Effect of Heat Rejection Load and Wet Bulb on Cooling Tower Performance

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To improve system efficiency and accurately predict the savings provided by water economizers, it is imperative to understand cooling tower performance, and not rely on rules of thumb. This article is the first of three in a cooling tower technology series. It explores the relationship of cooling tower approach temperature, heat rejection load, and wet-bulb temperature.

Understanding these dynamics enables optimization of tower setpoint and increased system efficiency, particularly in regards to water economizer operation where these relationship are often misunderstood. Additional information on optimizing tower and system energy will be covered in the second article, including tower-related updates to the recently published (2013) edition of ASHRAE/IES Standard 90.1. The final article in the series will address cold weather operation of cooling towers, including water economizer applications.

For the purposes of this article, we will examine an example cooling tower (*Table 1*) designed in accordance with the flow rate guidance provided by the *ASHRAE GreenGuide*[1] and also Taylor[2] – in this case 2 gpm per ton of refrigeration. To demonstrate tower performance at various wet-bulb temperatures and range (tower ΔT) (*Figure 1*), a portion of Figure 27 from the *2012 ASHRAE Handbook* is used. At first glance the 4.5°F (2.5°C) approach temperature may seem low. The *Handbook* states that this performance is for a cooling tower originally selected for a 7°F (3.8°C) approach and 3 gpm/ton, then reselected at a flow rate of 2 gpm/ton.

TABLE 1 Cooling tower design performance.

Chiller Capacity (tons)	500
Cooling Tower (Condenser) Flow Rate (gpm)	1000
Chiller Efficiency (COP)	6.10
Design Wet Bulb (°F)	78
Design Approach Temperature (°F)	4.5
Tower Entering Water Temperature (°F)	96.5
Tower Leaving Water Temperature (°F)	82.5
Design Range (Condenser Water ΔT) (°F)	14

Towers designed at other conditions perform similarly. For simplicity, constant cooling tower water-flow rate is assumed.

These *Handbook* data are used to chart cooling tower approach temperature (*Figure 2*). For the purposes of this article, range and percent load are treated proportionally. For example, a 4.0°F (2.2°C) range is 29% load (4/14 = 0.29).

For the purposes of the first example in *Table 2*, a condition at which mechanical cooling is required

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(60°F [15.6°C] wet-bulb temperature) is used to examine approach temperatures at various load conditions. At 60°F [15.6°C] wet-bulb temperature, the cooling tower approach temperature ranges from 9.0°F (5.0°C) at design load to 2.8°F (1.5°C) at a 29% load (*Table 2*).

Note the approach temperatures at a constant 100% heat rejection load (14°F [7.8°C] range) (*Table 3*).

Between 30°F and 85°F (–1°C and 29°C) wet-bulb temperature, the approach changes by a factor of six—and factor of almost five between 30°F (–1°C) and the 78°F (26°C) design wet bulb! This may be a phenomenon that was previously unknown to many. It's important to understand which mode sets the cooling tower design; summer or water economizer mode. In addition, it must be considered when determining tower setpoints at reduced wet-bulb temperatures. If inaccurate assumptions are made, tower design and/or the method of controlling cooling tower setpoint will be less than optimal.

Why do these phenomena occur? They are related to the psychrometric properties of air. At lower temperatures, air simply cannot hold as much moisture. Interestingly, at these lower temperatures, a greater proportion of heat rejection is sensible, so the amount of water evaporated is reduced compared to design conditions.

FIGURE 1 Cooling tower performance.

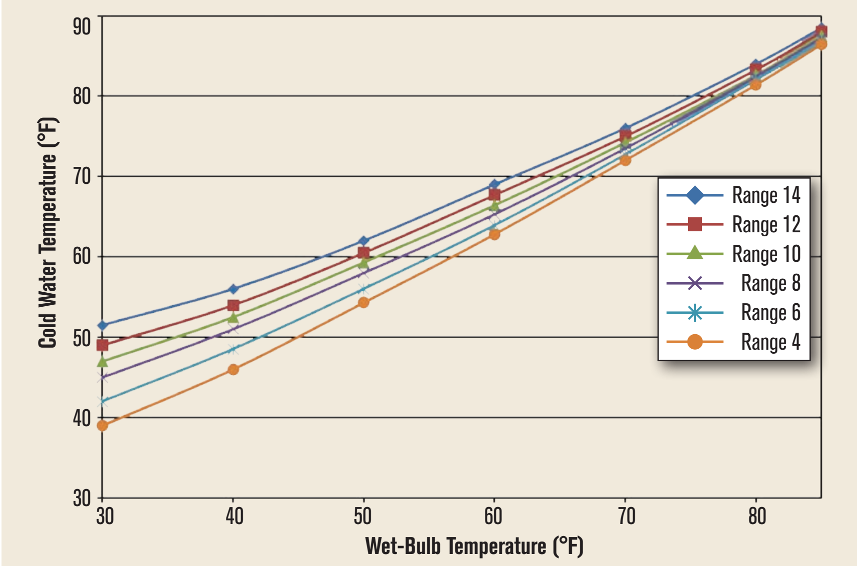

FIGURE 2 Cooling tower approach temperature.

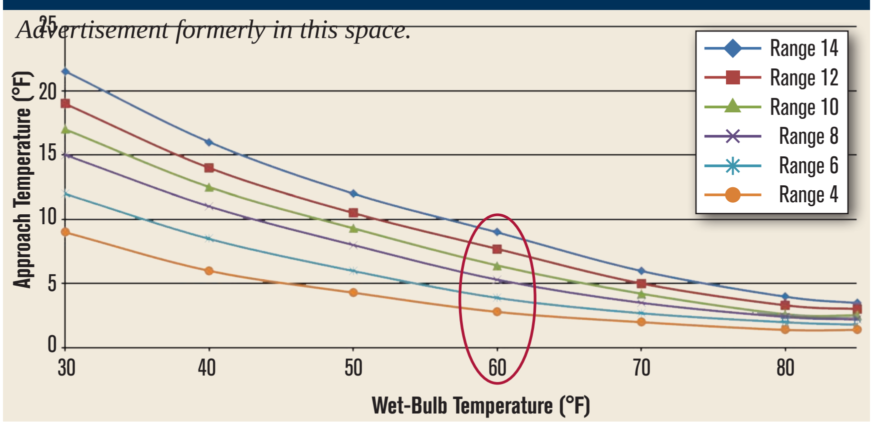

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TABLE 2 Cooling tower approach temperature at 60°F wet-bulb temperature.

RANGE (°F)	PERCENT LOAD	APPROACH (°F)
4	29%	2.8
6	43%	3.9
8	57%	5.3
10	71%	6.4
12	86%	7.7
14	100%	9.0

So What?

What difference can this make when controlling cooling towers for optimal system performance or performing analyses? Two examples follow.

Example 1

A project team decides that in lieu of full-year analysis they will use a spreadsheet to estimate conditions. They incorrectly assume that the cooling tower approach temperature remains constant at the design approach temperature of 4.5°F (2.5°C). (The author has seen similar assumptions used in a number of "spreadsheet calculations.")

To compare this assumption with actual performance, the 4.5°F (2.5°C) approach and *Table 2* data are used to construct *Table 4*.

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The *incorrectly assumed* tower temperature available is 64.5°F (18.1°C) at all loads, while the actual temperature ranges from 62.8°F to 69.0°F (17.1°C to 20.5°C). Therefore, an analysis that assumes a constant approach temperature provides inaccurate results.

In addition, if the incorrect analysis is accepted, during actual operation the cooling tower fan may be controlled to a constant 4.5°F (2.5°C) approach temperature. The fan would operate at constant tower fan speed until the chiller load is about 50%. Stout[10] has shown this not to be optimal control. Controlling to a constant approach temperature leads to inefficient *system* operation at many conditions, since it tends to drive the tower water to colder temperatures than would optimize the system.

Many[(4–9)] have found that optimizing the sum of chiller plus tower energy consumption provides reduced system energy consumption. The intent of this article is not to describe the various methods of optimizing chiller plus tower performance. Different providers implement "near optimal" tower setpoint control in different ways, and most are a function of chiller design, tower design, chiller load and outdoor conditions. For specific information, please see the references. To offer the reader a savings estimate range, Crowther and Furlong[8] showed 2.6% to 8.5% savings by optimizing the tower setpoint, rather than driving it as cold as possible.

TABLE 3 Cooling tower approach temperature at constant load.

WET BULB (°F)	APPROACH (°F)
30	21.5
35	18.6
40	16.0
45	13.9
50	12.0
55	10.4
60	9.0
65	7.4
70	6.0
78	4.5
80	4.0
85	3.5

TABLE 4 Comparison of available cooling tower water temperatures.

	INCORRECTLY ASSUMED		ACTUAL (AT 60°F OAWB)	
PERCENT LOAD	APPROACH (°F)	TEMPERATURE AVAILABLE (°F)	APPROACH (°F)	TEMPERATURE AVAILABLE (°F)
29%	4.5	64.5	2.8	62.8
43%	4.5	64.5	3.9	63.9
57%	4.5	64.5	5.3	65.3
71%	4.5	64.5	6.4	66.4
86%	4.5	64.5	7.7	67.7
100%	4.5	64.5	9.0	69.0

Example 2

A project team applies a waterside economizer for use in a data center. The chilled-water system design temperature is 54.0°F (12.2°C). The heat exchanger has a 2.0°F (1.1°C) approach temperature, so the tower must produce 52.0°F (11.1°C) water to satisfy the entire load. The chilled-water temperature difference at that load is 10.0°F (5.5°C), which results in constant return-water temperature of 64.0°F (17.8°C). The system load is constant at 100%; therefore, the cooling tower range is 14.0°F (7.8°C). In its analysis, the project team incorrectly assumes a constant 4.5°F (2.5°C) tower approach temperature.

Clearly, significant discrepancies exist between the incorrect assumption and actual performance. The error in estimated savings depends on the number of operational hours in the range between 35°F and 55°F (1.5°C and 12.8°C) wet-bulb temperature for the specific weather location.

TABLE 4 Comparison of tower approach temperatures.

	INCORRECTLY ASSUMED				ACTUAL			
WET-BULB TEMPERATURE (°F)	APPROACH (°F)	TOWER LEAVING (°F)	TOWER ENTERING (°F)	LOAD HANDLED	APPROACH (°F)	TOWER LEAVING (°F)	TOWER ENTERING (°F)	LOAD HANDLED
30	4.5	34.5	48.5	100%	21.5	51.5	65.5	100%
35	4.5	39.5	53.5	100%	18.6	53.6	67.6	84%
40	4.5	44.5	58.5	100%	16.0	56.0	70.0	60%
45	4.5	49.5	63.5	100%	13.9	58.9	72.9	31%
50	4.5	54.5	68.5	75%	12.0	62.0	76.0	0%
55	4.5	59.5	73.5	25%	10.4	65.4	79.4	0%
60	4.5	66.5	80.5	0%	9.0	69.0	83.0	0%
65	4.5	69.5	83.5	0%	7.4	72.4	86.4	0%
70	4.5	76.5	90.5	0%	6.0	76.0	90.0	0%
78	4.5	82.5	98.5	0%	4.5	86.5	98.5	0%

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Summary

For a given cooling tower, approach temperature is dependent on heat rejection load and entering wet-bulb temperature. At reduced wet-bulb temperature, colder tower water temperature is available—but it is not as cold as many think. Therefore, accurate knowledge of these correlations is necessary. Many cooling tower suppliers can offer assistance in predicting the tower leaving temperature at various wet bulb and load conditions. Practitioners can use this knowledge to improve system operation and, therefore, efficiency during both "normal" and waterside economizer operation. The second article of this series will discuss additional energy savings opportunities for water-cooled systems.

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