

COOLING TOWER [COUNTER FLOW] THEORY

Introduction:

The purpose of this document is to assist the purchaser/consultant in effectively sizing, selecting and evaluating a particular cooling tower. This document mainly focuses on the performance variables of a cooling tower and sizing of cooling towers to optimize costs and performance.

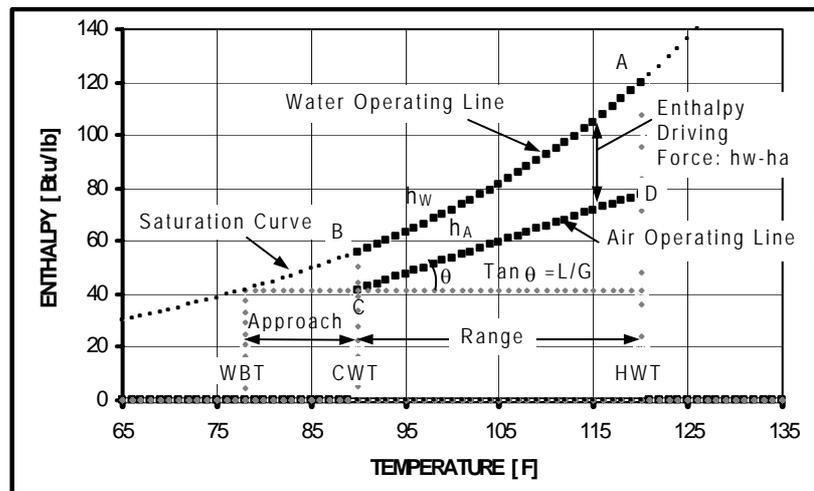
Merkel's Equation:

The basic function of a cooling tower is to cool water by intimately mixing it with air. This cooling is accomplished by a combination of sensible heat transfer between the air and the water and the evaporation of a small portion of the water. This type of transfer is represented by the following equation:

$$KaV/L = \int_{CWT}^{HWT} \frac{dT}{h_w - h_A}$$

This equation is commonly referred to as the Merkel equation. The left-hand side of this equation is called the "tower characteristic," which basically indicates the 'degree of difficulty to cool' the water or the 'performance demand' of the tower.

The tower characteristic and the cooling process can best be explained on a Psychrometric Chart. The process is shown in the figure on the right -known as the Driving Force Diagram. The upper curve shows the relation between the temperature and enthalpy of the *saturated air*. This curve applies to the air film surrounding the water. Merkel assumed that the drops of water falling through the tower are surrounded by a film of saturated air and the heat and mass transfer basically takes place between this film



[which has the same temperature as of the water] and the upstream air. The condition of the air film is represented by the *Water Operating Line* and is limited by the hot and cold water temperatures, points A and B.

The lower curve known as the *Air Operating Line*, represents the condition of air flowing through the cooling tower. The origin of this line, point C, is vertically below B and is positioned to have an enthalpy corresponding to that of the entering wet bulb temperature. As the water is cooled one degree, the enthalpy of the air is increased 1 Btu multiplied by L/G [water circulation -lbs.per unit time/ air circulation -lbs. per unit time]. Thus, the L/G ratio is the slope of the air operating line C-D. Point D, representing the air leaving the cooling tower, is the point on the air operating line vertically below point A. The projected length C-D is the cooling range.

The Merkel Equation primarily says that at any point in the tower, heat and water vapor are transferred into the air due [approximately] to the difference in the enthalpy of the air at the surface of the water [represented by the Water Operating Line A-B] and the main stream of the air [represented by the Air Operating Line C-D]. Thus, the driving force at any point is the vertical distance between the two operating lines. And therefore, the performance demanded from the tower is the inverse of this difference. The integrand of the Merkel equation can be represented by the Demand Curve -shown on page 1. The value of the integral is the area under the curve.

Effects of Variations in Design Conditions on Cooling Tower Performance:

An increase in the entering wet bulb temperature moves the origin C upward and the line C-D shifts to the right to establish equilibrium. Both the inlet and outlet water temperatures increase, while the approach decreases. The curvature of the saturation line is such that the approach decreases at a progressively slower rate as the wet bulb temperature increases.

An increase in the heat load increases the cooling ranges and increases the length of line C-D. To maintain equilibrium, the line shifts to the right, increasing the hot and cold water temperatures and the approach. The increase causes the hot water temperature to increase considerably faster than does the cold-water temperature.

In both these cases, the KaV/L should remain constant. However, a change in L/G will change the KaV/L value.

Cooling Tower Variables

On the basis of the above discussion, it is clear that there are following *five* parameters that *in combination* dictate and define the performance of a cooling tower:

- [I] Hot Water temp, HWT, [II] Cold Water temp, CWT, [III] Wet Bulb temp, WBT
- [IV] Water Flow Rate, L, [V] Air Flow Rate, G

The first four data are the ones, which are given by the user. The fifth one (G), is selected by the cooling tower designer. Once these five data are available, the tower characteristic (KaV/L), can be calculated through the Merkel Equation.

The fill height (FH), depends on the fill characteristic and L/G , and is computed by the following equation:

$$KaV/L = C \times FH \times [L/G]^n$$

Where 'C' and 'n' are constants, which depend on the tower fill. These both factors are determined through fill test.

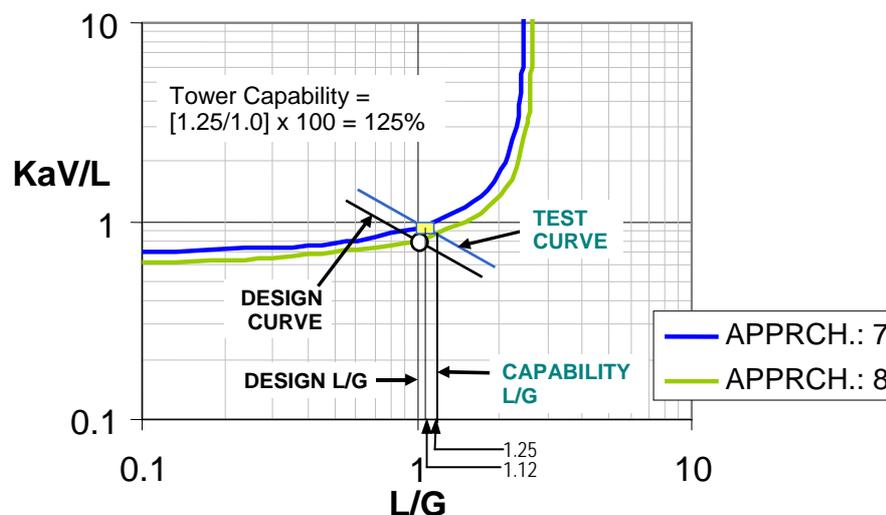
Evaluation of Operating Performance of Cooling Towers

The only correct way of evaluating the performance of a cooling tower is to carry out Capability Test as per ATC-105 code of CTI [Cooling Tower Institute, USA], which specifies the following two methods:

A. Characteristic Curve

Method

The manufacturer must submit a tower Characteristic Curve similar to the one shown on the right. From test data, values of test L/G and KaV/L are calculated and then located on the manufacturer's characteristic graph. Through this test point a line shall be drawn parallel to the manufacturer's characteristics line. The intersection of this line with designing approach determines the value of L/G at which the tower would produce design cold water when operating at design conditions. The ratio of the L/G so determined to design L/G is defined as tower capability.



	HWT	CWT	WBT	L/G	KaV/L
Design Data	100	90	82	1.0	0.81
Test Data	97	88	81	1.12	0.92

Apart from the performance assessment, this graph is very useful in selecting an optimum tower size. There is an inverse relationship between *fan airflow* [G] –which translates to higher HP and therefore higher running cost- and *fill volume* [KaV/L] –which corresponds to a larger tower and consequently higher initial costs. So, to beat the competition, a clever manufacturer can easily offer a higher HP lower first cost cooling tower, which is infact expensive to the user in the long run. It is important that the user or the consultant selects a tower with optimized HP versus size relationship.

B. Performance Curve Method

In this method the manufacturer is required to submit 3 sets of 3 curves. For varying cooling tower loads and wet bulb temperatures, design cold water temperatures [shown on the curves] can easily be compared with test cold water temperatures.

Sizing Cooling Towers to Optimize Costs and Performance

Service factors are used in the preparation of specifications for most industrial equipment. These can be thought of as multipliers to help ensure that the device will equal or exceed the desired performance. In some cases the factors are used to increase flexibility. Possible operation at conditions appreciably different from the initial is sometimes made possible in this manner. Quite often during the design stage of a cooling tower, it is deemed appropriate that a service factor be built into the thermal performance capability of the cooling tower.

Consequently, in many instances the numbers presented in a cooling tower inquiry for thermal performance design represent a somewhat more stringent condition than that actually to be encountered in the operation of the unit. This conservative “factor” in the cooling tower design's parameters is certainly not an unwarranted factor; however, we should give some close attention to where this factor should be applied and its consequent effect on the overall cost of the installed cooling tower. The following is a table exploring the different service factors generally used:

Safety Factor Area	Discussion	Remarks
CWT or WBT	<ul style="list-style-type: none"> ▪ Such a safety factor reduces the Approach [CWT - WBT]. ▪ Closing the approach does NOT vary linearly with increasing difficulty of duty for the cooling tower, & consequently does not represent a straight-line increase in size or cost. ▪ A decrease in the specified approach is equivalent to a decrease in the driving force. The percentage reduction in driving force is much greater for a low approach than a high approach. For example, a decrease in approach from 20 °F to 19 °F would result in an increase in cost of about 5%, while a decrease from 5 °F to 4 °F would require about 20% larger cooling tower. 	<i>Not recommended</i>
GPM	<ul style="list-style-type: none"> ▪ The effect on the cooling tower size and price is essentially a one-to-one or straight-line effect. ▪ One caution must be observed; if the actual operating water loading is appreciably lower, the efficiency of the tower may be markedly reduced due to poor water distribution and/or improper wetting of the fill. ▪ An overzealous effort to obtain a safety factor in this manner could, in some instances, result in an actual LOSS in performance. 	<i>This is the most realistic method. It gives the most flexibility in connection with possible future needs.</i>
RANGE [HWT – CWT]	<ul style="list-style-type: none"> ▪ In this case the HWT is raised arbitrarily. ▪ This method results in an increased driving force. Consequently, it is much easier for the tower to accept additional load and perform satisfactorily when this load is being added in the form of higher HWT. ▪ For most ordinary conditions, an appreciable increase in HWT requires only a relatively small increase in size and cost of the cooling tower. ▪ Again, there is a caution to be observed. Be certain that the condenser, or equipment being served with this cooling water, is capable of taking the higher hot water temperatures. 	<i>Use with caution.</i>

Performances of One Cooling Tower

Following is a table that shows the performances of a single tower. The purpose of this table is to give you some idea of the interaction of the five cooling tower performance variables.

Scenario	HWT [°F]	CWT [°F]	WBT [°F]	L/G	KaV/L	Fill Ht. [ft.]
1	101	86	80	1	1.55	3.87
2	103	87	81	1	1.55	3.87
3	106	87	80	1	1.55	3.87
4	108	88	81	1	1.53	3.84
5	111	88	81	0.95	1.61	3.89
6	108.2	87	80	0.95	1.61	3.89
7	102.6	86	80	0.95	1.61	3.89
8	100.5	85.5	80	0.95	1.61	3.89