COOLING TOWER INFORMATION INDEX

Marley® Beyond Cool

ISSUE: 1
SECTION: Basics

SUBJECT: **COOLING TOWER PERFORMANCE**

Basic Theory and Practice

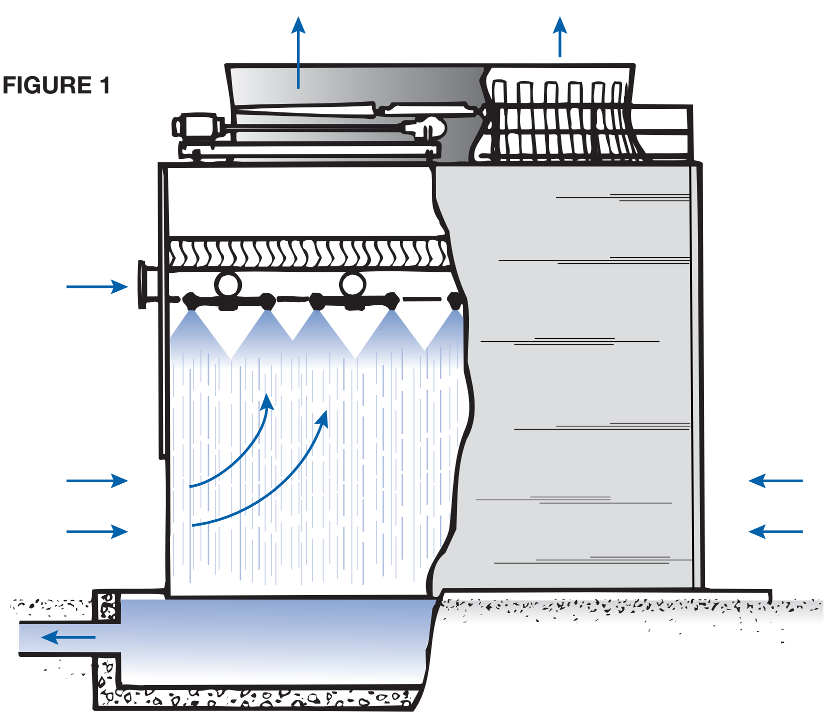
INTENT

In the foreword of *Cooling Tower Fundamentals* (published by Marley Cooling Technologies, Inc.) the scope of cooling tower knowledge was recognized as being too broad to permit complete coverage in a single publication. As a consequence, treatment of the subject matter appearing in that book may have raised more questions than it gave answers. And, such was its intent—"to provide a level of basic knowledge which will facilitate dialogue, and understanding, between user and manufacturer." In short, it was designed to permit questions to spring from a solid foundation—and to give the user a basis for proper evaluation of the answers received.

This is the first of a series of papers intended to expand upon the basic information already published. The plan for the series is to limit individual topics to as few aspects of cooling tower design, application, and operation as necessary to make for quick and informative reading. From time to time, however, subjects will arise whose scope precludes adequate coverage in a short paper, and whose thread of continuity would be lost in separate installments. Those subjects will be treated in "Technical Reports" of somewhat greater length, receiving the same distribution as will have been established by evidence of reader interest. In addition, existing publications whose content remains current and fundamentally sound will become part of the useful cooling tower library that recipients will compile.

Although this first paper touches briefly upon the theory of cooling tower performance, the basic content of future papers will be far more practical than theoretical. This is because Marley Cooling Technologies, in the course of its existence, has designed and manufactured every type of tower currently utilized in the industry, which allows all information and comparisons given to come from experience. However, since the operating characteristics of any cooling tower are governed by the laws of physics, psychrometrics, and thermodynamics, such laws may be described occasionally for purposes of promoting complete understanding.

FIGURE 1



TOTAL HEAT EXCHANGE

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 the "spray-filled" 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 is induced by the action of a fan.

Ignoring any negligible amount of sensible heat exchange that may occur through the walls (casing) of the 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 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.

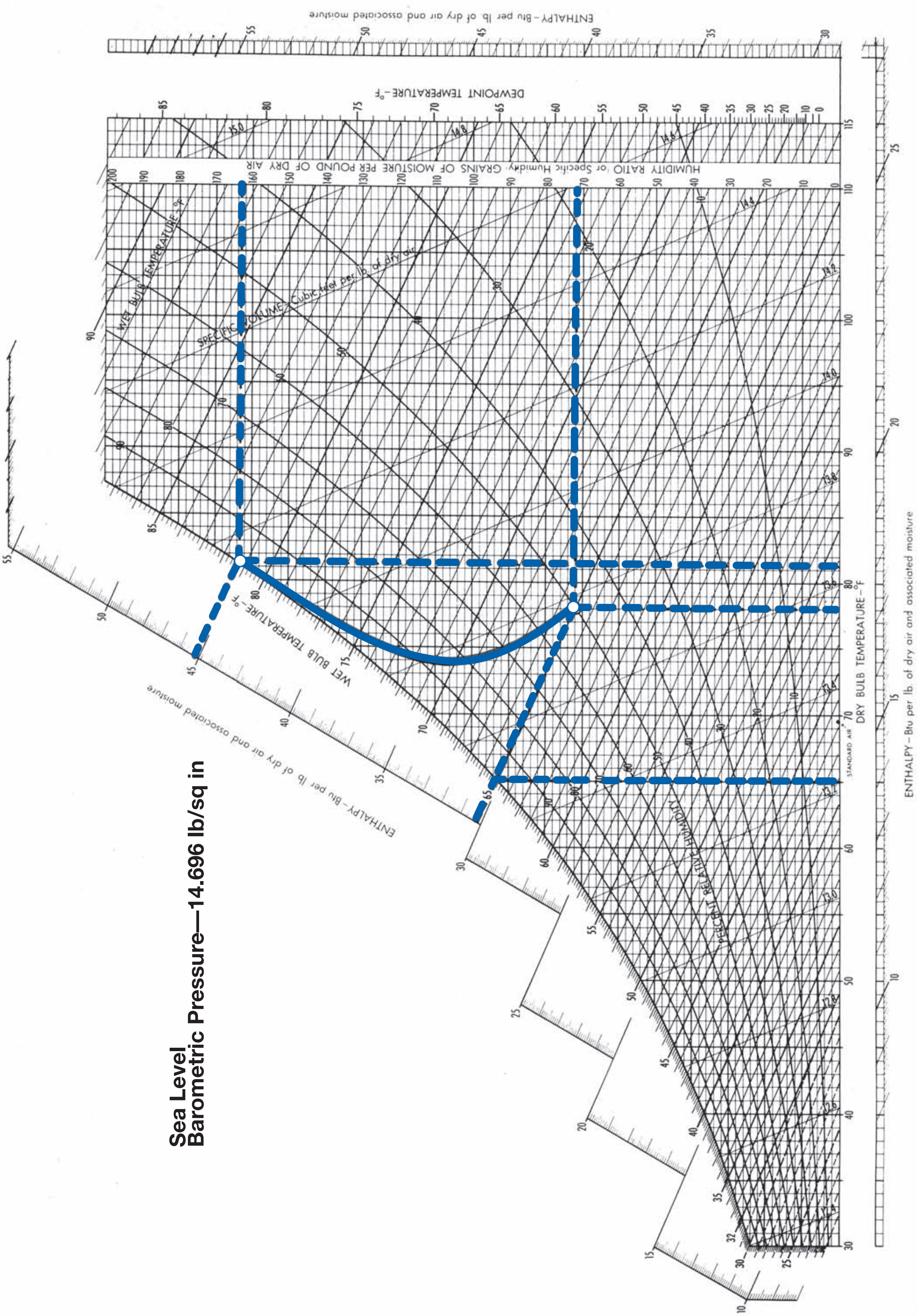
Within the water stream, the rate of heat loss would appear to be $L (t_1 - t_2)$, where:

L = Mass flow of water entering the tower—lb/min.
t_1 = Hot water temperature entering the tower—°F.
t_2 = Cold water temperature leaving the 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.

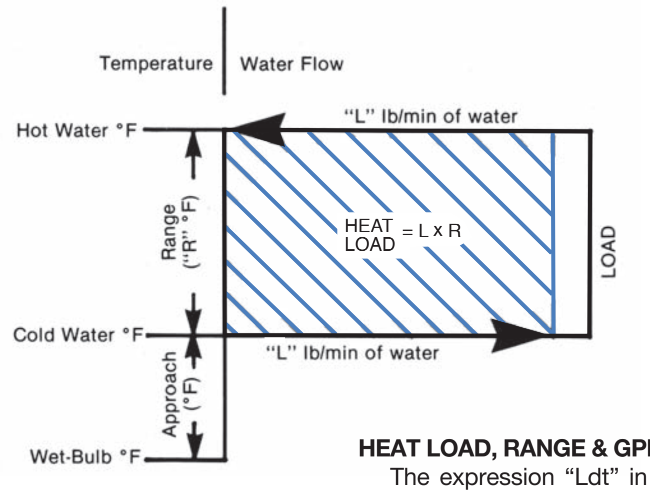
However, because of the evaporation that takes place within the tower, the mass flow of water leaving the tower is less than that entering it, and a proper heat balance must account for this slight difference. Since the rate of evaporation must equal the rate of change in the humidity ratio (absolute humidity) of the air stream, the rate of heat loss represented by this change

FIGURE 2



Sea Level
Barometric Pressure—14.696 lb/sq in
ENTHALPY–Btu per lb. of dry air and associated moisture
DEWPOINT TEMPERATURE–°F
HUMIDITY RATIO or Specific Humidity, GRAINS OF MOISTURE PER POUND OF DRY AIR
WET BULB TEMPERATURE–°F
SPECIFIC VOLUME–Cubic feet per lb. of dry air
DRY BULB TEMPERATURE–°F
PERCENT RELATIVE HUMIDITY
STANDARD AIR

FIGURE 3



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:

$$Gdh = Ldt + GdH\,(t_2 - 32) \qquad (1)$$

The total derivation of equation (1) can be found in *A Comprehensive Approach to the Analysis of Cooling Tower Performance* by D.R. Baker and H.A. Shryock, printed in the August 1961 issue of the Journal of Heat Transfer, and available from Marley Cooling Technologies.

HEAT LOAD, RANGE & GPM

The expression "Ldt" in equation (1) represents the heat load imposed on the 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" = Difference between hot and cold water temperatures—°F. (See Fig. 3)
8⅓ = Pounds per gallon of water.

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—namely, gpm and cold water temperature. The heat load developed by the process establishes a third parameter—hot water temperature coming to the 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:

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

Therefore, the hot water temperature coming to the 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 only air parameter needed to properly size a cooling tower, and its relationship to other parameters is as shown in the **Figure 3** diagram.

FIGURE 4

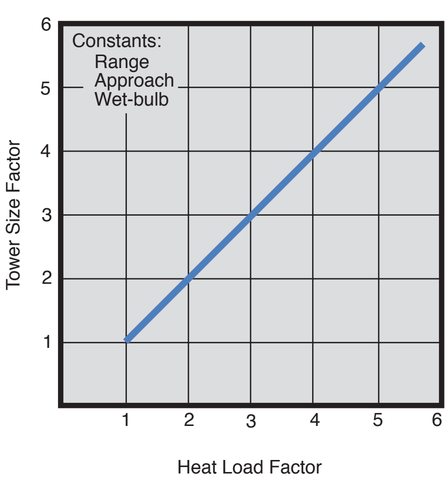


FIGURE 5

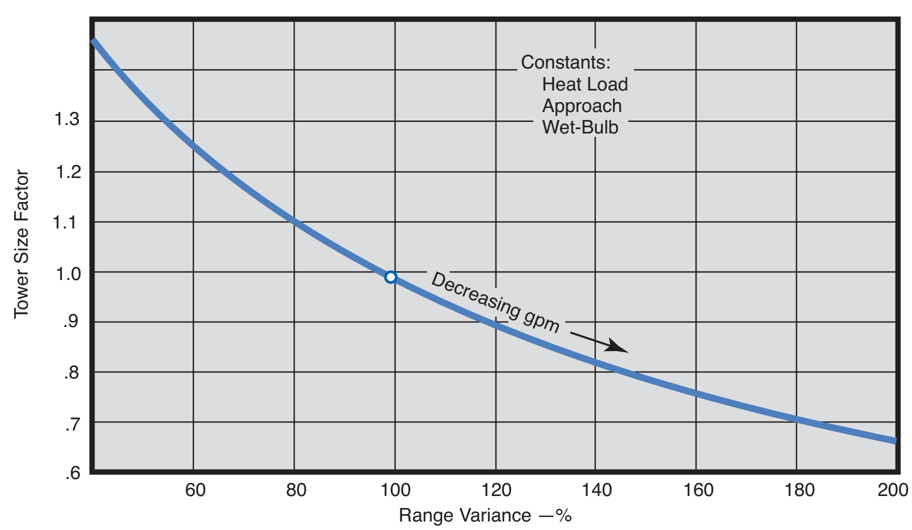


FIGURE 6

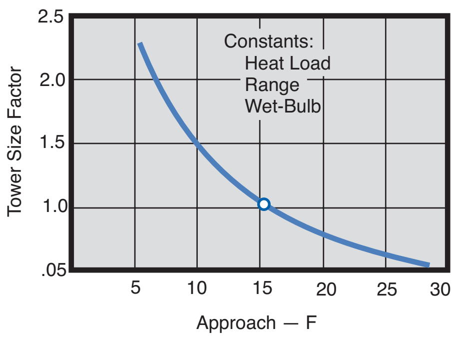
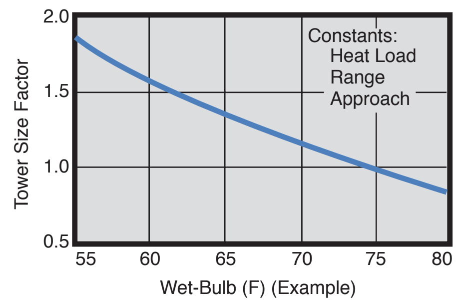


FIGURE 7



EFFECTS OF VARIABLES

Although several parameters are defined in **Figure 3**, each of which will affect the size of a 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 tower size as follows:

1) Tower size varies directly and linearly with heat load. See **Figure 4**.
2) 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) Tower size varies inversely with approach. A longer approach requires a smaller tower. See **Figure 6**. Conversely, a smaller approach requires an increasingly larger tower and, at 5°F approach, the effect upon tower size begins to become asymptotic. For that reason, it is not customary in the cooling tower industry to guarantee any approach of less than 5°F.
4) 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 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 Btu's 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 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 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 tower.

Air enters the 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 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 Btu to 45.1 Btu. This enthalpy increase of 15 Btu 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 lbs. 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 Btu's 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 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-filled tower is difficult at best, and is highly dependent upon good nozzle design as well as a constant water pressure.

Subsequent issues will deal with water distribution system arrangements used in other types of towers, along with the various types of "fills" utilized to increase water surface area exposure and enhance thermal performance.