CE427 - CHEMICAL ENGINEERING LABORATORY III
FALL 2005

COOLING TOWER

Objectives:

1. Determine at various ratios of water to air mass flow rate, the tower characteristic for the cooling tower located in Jarvis 116.
2. Determine at a water to air mass flow ratio of ~1, how the range, and the approach vary with increasing water flow rate.
3. Estimate the evaporation rate of water (water loss) for the tower.

System:

In the cooling tower system located in Jarvis 116, warm water is brought into contact with unsaturated air over the surface of horizontal redwood slats. During this process, part of the water evaporates, lowering the water temperature. The water flow rate is measured with a rotameter while the air flow rate is measured using a pitot tube. Wet and dry-bulb temperatures for inlet air, and dry-bulb temperature for outlet air, as well as inlet and outlet water temperatures are measured by thermocouples which are interfaced with a data acquisition board controlled by LabView software.

Theory:

Cooling towers are commonly used in industry to reduce the temperature of utility cooling water to allow its reuse in heat exchangers. Inside a cooling tower, a liquid warm water stream is exposed to unsaturated air. The temperature of the water is decreased by the simultaneous transfer of mass and heat at the gas-liquid interface. The theoretical background for this assignment is contained in the first two portions of Section 12 (Psychrometry, Evaporative Cooling, Air Conditioning, and Refrigeration) of Perry's Chemical Engineers Handbook and the experimenter is advised to read this material.

Physical properties of air-water vapor mixtures

Analysis of the operation of a cooling tower requires the determination of the physical properties of air-water vapor mixtures. A psychrometric metric chart represents a concise compilation of a number of physical properties for a particular gas-vapor mixture. It is recommended that you review the psychrometric chart tutorial located at the following site:

www.uwsp.edu/it/tlrn/LOs2003/paperlo

The key definitions:

- **Wet-bulb temperature**- the steady-state, non-equilibrium temperature reached by a small mass of liquid exposed to a continuous gas stream. In the lab, the web-bulb temperature is measured with a thermocouple that is covered with a water-saturated wick. This thermocouple is located in the inlet air stream and the wet-bulb temperature is used to determine the moisture level and other physical properties of the incoming air
- **Absolute Humidity** (Humidity ratio)- mass of water vapor per mass of bone-dry air.
- **Humid Volume** (Specific volume)- volume of the humid air per mass of bone-dry air.
- **Enthalpy**- the measure of the heat content of the humid air. Enthalpy of the air is the saturation enthalpy minus the enthalpy deviation.

Operating Line

For a short section, dZ, of a counterflow cooling tower, an enthalpy balance can be written as:

$$Gdh_y = d(Lh_x) \tag{1}$$

Here *h* denotes the enthalpy (Btu/lb or J/g). The subscript *x* is associated with the liquid phase, while *y* with the gas phase. The mass velocity of the air is G , the mass of vapor-free air per hour per unit cross section of tower. The mass velocity of water is denoted by L .

Assuming that only a small fraction of the liquid evaporates in this process compared to the total amount of liquid fed into the tower, we can assume L to be constant. The datum plane (or reference temperature, T_0) for all enthalpy calculations is arbitrary and it eventually cancels out on both sides of the equations. For water, it is usually taken at a temperature of T_o=32°F (according to Perry's Handbook). For liquid water then, $h_x = c_l(T_x - T_o)$ where c_L is the specific heat of water. Thus, the differential form of Equation (1) becomes:

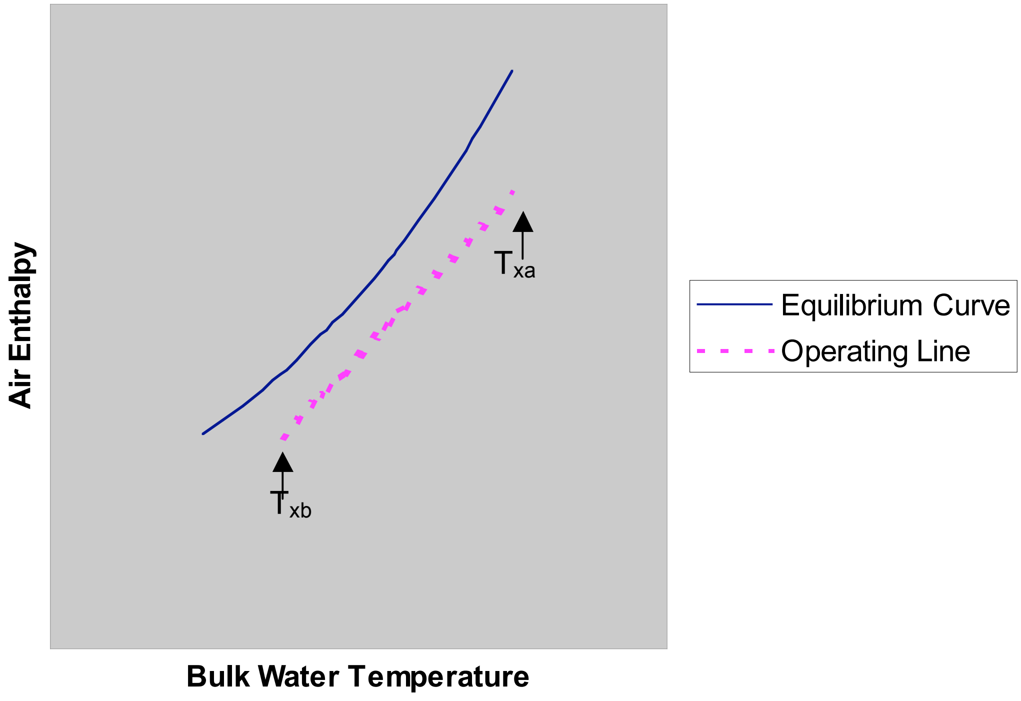
$$Gdh_y = Lc_L dT_x \tag{2}$$

Using the convention that the subscript *a* depicts the top and *b* the bottom of the cooling tower, and integrating from the bottom of the column to any particular point the column, one obtains:

$$G(h_y - h_{yb}) = Lc_L(T_x - T_{xb}) \tag{3}$$

This equation is known as the operating line for the tower and it appears as a straight line of slope Lc_L/G on a plot of air enthalpy versus water temperature as in Figure 1. With this equation, one can determine the enthalpy of the air at any point in the tower in BTU/lb dry air or J/g dry air given the conditions of the inlet air and exiting water and the temperature of the water at that same point. An equilibrium line is shown on the same graph giving the enthalpy of air saturated with water vapor as a function of water temperature. The air enthalpy given by this equilibrium line is assumed to be equal to the enthalpy at the liquid water-air interface. Thus, the enthalpy difference between the equilibrium line and the operating line provides the driving force for the cooling process.

Fig.1 Operating Diagram for Cooling Tower



Tower Characteristic

The most common method of characterizing cooling tower performance is to determine the tower characteristic $\frac{KaV}{L}$ given by integrated form of the Merkel equation as

$$\frac{KaV}{L} = \int_{T_{xb}}^{T_{xa}} \frac{dT_x}{h_y' - h_y} \qquad (4)$$

where K is the overall mass-transfer coefficient, a is the contact area per tower volume, V is the effective cooling volume per tower cross sectional area, L is the water mass velocity, $h_y^{'}$ is the enthalpy of saturated air at water temperature, h_y is the enthalpy of the air stream, and T_{xa} and T_{xb} are the entering and exiting water temperature, respectively.

Equation 4 is similar to the definition of the number of transfer units (NTU) and thus the tower characteristic represents the change in temperature of the water stream divided by the average driving force. The tower characteristic is determined by numerical integration. One could use the trapezoidal rule or Simpson's rule, but according to Perry's Handbook, the tower characteristic is normally determined used the Chebyshev rule. In this case the integral in Eqn. 4 is approximated by

$$\frac{KaV}{L} \cong \frac{T_{xa}-T_{xb}}{4}\left(\frac{1}{\Delta h_1}+\frac{1}{\Delta h_2}+\frac{1}{\Delta h_3}+\frac{1}{\Delta h_4}\right) \tag{5}$$

where Δh_1 = value of $(h_y^{'}-h_y)$ at $T_{xb}+0.1(T_{xa}-T_{xb})$

Δh_2 = value of $(h_y^{'}-h_y)$ at $T_{xb}+0.4(T_{xa}-T_{xb})$

Δh_3 = value of $(h_y^{'}-h_y)$ at $T_{xa}-0.4(T_{xa}-T_{xb})$

Δh_4 = value of $(h_y^{'}-h_y)$ at $T_{xa}-0.1(T_{xa}-T_{xb})$

While the tower characteristic varies with $\frac{L}{G}$, knowing the tower characteristic at fixed flow rates can be used to predict changes in tower performance with changes in ambient air conditions.

Comments and Items to be Addressed

1. While performing the experiment, make sure the wick of the wet-bulb thermocouple is completely wet at all times.

2. Examine at least three water to air mass flow rate ratios (approximately 1, 2 and 3) at each of three water flow rates.

3. Ensure that the system has reached steady state before starting acquisition of temperature data.

4. Report the approach and range for the cooling tower under your experimental operating conditions. How does the approach and range vary with changes in operating conditions?

5. Use the Chebyshev method as described in the Evaporative Cooling section of Perry's Handbook to carry out the integration to help determine the tower characteristic (also called the Mass-Transfer Coefficient Group in an example in Perry's).

6. How does the tower characteristic change with water/air ratio? Theoretically, the tower characteristic should remain constant at a constant water to air mass ratio. Do your data indicate this? Explain any differences.

7. In the theoretical analysis, it was assumed that the evaporation of water is negligible to the water phase. Estimate the rate of evaporation (water loss) in the cooling tower in gal/min or l/min. What percentage of the total water stream is this? (Hint: Assume exiting air stream is saturated, do a mass balance to determine how much water the air has gained) Was the assumption valid?

References

1. McCabe, Smith, and Harriott, *Unit Operations of Chemical Engineering,* 6th Edition, McGraw-Hill, 2001.
2. Felder, R.M and Rousseau, R.W., *Elementary Principles of Chemical Processes,* John Wiley &Sons, 1978.
3. Perry, R.H. and D.W. Green (eds.), *Chemical Engineer's Handbook*, 7th ed., McGraw-Hill, 1997.

Pre-lab Homework for Cooling Tower Experiment (to be completed individually)

1. Using a psychrometric chart determine the enthalpy of humid air at a dry-bulb temperature of 75 F and a wet-bulb temperature of 60 F.

2. At the air conditions described in problem #1, determine the air mass velocity of dry air in $lb/_{\min \cdot ft^2}$ when the pitot tube indicates a flow rate of 100 ft^3/min (Assume a square foot cross sectional area) .

3. Draw an equilibrium curve like that shown in Figure 1 (except include specific values for air enthalpy), for air saturated at water temperatures between 70 and 100°F. Use 4 temperatures in this range. (Hint: use psychrometric chart)

4. Draw an operating line on the figure in problem #3 using the inlet air conditions described in problem #1 if water enters the tower at 100 F and exits at 70 F and the L/G ratio is 1.