed from the water (about 86% of the total) occurred by virtue of evaporation. (The latent heat of vaporization of water varies with temperature, from about 1075 Btu/lb at 32°F to 970 Btu/lb at 212°F. Actual values at specific temperatures are tabulated in various thermodynamics manuals.)

At a given rate of air moving through a cooling tower, the extent of heat transfer which can occur, depends upon the amount of water surface exposed to that air. In the cooling tower depicted in **Figure 1**, total exposure consists of the cumulative surface areas of a multitude of random sized droplets, the size of which depends largely upon the pressure at which the water is sprayed. Higher pressure will produce a finer spray — and greater total surface area exposure. However, droplets contact each other readily in the overlapping spray patterns and, of course, coalesce into larger droplets, which reduces the net surface area exposure. Consequently, predicting the thermal performance of a spray-type cooling tower is difficult at best and is highly dependent upon good nozzle design as well as a constant water pressure.

An extensive library of technical papers — available on spxcooling.com — deal with water distribution system arrangements, other types of cooling towers, along with the various types of "fill" utilized to increase water surface area exposure and enhance thermal performance.

SPX®