COOLING TOWER

Skill Outcomes:
In completing this particular experiment, the student should develop or improve mastery of the following skills:
- Ability to safely operate the cooling tower apparatus located in 116 Jarvis
- Understanding of psychrometric charts
- Ability to use a psychrometric chart for air + water system
- Understand the difference between wet-bulb and dry-bulb temperatures
- Understand the mass transfer operation that occurs in a cooling tower
- Definition of approach, range, and maximum heat load in a cooling tower
- Understand the meaning of mass velocity and how to calculate it
- Ability to estimate the water loss due to evaporation in a cooling tower
- Ability to calculate the number of overall transfer units via graphical integration and to estimate the height of a transfer unit in a cooling tower

Objectives:
1. Determine at various water and air flow rates the number of overall transfer units based on the gas-phase and the overall mass transfer coefficient based on the gas phase for the cooling tower located in Jarvis 116. (Assume a packing height of 6 feet)
2. Find the maximum cooling rate (maximum heat load) provided by the tower.
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. 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:

The theoretical background for this assignment is contained in Chapter 19 of McCabe, Smith, and Harrriot, 6th edition (M,S,&H) and the experimenter is advised to read the entire chapter. The section entitled "Equations for cooling-tower analysis" (pg 612) is particularly pertinent and will be summarized here.

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

$$G'_y dH_y = d(G_x H_x)$$
(M,S,&H eq. 19.22)   (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'_y, the mass of vapor-free air per hour per unit cross section of tower. The mass velocity of water is denoted by G_x.

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 G_x 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:

$$G'_y dH_y = G_x c_L dT_x$$
(M,S,&H eq. 19.23)   (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:

$$G'_y (H_y - H_{yb}) = G_x c_L (T_x - T_{xb})$$
(similar to M,S,&H eq. 19.27)

(3)

This is the equation of the "Operating Line" required for the determination of the number of transfer units (NTU) as described later.

In a cooling tower, heat is transferred into the gas stream at the gas-liquid interface by two mechanisms. The first is sensible heat transfer and is given by Equation (19.29). The second is the latent heat transfer into the gas stream. This involves the mass transfer rate [Equation (19.31)] of water vapor through the gas film interface. To convert the mass transfer rate to an energy basis, Eqn. 19.31 is multiplied by the latent heat of vaporization, λ_o, at the datum plane temperature. The equations representing both types of heat transfer are then combined and then by using the Lewis relationship (Equation 19.21) and by relating the total enthalpy of the gas stream to the humidity, we obtain:

$$G'_y dH_y = k_y M_B a(H_i - H_y) dZ$$
(M,S,&H eq. 19.35)   (4)

Here M_B is the molecular weight of the liquid; a is the interfacial area between the two phases which is assumed to be the same for both heat *and* mass transfer; ky is the mass transfer coefficient in lb-mol/ft^2/hr. or equivalent SI units; and Z is the height of the element being considered measured from the base of the Cooling tower. H_i and H_y are the gas-phase enthalpies measured at either the interface (i) or the bulk (y) of the gas phase at the particular height Z in the Cooling tower. In integrated form, this equation is:

$$\int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H_i - H_y} = \frac{k_y M_B a}{G'_y} Z_T \qquad \text{(M,S,\&H eq. 19.38)} \qquad (5)$$

where Z_T is the overall height of packing in the tower. It can be seen that the integral on the left has the general form of the integral defining the number of transfer units (*NTU*) in terms of the gas film.

The equation (5) is difficult to use since it requires some means for determining the temperature at the air-water interface in order to calculate H_i. However, there is a reasonable way out of this complication if we assume that the resistance to mass transfer is predominantly in the gas-phase. This is a reasonable assumption for this system since air (in comparison to water) is a much poorer medium for heat transfer. If we assume that the temperature T_x in the liquid bulk is not very different from T_i (at the interface), then the enthalpy at the interface H_i, can be replaced by H'_x, the enthalpy of **_air saturated at the bulk temperature of the liquid, T_x._** Note that the symbol, H_x , was earlier defined as the enthalpy of the liquid, but here the *prime sign* emphasizes the fact that this is the saturation enthalpy of the <u>vapor phase</u> at temperature T_x.

With this assumption, Equation (5) takes the form:

$$N_{Oy} = NTU \equiv \int_{H_{yb}}^{H_{ya}} \frac{dH_y}{H'_x - H_y} = \frac{Z_T}{H_{oy}} \quad \text{where } H_{oy} = \frac{G'_y}{K_y a} \quad \text{(M,S,\&H eq. 19.40)} \quad (6)$$

and $K_y a$ is the overall mass transfer coefficient. This Eq (6) will be the defining equation for the number of overall transfer units, NTU in the current assignment.

<u>Comments and Items to be Addressed</u>

1. Use at least three water rates and vary the air flow at least three times for each water rate.

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

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.

5. Use graphical integration to determine the number of transfer units in the column. For one set of operating conditions, also estimate the NTUs assuming a Logarithmic Mean Driving Force. Compare the values.

6. Plot a graph of NTU versus air flow rate at various water flow rates

7. Plot a graph of $K_y a$ versus air flow rate at various water flow rates. How does the relationship compare to that mentioned in Ref. 1 page 618?

8. 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. Was the assumption valid?

<u>References</u>

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.