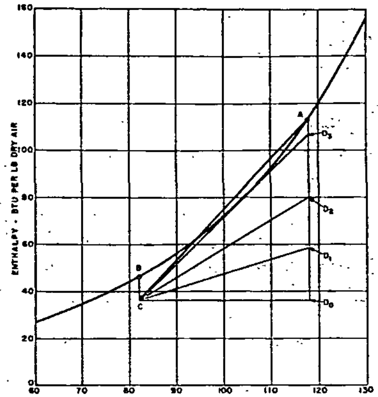

Fig. 10 .... Counterflow Cooling Diagrams for Constant Conditions, Variable L/G Ratios[3]

of degree-of-difficulty. The NTU corresponding to a set of hypothetical conditions is called the *required* coefficient, and evaluates the degree-of-difficulty presented by the problem. When test results are being considered, the NTU represents the *available* coefficient, and is an evaluation of the equipment involved.

Required Coefficients

The calculations consider the temperatures and the L/G ratio. The minimum *required* coefficient for a given set of temperatures occurs at $L/G = 0$, corresponding to an infinite air rate. There will be no increase in air enthalpy, so the maximum driving force will prevail, and the degree-of-difficulty will be a minimum. A decrease in air rate, reflected as an increase in L/G ratio, decreases the driving force, and the greater degree-of-difficulty is reflected as an increase in NTU. This is shown graphically for counterflow in Fig. 10. The maximum L/G ratio (or minimum air rate) for a given set of temperatures occurs when CD intersects the saturation curve. The driving force becomes zero and the NTU is infinite. The point of zero driving force may occur at the air outlet or at an intermediate point, due to the curvature of the saturation curve as shown in Fig. 10. The temperatures determine where the curves meet.

Similar variations occur in crossflow cooling. Variations in L/G ratio are reflected as variations in the shape of the operating area. At $L/G = 0$, the operating area becomes a single horizontal line which is identical to the counterflow diagram and both coefficients are the same. An increase in L/G ratio causes an increase in height of the operating area, the average width remaining constant for a constant cold-water temperature. This continues as the area extends to point A as a limit. This maximum L/G ratio always occurs when the wet-bulb temperature of the air equals the hot-water temperature, and not at an intermediate point as may occur in counterflow.

Thus, both types of flow have the same minimum coefficient corresponding to $L/G = 0$, and both increase to infinity at a maximum L/G ratio. The maximum values are the same if the counterflow potential reaches zero at the air outlet, but the counterflow tower will have a lower maximum L/G ratio when the potential reaches zero at an intermediate point, as shown in Fig. 10. A cooling tower can be designed to operate at any point within the two limits, but practical considerations limit the design to much narrower limits that are determined by air velocity. A low air rate requires a large tower, while a high air rate in a smaller tower requires greater fan power. The limits in air velocity are about 250 to 400 fpm in counterflow and 350 to 650 in crossflow. The higher velocities are obtainable in crossflow because of the larger air inlet and greater eliminator area, and the outgoing air does not pass through the water distribution system.

Available Coefficients

A cooling tower will operate over a wide range of water rates, air rates, and heat loads, and the variations will be reflected in the approach of the cold-water to the wet-bulb temperature. The analysis of a series of tests points will show that the *available* coefficient is not a constant, but varies with the operating conditions.

TOWER CHARACTERISTIC

A tower characteristic is developed from the analysis of test results. The variations in the *available* coefficient occur because the calculations consider temperature change per unit of driving force without regard to height of tower or water rate. An increase in water loading makes it more difficult to obtain a given temperature change, and this is reflected in operating temperatures representing a decrease in *available* coefficient. The coefficients of mass and energy transfer increase with an increase in air velocity, and this is reflected in the *available* coefficient. The tower characteristic is an empirical correlation between the *available* coefficient and the operating conditions.

Fig. 11 is a common type of correlation, showing the variation of KaV/L with L/G for parameters of constant air velocity. The characteristic usually plots as a series of straight, parallel lines when logarithmic coordinates are used, but there is no fundamental reason why this should occur.

A common practice is to ignore the effect of air velocity and consider a single average curve which then corresponds to:

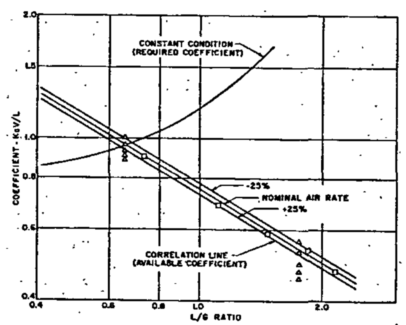

Fig. 11 .... Tower Characteristic, KaV/L vs L/G[3,a]

[a] *Plotted points at nominal air rate. Square points at 100 F hot-water temperature. Triangular points vary from 80 to 160 F hot-water temperature.*

$$\frac{KaV}{L} \sim \left(\frac{L}{G}\right)^n \tag{11}$$

The exponent, n, varies within a range of about -0.35 to -1.1, but averages between -0.55 and -0.65.

The family of curves correspond to the equation:

$$\frac{KaV}{L} \sim (L)^n(G)^m \tag{12}$$

where n is as above and m varies between 0.60 and 1.1, but is usually somewhat less than unity.

The triangular points in Fig. 11 show the effect of varying temperature conditions at the nominal air rate. The deviations follow trends that should not occur because temperature levels are considered in the calculations. The deviations are due to simplifying assumptions and may be overcome by modifying the procedure used in the mechanical integration as follows.

Heat Balance

Usual practice is to ignore evaporation and assume that:

$$G dh = L dt \tag{13}$$

The true enthalpy rise is greater than this because a portion of the heat in the water stream leaves as vapor in the air stream. The correct heat balance is[3]

$$G dh = L dt + G dh (t_{wa} - 32) \tag{14}$$

This reduces the driving force and increases the NTU.

Variable L/G Ratio

Evaporation causes the water rate to decrease from L at the inlet to $L - L_E$ at the outlet. The water-to-air ratio varies from L/G at the water inlet to $(L - L_E)/G$ at the outlet. This results in an increase in NTU.

Film Resistance

Basic theory considers the transfer from the interface to the air stream. The film conditions are indeterminate so the usual procedure is to ignore the film resistance. The resulting coefficients show deviations that are closely associated with the hot-water temperature and may be modified by using an empirical hot-water correction factor.[6]

The effect of film resistance[7] is shown in Fig. 12. Water at temperature t is assumed to be surrounded by a film of saturated air at the same temperature. This corresponds to point B, having enthalpy h', on the saturation curve. The

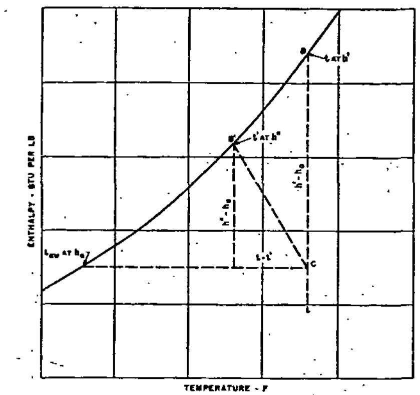

Fig. 12 .... True vs Apparent Potential Difference[7]

film is actually at a lower temperature, point B', having an enthalpy h''. The surrounding air at enthalpy h_a corresponds to point C. The usual procedure is to consider the *apparent* potential difference $(h' - h_a)$, but the *true* potential difference[7] is $(h'' - h_a)$. Equating Equations 1 and 6:

$$\frac{h'' - h_a}{t' - t} = -\frac{K_L}{K'} \tag{15}$$

The slope of CB' equals the ratio of the two coefficients. No practical means of evaluating the coefficients has been proposed, but a slope of -11.1 for crossflow towers has been reported by Baker and Shryock.[3]

Establishing Tower Characteristics

It is frequently, but incorrectly, assumed that the performance of a cooling tower is determined by the characteristic of the filling. The maximum performance is obtained in a given volume of filling when water distribution is uniform and air velocity is constant throughout. Changes in the water

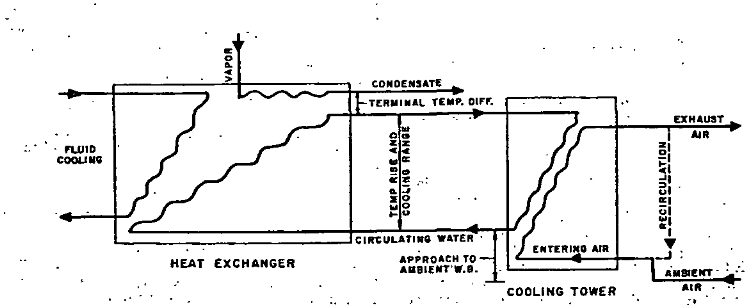

Fig. 13 .... Relation of Cooling Tower to Process