TFES Lab (ME EN 4650)
Cooling Tower

Textbook Reference: Chapter 14 from Cengel and Boles, 5th ed., McGraw-Hill

Objectives

(i) measure the wet-bulb and dry-bulb water vapor temperatures in a scaled-model cooling tower,

(ii) determine the cooling tower efficiency as a function of water inlet mass flow rate,

(iii) estimate the mass of water lost to evaporation, and

(iv) the heat rejected from the water using an energy balance analysis.

Background

A cooling tower is an open-system that rejects waste heat to the atmosphere through the evaporative cooling of a hot water stream. The purpose of a cooling tower is to cool liquid water, which is done by two mechanisms. The primary cooling mechanism is through evaporation, in which water undergoes a phase change from a liquid to a vapor. Heat of vaporization is released by the hot water, which serves to decrease the temperature of the liquid water moving through the system. The secondary mechanism of cooling is a combination of convection and radiation heat transfer from the liquid water to the air/surroundings.

A diagram of an induced draft counterflow cooling tower is shown in Figure 1. In a *counterflow* configuration, air enters through the bottom of the tower and rises (due to either buoyancy or a fan); while, water enters through the top and flows downward via gravity. In a *crossflow* configuration, the air flows perpendicular to the direction of water flow, i.e.,

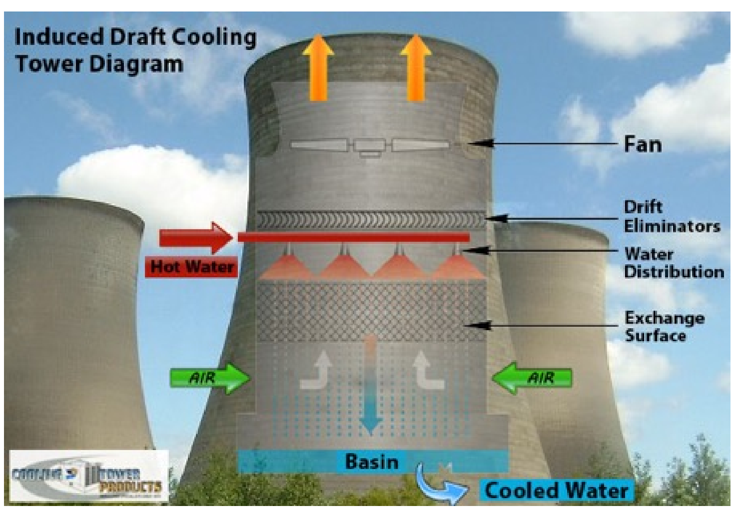

Figure 1. Diagram of a typical induced draft, counterflow cooling tower.

the air enters through multiple vertical faces along the height of the tower. In an *induced draft* configuration, the fan driving the air flow is located near the discharge, at the top of the tower. In this lab exercise, we will investigate the performance of a forced draft cooling tower, which utilizes a blower-type fan located at the air intake near the bottom of the tower. Conversely, in a natural draft configuration, buoyancy drives the air flow, i.e., the air inside the tower is warmer than the outside air and thus rises producing an upwards current of air through the tower (without the use of a fan/prime mover).

Cooling towers are used to reject heat through the natural process of evaporation. The amount of heat that can be rejected is directly tied to the humidity, or moisture content of the air. Ambient air with a lower humidity has a greater ability to absorb water vapor through evaporation than air with a higher humidity. For this reason, cooling towers are only effective in environments with moderate to low humidity levels. The moisture content of an air–water vapor mixture can be expressed using different types of humidity measures. The most common ones are defined below. In this lab, we will only use the specific and relative humidities.

Absolute Humidity — mass of water vapor (moisture) per unit volume of air. Typical units are (g of water vapor)/(cm^3 of air).

Specific Humidity, ω — mass of water vapor per unit mass of *dry air*. Typical units are (kg water vapor)/(kg dry air).

Relative Humidity, ϕ — current absolute humidity over the maximum absolute humidity at the same temperature. Typical units are in terms of a percentage. That is, 100% relative humidity means the air is saturated with water vapor.

Dew Point Temperature — the temperature at which the air must be cooled to become saturated with water vapor (and hence condense). This is also referred to as the saturation temperature of the air. Typical units are °C.

Experimental Setup

The experimental setup in this laboratory is a forced draft, counterflow type cooling tower, as shown in Figure 2. A schematic of the entire experimental apparatus is shown in Appendix I. Because of the counterflow nature of the cooling tower, location A (at the bottom of the tower) represents the inlet for the air, and the outlet for the water. Similarly, location B (at the top of the tower) represents the outlet for the air, and the inlet for the water. The water path through the cooling tower is as follows:

- → hot water enters near the top of the tower through a manifold,
- → hot water is distributed to spray nozzles and directed downward along the cross-sectional opening of the tower,
- → hot water droplets fall through the tower center via gravity,
- → the water droplets impact plastic fill inside the tower that slows the velocity of the water and also serves as a heat transfer surface,
- → the water droplets interact with the cooler rising air causing evaporation,

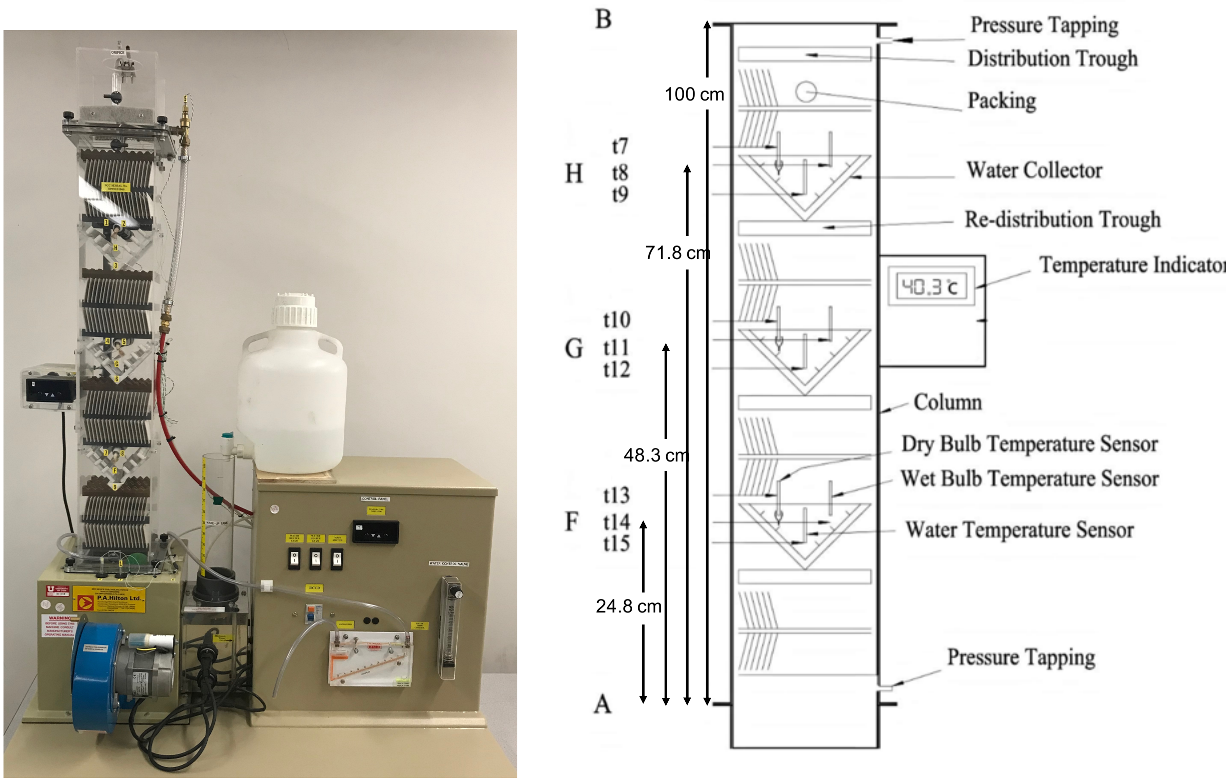

Figure 2. Experimental setup to measure the performance of a water cooling tower in the laboratory.

→ as the water evaporates, its temperature drops,

→ cool water is collected at the bottom of the tower in a basin,

→ the cool water is recirculated via a pump from the basin back to a condenser to absorb heat from some other process.

Note, in the laboratory setup, the cool water collected in the basin at the bottom of the tower is reheated using electric heaters and then pumped back to the top of the tower. Switches on the front panel of the control unit allow for heating options of 0.5 kW, 1.0 kW, and 1.5 kW. According to the manufacturer, the water pump also adds 100 W of heat to the system during normal operation. Because liquid water is lost to water vapor during the evaporation process in the tower, fresh water makeup must be added to the basin during normal operation to compensate.

The air path through the cooling tower is as follows:

→ outside air enters the bottom of the tower through an inlet vent,

→ air is pushed upward through the tower by the pressure from the blower,

→ as air rises, it mixes with the water vapor and also absorbs heat,

→ hot, moist air discharges through the top of the tower and into the atmosphere.

Table 1 lists the measurements acquired in the experiment along with the native units of the instruments. Type K thermocouples are used to measure the wet and dry bulb temperatures along the height of the tower. An orifice flow meter with pressure taps connected via flexible tubing to an inclined manometer is used to measure the air flow rate at locations A and B. The water inlet flow rate is measured with a rotameter. The location of the thermocouples used to measure the air and water temperature along the height of the tower are listed in Table 2. Note, there are two display units used for the thermocouple readings: one on the front of the main control unit for the apparatus and one on the side of the cooling tower.

Table 1. List of measurements acquired in the experiment with their native units.

Quantity	Symbol	Units	Instrument
Dry bulb temperature	T_{db}	°C	thermocouple
Wet bulb temperature	T_{wb}	°C	thermocouple with wet cloth
Water temperature	T_w	°C	thermocouple
Orifice meter pressure drop	ΔP	mm H_2O	inclined manometer
Inlet water flow rate	$\dot{m}_{w_{\text{in}}}$	g/s	rotameter

Table 2. Location of the temperature measurements.

Display	Channel	Symbol	Position	Height (cm)	Temperature
Front	1	T1	A	0	Air inlet, dry-bulb
	2	T2			Air inlet, wet-bulb
	3	T3	B	100	Air outlet, dry-bulb
	4	T4			Air outlet, wet-bulb
	5	T5	B	100	Water inlet
	6	T6	A	0	Water outlet
Side	1	t1	H	71.8	Air, wet-bulb
	2	t2			Air, dry-bulb
	3	t3			water
	4	t4	G	48.3	Air, wet-bulb
	5	t5			Air, dry-bulb
	6	t6			water
	7	t7	F	24.8	Air, wet-bulb
	8	t8			Air, dry-bulb
	9	t9			water

Laboratory Procedure

The primary control variable in this experiment is the water inlet flow rate ($\dot{m}_{w_{\text{in}}}$), which is adjustable via the needle valve on the top of the rotameter. Three different water inlet flow rates will be investigated. In each case, the air and water temperatures as a function of height in the tower will be measured and recorded once the system has reached steady state.

1. Measure the atmospheric pressure P_{atm} (mm Hg) and ambient temperature T_{amb} (°C) using the barometer and thermometer located on the north wall of the laboratory. Be sure to correct the atmospheric pressure reading based on the altitude. Record the readings on your data sheet.
2. Measure the inside diameter of the makeup water tank and record on your data sheet.
3. The water recirculation pump must be primed (filled with water) before running the apparatus. This will be done by one of the teaching staff before the start of the lab session.
4. Using the squirt bottle provided, fill the reservoirs for the wet bulb socks using distilled water.
5. Turn the needle valve on the rotameter to its fully-open position, by rotating the knob <u>counter-clockwise</u> as far as possible.
6. Connect a piece of flexible tubing between the pressure tap on the orifice meter at the <u>TOP</u> of the cooling tower to the <u>RIGHT</u> port on the inclined manometer. Note, the left port of the manometer should remain open to atmospheric pressure.
7. Ensure that the water level in the makeup tank is filled to the mark indicated on the tank. Note, fresh water MUST be added frequently to the makeup tank during the experiment to keep the water level in the basin above the heating units (see Figure 7 in Appendix I). Only <u>distilled water</u> should be used in the apparatus to avoid the build-up of mineral deposits on the packing material inside the cooling tower, and to minimize the possibility of bateria growth in the moist environment of the tower.
8. Flip the main switch on the front control panel to the "on" position. This will start both the water pump and the fan.
9. Set the air flow through the tower to ensure a pressure difference (ΔP) of about 10 mm H_2O on the inclined manometer. The air flow may be adjusted by rotating the intake damper in order to restrict the opening to the fan accordingly.
10. Flip BOTH switches for the water heaters located on the front control panel to the "on" position to ensure 1.5 kW of heat load on the system. Record the input power setting on your data sheet.
11. Adjust the water inlet flow rate to approximately 30 g/s using the needle valve on the rotameter. Note, <u>the rotameter scale should be read from the TOP of the float</u>.
12. Wait for the temperatures in the cooling tower to reach steady-state. This may take 10–15 minutes.
13. Once the system has reached steady state, start the timer and allow the system to run for an addition 5–10 minutes.

14. Record the following measurements on your data sheet:
    a. Initial height of makeup water level (cm). Note, the water level should be near the indicator mark.
    b. Water inlet flow rate from the rotameter (g/s). Note, the rotameter scale should be read from the TOP of the float.
    c. Thermocouple temperatures T1–T6 (°C) from the FRONT display unit.
    d. Thermocouple temperatures t1–t9 (°C) from the SIDE display unit.
    e. Pressure drop of the air flow at the top of the tower (location B), as measured from the inclined manometer (mm H_2O). Note, be sure that the tubing from the pressure tap at the top orifice flow meter is connected to the right port on the manometer before recording the pressure drop reading.
    f. Final height of makeup water level (cm), after running the system for 5–10 minutes at steady-state.
    g. Time of the experiment (s).
15. Repeat steps 11–14 for water inlet flow rates of about 20 g/s and 40 g/s. The air flow rate and heater settings should NOT be adjusted.
16. Turn off the heaters using the two switches on the front control panel.
17. Turn off the main power switch on the front control panel.
18. The last lab section of the day needs to drain the makeup water tank. To do this, turn the shut-off valve on the back of unit and fill the provided graduated cylinder with an equivalent VOLUME of water so that makeup water tank level will be at about 1 inch (according on the ruler tape on the tank). Importantly, the makeup water tank does NOT drain immediately when you turn the shut-off valve. This is due to the fact that the makeup water tank is connected to the sump via a very small orifice that restricts the flow considerably. Therefore, you need to drain the water based on the volume filled in the graduated cylinder, and NOT by visual inspection of how far the water level in the makeup tank drops during the draining procedure.

Data Analysis

The performance of a cooling tower is typically specified according to the total amount of heat gain to the air and the temperature drop of the water, which can be expressed in terms of an efficiency. Since the heat transfer process is driven predominantly by evaporation, the humidity as a function of tower height is also an important performance characteristic. Perform the following data analysis steps for each data set.

1. Cooling Tower Efficiency, η

   The efficiency of a cooling tower is determined by how closely the outlet temperature of the water approaches the inlet wet bulb temperature of the air. In order to calculate efficiency, we need to first define the Range (R) and Approach (A), which are illustrated qualitatively in Figure 3. Mathematically, the cooling range of the water is defined as the difference between the inlet and outlet water temperatures,

$$R = T_{w_{\text{in}}} - T_{w_{\text{out}}}. \tag{1}$$

The approach represents how closely the outlet water temperature is to the inlet wet bulb temperature of the air, which represents the limit of cooling that can be achieved. Mathematically, the approach is defined as

$$A = T_{w_{\mathrm{out}}} - T_{wb_{\mathrm{in}}}. \tag{2}$$

The efficiency of the cooling tower (in terms of a percentage) can be written as

$$\eta = \frac{R}{R+A} \cdot 100. \tag{3}$$

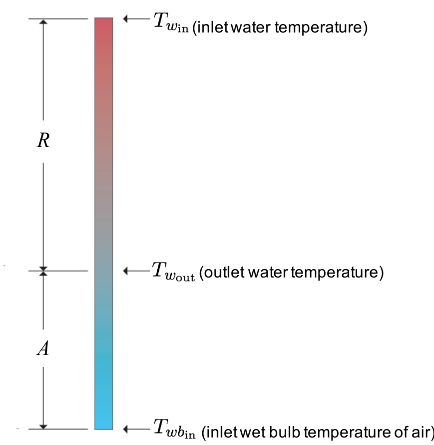

Figure 3. Temperature scale illustrating the definitions of the Range, R, and Approach, A.

2. Specific Humidity, ω

The specific humidity is defined as the mass of water vapor per unit mass of dry air,

$$\omega = \frac{m_v}{m_a}, \tag{4}$$

where the subscripts v and a are used here to denote "water vapor" and "dry air", respectively. We will follow this convention throughout. The specific humidity (also called the "humidity ratio") can be determined from the dry bulb and wet bulb temperatures (T_{db}, T_{wb}) using a Psychrometric Chart as explained in lecture. Note, when using a Psychrometric Chart, be sure that the chart is appropriate for the local barometric pressure. For example, the Psychrometric Chart for measurements made at sea level is different than that for Salt Lake City. A Psychrometric Chart appropriate for the measurements you acquired in the laboratory is provided in Appendix II. The instructor will also provide a user-defined Matlab function that can be utilized to evaluate psychrometric charts (see Appendix II).

You can also calculate the specific humidity directly using the procedure outlined below. We start by writing (4) in terms of the density, which gives

$$\omega = \frac{m_v}{m_a} = \frac{\rho_v \mathcal{V}}{\rho_a \mathcal{V}} = \frac{\rho_v}{\rho_a}, \tag{5}$$

where the mass is calculated using the same unit volume. Since both water vapor and air can be considered as ideal gases, we can rewrite the density in terms of the local pressure and temperature,

$$\omega = \frac{\rho_v}{\rho_a} = \frac{P_v/(R_v\,T)}{P_a/(R_a\,T)} = \frac{R_a}{R_v}\frac{P_v}{P_a}, \tag{6}$$

$$\omega = 0.622\frac{P_v}{P_a}, \tag{7}$$

where we have used the following values for the gas constants of water vapor and dry air, respectively: $R_v = 0.4615$ kJ/kg·K and $R_a = 0.287$ kJ/kg·K. In (7), P_v and P_a denote the partial pressures of the water vapor and dry air, respectively. Both of which must be calculated, as discussed below.

→ Partial Pressure of Water Vapor, P_v

In order to determine the partial pressure of the water vapor, we use the definition,

$$P_v = \phi\,P_g, \tag{8}$$

where ϕ denotes the relative humidity (in terms of a fraction) and P_g denotes the saturation pressure of water vapor. We can use the Saturated Water–Temperature Table to look up P_g for a given dry bulb air temperature T_{db}. Alternatively, you can use the following empirical relation,

$$P_g = 610.78\,\exp\left(\frac{17.2694\,T_{db}}{T_{db}+238.3}\right), \tag{9}$$

where P_g is in Pa and T_{db} is the dry bulb air temperature in °C.

→ Relative Humidity, ϕ

The relative humidity is function of the dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), and atmospheric pressure (P_{atm}). The relative humidity of a gas-vapor mixture can be determined using either a Psychrometric Chart or an empirical relation. For air, the following empirical formula may be used to calculate relative humidity in terms of a percentage,

$$\phi = \frac{\exp\left[1.8096 + \left(\frac{17.2694\,T_{wb}}{237.3+T_{wb}}\right)\right] - 7.866\times 10^{-4}\,P_{\text{atm}}\,(T_{db}-T_{wb})\left(1+\frac{T_{wb}}{610}\right)}{\exp\left[1.8096 + \left(\frac{17.2694\,T_{db}}{237.3+T_{db}}\right)\right]}\cdot 100 \tag{10}$$

where T_{db} and T_{wb} are the dry bulb and wet bulb temperatures in °C, and P_{atm} is the atmospheric pressure in Pa. Note, you may find similar relationships in other sources with slightly different coefficients, depending on the data set used for the curve fit.

→ Partial Pressure of Dry Air, P_a

In order to determine P_a, we recall Dalton's Law of Partial Pressures that states

$$P = P_v + P_a, \tag{11}$$

where P represents the total absolute pressure of the gas-vapor mixture. In the cooling tower experiment, P in (11) is approximately equal to the measured barometric pressure, $P \approx P_{\text{atm}}$. Rearranging (11) yields

$$P_a = P_{\text{atm}} - P_v. \tag{12}$$

Note, since the gas-vapor mixture flows through the cooling tower, the static pressure at the location of the temperature measurements is expected to be slightly less than atmospheric (recall Bernoulli's equation from fluid mechanics). However, this difference will be negligible. For example, during the experiment, you will adjust the damper on the blower, such that the differential pressure on the air discharge side (top of the tower) is around 10 mm H_2O. For comparison, the atmospheric pressure in Salt Lake City is typically about 353 in H_2O (or ∼9000 mm H_2O). Once the partial pressure of the water vapor P_v is known from (8), we can use (12) along with our atmospheric pressure measurement to determine P_a.

3. <u>Water Outlet Mass Flow Rate, $\dot{m}_{w_{\text{out}}}$</u>

In order to calculate the mass flow rate of water out of the cooling water, we need to consider the mass conservation law as illustrated in Figure 4. Note, we are only interested in the mass of the water (and water vapor) in this case, and not the dry air. Mathematically, conservation of mass for the water is given by

$$\dot{m}_{w_{\text{in}}} + \dot{m}_{v_{\text{in}}} = \dot{m}_{w_{\text{out}}} + \dot{m}_{v_{\text{out}}}, \tag{13}$$

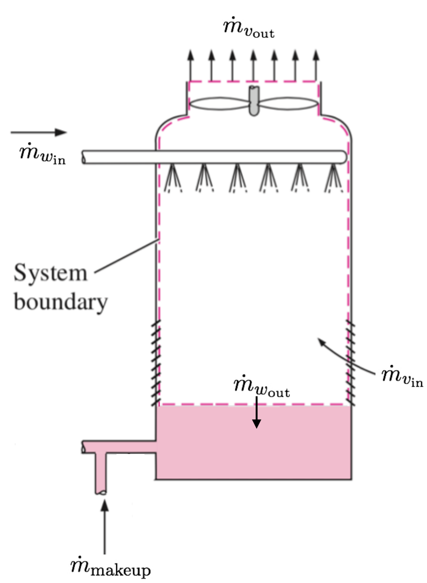

Figure 4. Diagram for calculating the mass conservation of water in the cooling tower system.

where the subscripts w and v denote the liquid water and water vapor, respectively. Because of the way that we have drawn the system boundary, the "makeup water" added to the basin of the cooling tower (to maintain a constant water level in the basin) is not included in the above mass conservation equation. Rearranging (13) yields

$$\dot{m}_{w_{\text{out}}} = \underbrace{\dot{m}_{w_{\text{in}}}}_{\text{measured}} + \underbrace{\dot{m}_{v_{\text{in}}}}_{\text{calculate}} - \underbrace{\dot{m}_{v_{\text{out}}}}_{\text{calculate}} . \tag{14}$$

The water vapor mass flow rates in (14) can be calculated as described below.

→ Water Vapor Mass Flow Rate

The mass flow rate of the water vapor is simply the proportion of water vapor in the air times the mass flow rate of dry air, i.e.,

$$\dot{m}_v = \omega\, \dot{m}_a, \tag{15}$$

where ω is the specific humidity calculated from (7) and the subscript a denotes the *dry air*. Since we have already calculated ω_{in} and ω_{out}, we only need to determine the mass flow rate of dry air through the cooling tower.

→ Mass Flow Rate of Dry Air

The pressure difference (ΔP), measured from the pressure tap mounted on the side wall of the cooling tower orifice meter and connected to the inclined manometer, can be used to calculate the mass flow rate of dry air through the cooling tower. The manufacturer has already performed a calibration to this effect and has supplied the relevant *empirical* equation,

$$\dot{m}_a = 0.0137 \sqrt{\frac{\Delta P}{(1+\omega)\, v_a}} \tag{16}$$

where ΔP is the manometer reading in mm H_2O, ω is the specific humidity in kg of water vapor per kg of dry air, v_a is the specific volume of dry air in m^3/kg, and $\dot{m}_a$ is the mass flow rate of *dry air* in kg/s. <u>Importantly, the values inserted into (16) MUST be in the units stated above because the coefficient in the equation is dimensional.</u> Because the dry air cannot escape the cooling tower, the mass flow rate of dry air into the cooling tower must equal the mass flow rate of dry air out of the cooling tower. Therefore, one measurement (at the top of the tower) is sufficient.

Note, the specific volume of dry air, v_a, may be obtained from the <u>Psychrometric Chart</u> given measurements of the dry bulb and wet bulb temperatures at the same location. Once $\dot{m}_a$ is known from (16), we can determine $\dot{m}_v$ from (15) and then $\dot{m}_w$ from (14), by successive substitution.

→ Mass Flow Rate of Makeup Water

The amount of water that vaporizes due to evaporation must be replaced with liquid water at some point in the cycle in order to maintain steady operation.

Typically, the makeup water is added to the basin at the bottom of the tower. To determine the amount of makeup water required per unit time of operation ($\dot{m}_{\text{makeup}}$), we simply apply mass conservation to the liquid water in the system. In this case, we would need to expand the system boundary to include the two water outlet ports off of the basin. This leads to the relation

$$\dot{m}_{\text{makeup}} = \dot{m}_{w_{\text{in}}} - \dot{m}_{w_{\text{out}}}. \tag{17}$$

The first term on the righthand side is measured directly; while the second term is calculated from the procedure described above. This is an important limitation of cooling towers. Namely, a constant supply of makeup water is required to maintain the water level in the basin. It is interesting to note what percentage of cooling water is saved and recirculated, versus the percentage that is lost through the top of the tower to the atmosphere.

4. Rate of Heat Gain by the Air, $\dot{Q}_a$

The rate of heat transfer to the air, $\dot{Q}_a$, can be calculated from the change in specific enthalpy of the air multiplied by the mass flow rate of the dry air. Note, due to conservation of mass, the mass flow rate of dry air into the tower is equal to the mass flow rate of dry air out of the tower. Therefore,

$$\dot{Q}_a = \dot{m}_a (h_{a_{\text{out}}} - h_{a_{\text{in}}}), \tag{18}$$

where h_a denotes the specific enthalpy of the air per unit mass of dry air. You can determine h_a from the Psychrometric Chart using the measured dry bulb and wet bulb temperatures. The mass flow rate of dry air is the same as that calculated from (16).

5. Rate of Heat Lost to Surroundings, $\dot{Q}_{\text{amb}}$

In order to calculate the rate of heat lost to the surrounding, $\dot{Q}_{\text{amb}}$, we need to write an energy balance of the system. For simplification, we consider a system boundary that comprises the entire cooling tower apparatus including the makeup water tank as shown in Figure 5. In this system, the liquid water remains entirely within the system boundary, i.e., no liquid water crosses the system boundary. Since the system does no shaft work, the simplified energy balance can be written as

$$\dot{Q}_{\text{in}} + \dot{Q}_{a_{\text{in}}} = \dot{Q}_{a_{\text{out}}} + \dot{Q}_{\text{amb}}. \tag{19}$$

Because the mass flow rate of the dry air does not change through the system ($\dot{m}_{a_{\text{in}}} = \dot{m}_{a_{\text{out}}}$), it is appropriate to represent the net heat transfer rate to the air by the change in specific enthalpy between the inlet and outlet as calculated in (18). Therefore the above equation can be written as

$$\dot{Q}_{\text{amb}} = \dot{Q}_{\text{in}} + \dot{m}_a (h_{a_{\text{in}}} - h_{a_{\text{out}}}). \tag{20}$$

The manufacturer specifies that 1.5 kW of heat are added to the system (via two electric heating coils that raise the temperature of the recirculating water from the basin before it is transported to the top of the cooling tower). Plus, an additional 100 W of power is added from the pump that serves to recirculate the water. Therefore, $\dot{Q}_{\text{in}} = 1.6$ kW, for the experiments conducted in the laboratory.

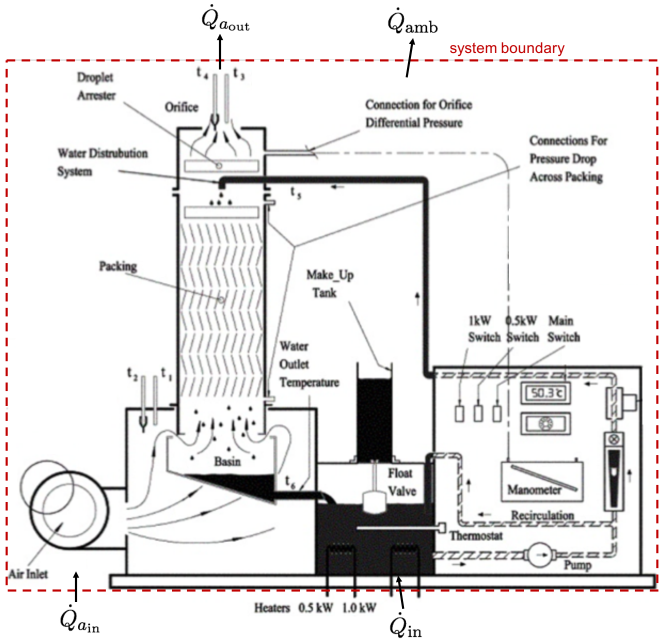

Figure 5. Diagram for calculating the energy balance of the entire cooling tower. The system boundary is drawn as a dashed box around the entire facility. Here, $\dot{Q}_a$ denotes the rate of heat transfer to/from the air.

Figures

A meaningful and comprehensive figure caption must accompany all figures. The figure caption must include the following label: Figure 1X. where X denotes the letter a – f according to the order listed below. For the first few labs, a Word template will be provided with instructions on how to write the figure captions (check under "Resources" in the CANVAS assignment).

1a. On a single figure, plot water temperature (T_w) and wet bulb temperature (T_{wb}), for the case of $\dot{m}_{w_{in}} \approx 30$ g/s, as a function of cooling tower height (z) at the 5 positions: A=0 cm, F=24.8 cm, G=48.3 cm, H=71.8 cm, B=100 cm. Plot height on the x-axis in units of m, and temperature on the y-axis in units of °C. Use the following marker styles: ■ T_w; ● T_{wb}. Do NOT connect the markers with a line. Include a legend. On the same figure, draw the Range (R) and Approach (A) using vertical lines with double arrows; and, label the two lines as R and A appropriately. Draw these lines in Matlab or using other software.

1b. Plot cooling tower efficiency (η) in terms of a percentage on the y-axis as a function of water inlet flow rate ($\dot{m}_{w_{in}}$) in units of g/s on the x-axis.

1c. On a single figure, plot specific humidity (ω) as a function of cooling tower height (z) at the 5 positions: A=0 cm, F=24.8 cm, G=48.3 cm, H=71.8 cm, B=100 cm. Plot height on the x-axis in units of m, and humidity on the y-axis in units of kg/kg of dry air. Use the following marker styles for the different water inlet flow rates: ◇ $\dot{m}_{w_{in}} \approx 20$ g/s; ○ $\dot{m}_{w_{in}} \approx 30$ g/s; □ $\dot{m}_{w_{in}} \approx 40$ g/s. Do NOT connect the markers with a line. Include a legend that lists the actual water inlet mass flow rate in g/s for each linestyle.

1d. On a single figure, plot the dry bulb temperature (T_{db}) as a function of cooling tower height (z) at the 5 positions: A=0 cm, F=24.8 cm, G=48.3 cm, H=71.8 cm, B=100 cm. Plot height on the x-axis in units of m, and humidity on the y-axis in units of °C. Use the same marker styles and legend as in plot 1c.

1e. Plot the ratio of the water outlet mass flow rate to water inlet mass flow rate ($\dot{m}_{w_{\text{out}}}/\dot{m}_{w_{\text{in}}}$) on the y-axis as a function of inlet water temperature ($T_{w_{\text{in}}}$) in units of °C on the x-axis.

1f. On a single figure, plot the heat transfer rates ($\dot{Q}_a$ and $\dot{Q}_{\text{amb}}$) in units of kW on the y-axis as a function of inlet water temperature ($T_{w_{\text{in}}}$) in units of °C on the x-axis. Use a different marker style for $\dot{Q}_a$ and $\dot{Q}_{\text{amb}}$. Include a legend.

Short-Answer Questions

2a. Briefly describe what happens to the dry bulb temperature and the specific humidity of the air-water vapor mixture passing through the tower from point A (air inlet, water outlet) to point B (air outlet, water inlet). Explain the reason for these observations. Your response should consider the effect of evaporation. [4–6 sentences]

2b. What percentage of the inlet water is evaporated? State how this percentage changes as the inlet water temperature increases. Provide a physical explanation for the observed trend. [2–4 sentences]

2c. Based on your analysis of the data, what is the makeup water flow rate required (in g/s) for this facility? Your answer should be an average over the three experiments. State how close this average value is (in terms of a percentage) to what you observed during the experiments. [2 sentences]

2d. State the maximum efficiency achieved (in %) over the measurement range investigated in the lab. Describe how efficiency varies with inlet water flow rate. [2 sentences]

APPENDIX I: Experimental Apparatus

Figure 6 shows a schematic of the experimental apparatus used in the lab. Figure 7 shows a schematic of the water loop. Figure 8 shows the instruments used to measure flow rate: (i) a rotameter, for measuring the inlet water flow rate, and (ii) an inclined manometer, for measuring the air flow rate. Figure 9 provides an illustration of how to measure the dry bulb temperature (T_{db}) and wet bulb temperature (T_{wb}). In the case of the latter, the bulb (i.e., the temperature sensitive portion of the thermometer) is covered in a water-soaked cloth. In the lab, temperatures are measured using thermocouples, instead of thermometers. The difference between the dry bulb and wet bulb temperatures indicates the humidity of the air. Note, in all cases $T_{wb} < T_{db}$, except at 100% relative humidity, in which case, $T_{wb} = T_{db}$.

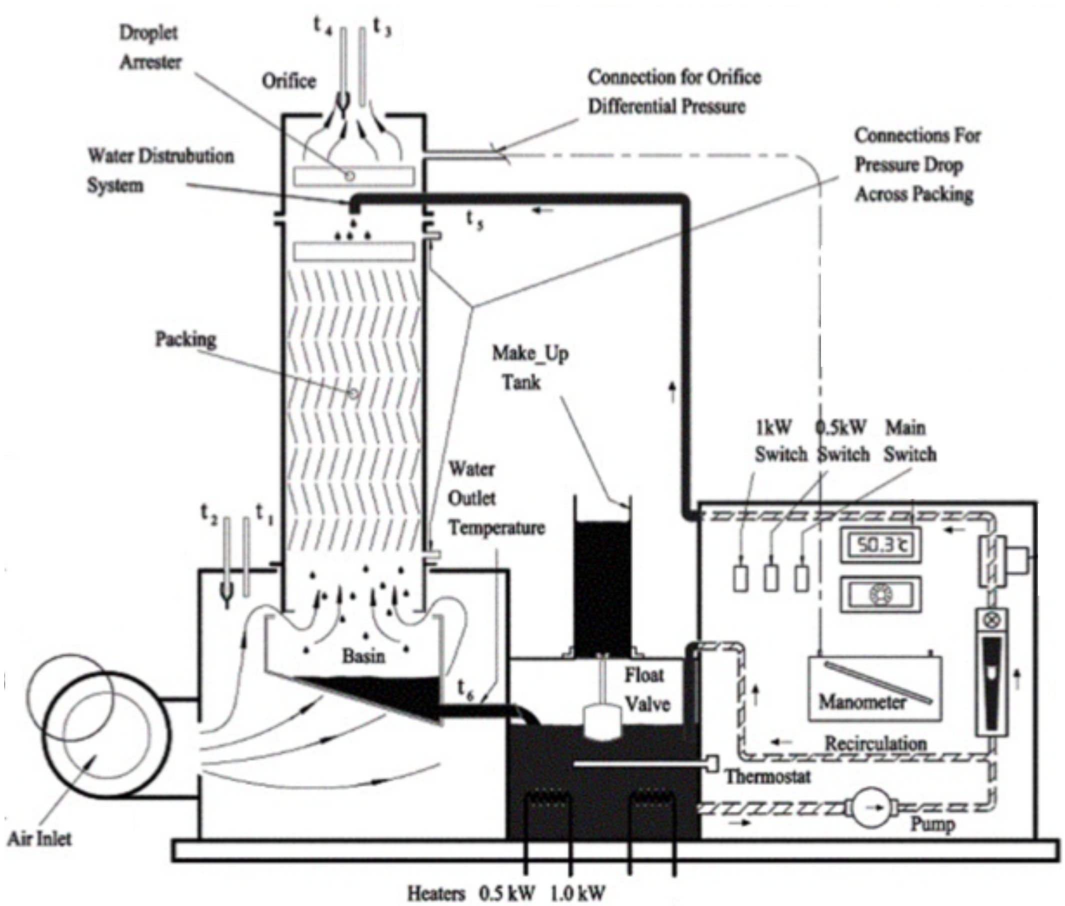

Figure 6. Schematic of the experimental apparatus used to investigate cooling tower performance in the laboratory.

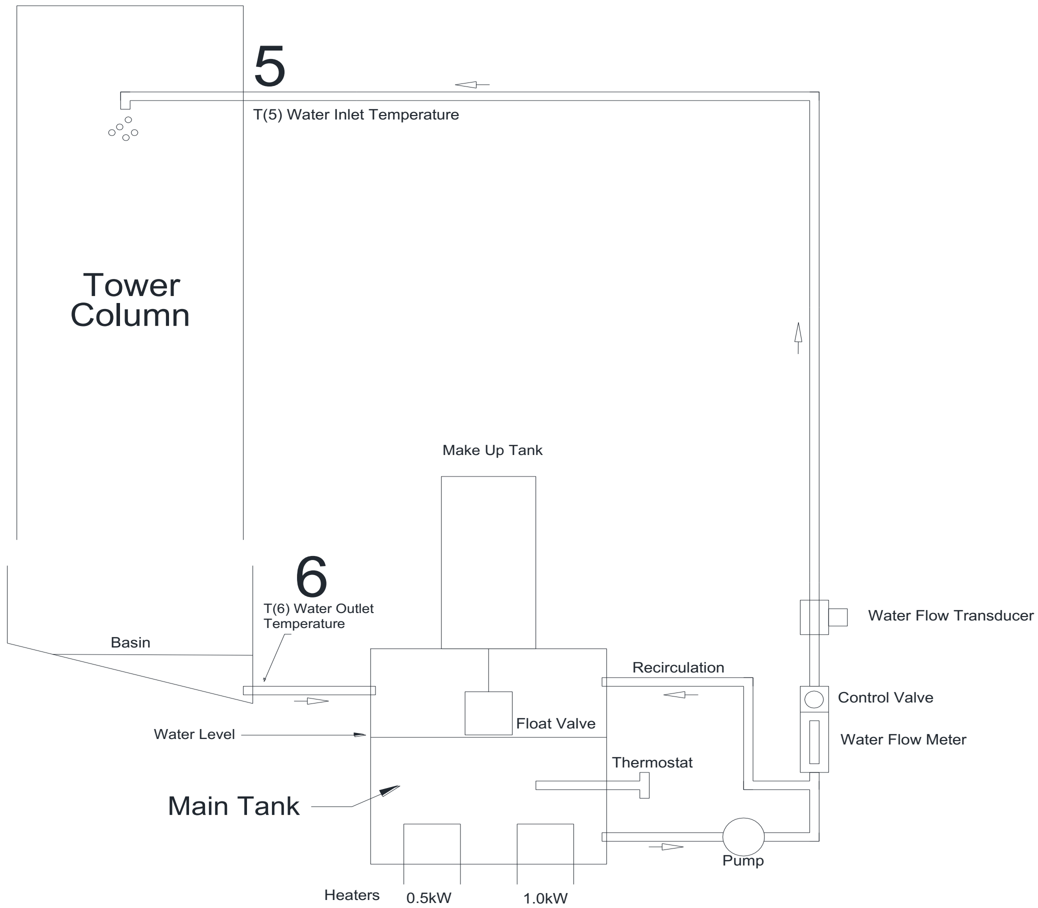

Figure 7. Schematic of the water loop in the cooling tower apparatus.

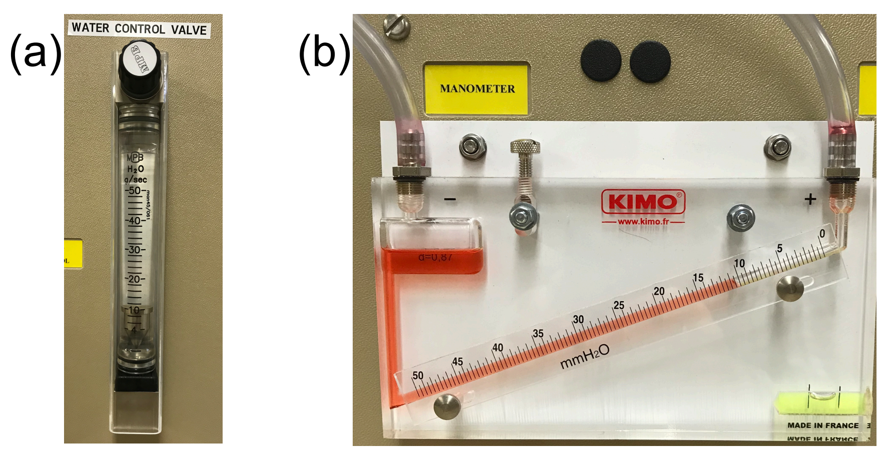

Figure 8. (a) Rotameter used to measure inlet water flow rate. (b) Inclined manometer used to measure air flow rate at the inlet and outlet of the cooling tower.

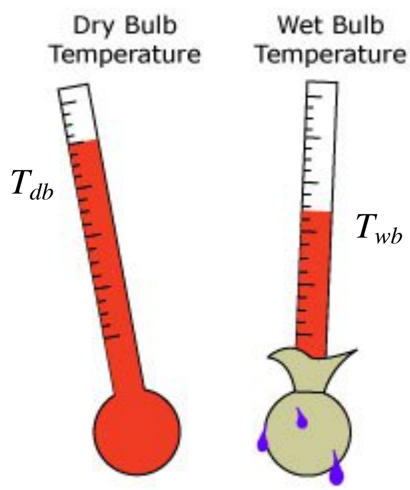

Figure 9. Illustration of how to measure the "dry bulb" and "wet bulb" temperature using a thermometer.

APPENDIX II: Orifice Flow Meter

An orifice flow meter is a type of restriction flow meter used for internal flows (such as flow through a pipe or channel). A schematic of an orifice flow meter is shown in Figure 10. The principle of operation is as follows, as the fluid flows through the restriction, it's velocity increases and it's pressure decreases. The pressure drop across the orifice can then be related to the flow rate.

The mass flow rate through the pipe is given by

$$\dot{m} = \rho\, A_2\, V_2, \tag{21}$$

where ρ is the density of the fluid, A_2 denotes the cross sectional area at location 2 of the vena contracta, and V_2 is the average velocity of the flow at location 2. We can use Bernoulli's equation along the center streamline between points 1 and 2 to relate the pressure and velocity,

$$\frac{P_1}{\rho} + \tfrac{1}{2}\, V_1^2 = \frac{P_2}{\rho} + \tfrac{1}{2}\, V_2^2, \tag{22}$$

where P_1 and P_2 denote the pressures at locations 1 and 2, respectively. Note, we have neglected the effects of gravity in (22), which is valid since the distance between 1 and 2 is very short in an orifice flow meter device. We can also use mass conservation to relate the velocity at 1 and 2,

$$\rho_1\, A_1\, V_1 = \rho_2\, A_2\, V_2\,. \tag{23}$$

Ignoring compressibility effects, which would only be important for high speed flows (near the speed of sound, i.e., supersonic flows), we can write $\rho_1 = \rho_2$. Therefore, from (23),

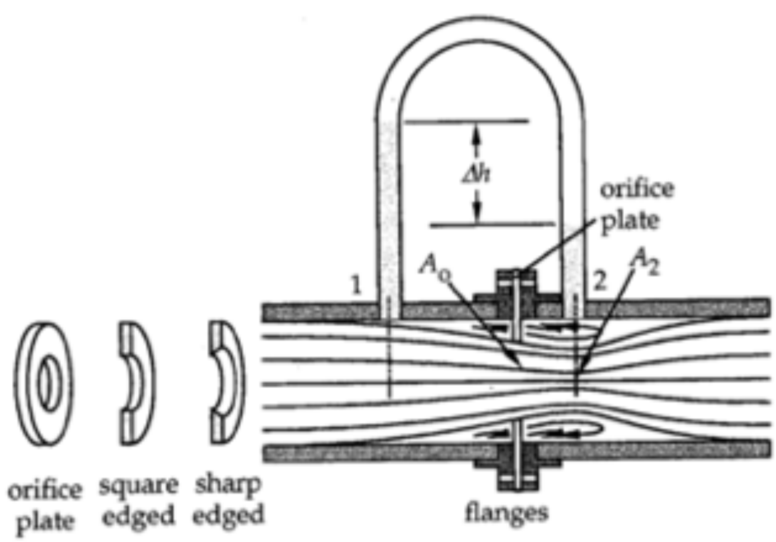

Figure 10. Schematic of an orifice flow meter showing the *vena contracta* effect downstream of the orifice opening. Orifice plates can have straight-edged or sharp-edged (beveled) openings.

$V_1 = (\frac{A_2}{A_1})\, V_2$. Substituting this relation in (22) and rearranging yields an expression for the velocity in the vena contracta,

$$V_2 = \tilde{A}\sqrt{\frac{\Delta P}{\rho}}, \tag{24}$$

where $\Delta P = P_1 - P_2$ and $\tilde{A} = \sqrt{2\,[1-(\frac{A_2}{A_1})^2]^{-1}}$. Substituting (24) into (21) yields an expression for the mass flow rate through the pipe in terms of the measured pressure drop across the orifice,

$$\dot{m} = C\,\sqrt{\rho\,\Delta P}, \tag{25}$$

where C $(= A_2\,\tilde{A})$ is referred to as the discharge coefficient. The manufacturer of the orifice plate will provide the value of the discharge coefficient. Note, C has to be determined experimentally by the manufacturer, because A_2 (the cross-sectional area of the flow at the vena contracta) is not equal to the cross-sectional area of the orifice opening and depends on the size of the recirculation regions along the side walls of the pipe. The pressure difference across the orifice plate is typically measured with a U-tube manometer or inclined manometer. An inclined manometer is used in the case of low flow speeds, in order to increase the sensitivity and ability to measure small pressure drops. Note, for the particular orifice meter used in the cooling tower experiment, P_1 is left open to atmospheric pressure.

APPENDIX III: Psychrometric Chart

A Psychrometric Chart appropriate for measurements made at an altitude of 1500 m (consistent with the location of our laboratory) is provided in Figure 11. See the lecture notes for help on how to read these types of charts.

A Matlab function is also provided that utilizes empirical relations to determine the variables in the Psychrometric Chart: specific volume, specific humidity, specific enthalpy, and humidity ratio. This greatly expedites the analysis of many data points. An example of how to call the function along with a description of the HELP information for the function is shown below. Note, units MUST be specified according to those given in the HELP. For example, atmospheric pressure must be given in kPa, and temperatures must be specified in °C.

```
% "read" psychrometric chart for a dry bulb temperature of 25oC
% and wet bulb temperature of 20oC at an atmospheric pressure of 86 kPa
[Tdb,w,phi,h,Tdp,v,Twb]=Psychrometrics('tdb',25,'twb',20,'p',86);
```

```
function [Tdb, w, phi, h, Tdp, v, Twb] = Psychrometrics (varargin)
% function [Tdb, w, phi, h, Tdp, v, Twb] = Psychrometrics (varargin)
%
% ACCEPTED VARIABLES
%   Tdb (dry bulb temperature) and Tdp(dew point temperature) in C
%   w (humidity ratio) in kg/kg of dry air
%   phi (relative humidity) in %
%   h (enthalpy) in J/kg of dry air
%   v (specific volume) in m3/kg of dry air
%   Twb (wet bulb temperature) in C
%   P (atmospheric pressure) in kPa
%
% The following cases are available:
%   Tdb, w; Tdb, phi; Tdb, h; w, phi; w, h; phi, h; Tdb, Twb;
%   w, Twb; phi, Twb;
%
% Example calculation for properties in Salt Lake City (~26 in Hg pressure)
%   [Tdb,w,phi,h,Tdp,v,Twb]=Psychrometrics('tdb',25,'h',44.5e3,'p',88);
%
% Following ASHRAE 2013 Fundamentals SI Psychrometrics chapter equations
% are used: Eq6:Pws=f(Tdb); Eq22: w=f(Tdb, phi, p); Eq24: phi=f(Tdb, w, p);
% Eq28:v=f(Tdb, w and p); Eq32:h=f(Tdb, w and p); Eq35:Twb=f(Tdb,w);
% Eq39:Tdp=f(Tdb, p);
```

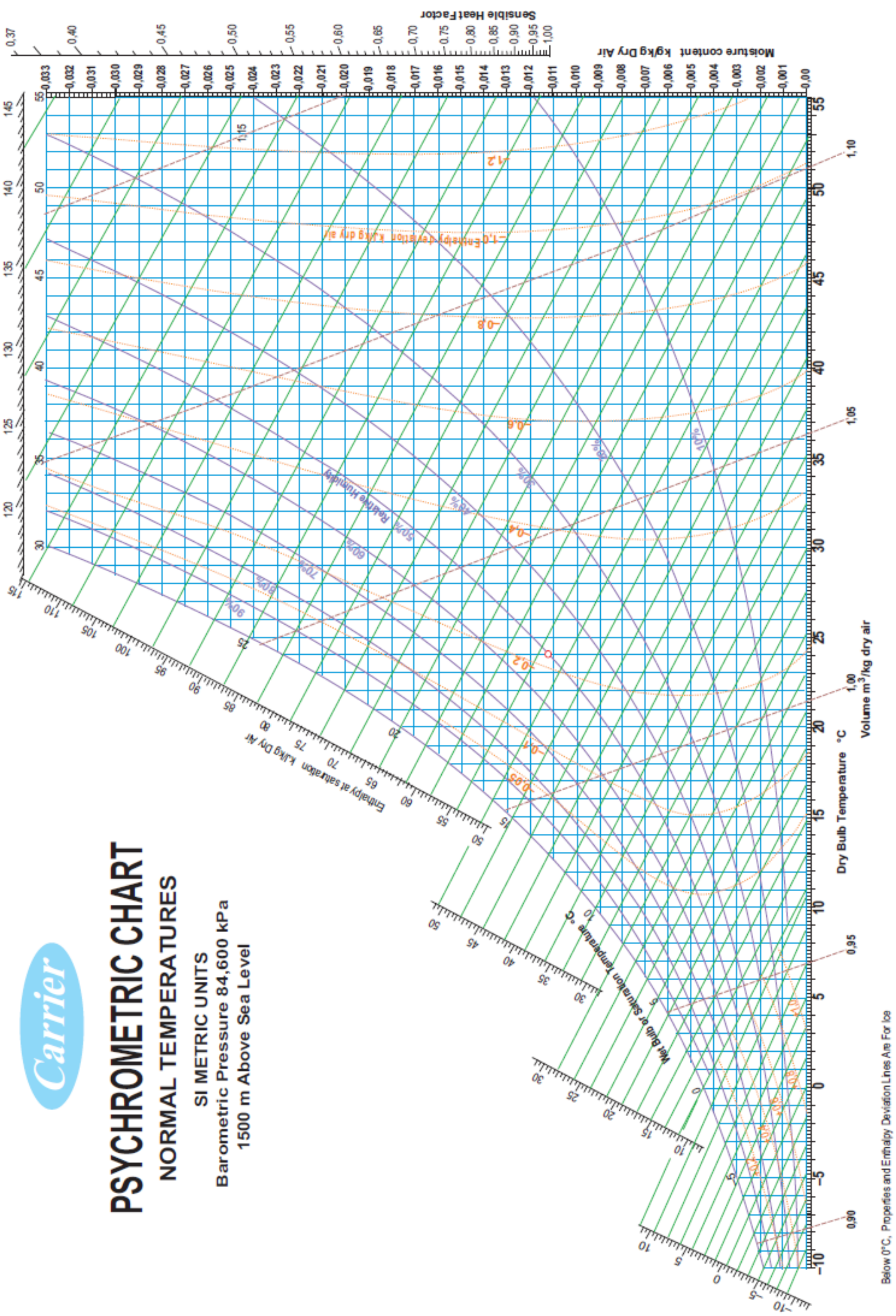

Figure 11. Psychrometric Chart appropriate for use in analyzing the data acquired in our laboratory.

APPENDIX IV: Evaporation Basics

Cooling towers are used to reject heat through the natural process of evaporation. As the warm water entering the cooling tower is evaporated, heat is rejected. During the evaporation process, the air flowing through the cooling tower absorbs the heat and the water vapor content in the air (or humidity) increases.

The amount of heat that can be rejected is directly tied to the relative humidity of the air. Ambient air with a lower relative humidity has a greater ability to absorb water vapor through evaporation, than air with a higher relative humidity. Consider, for example, cooling towers in two different locations one in Atlanta, Georgia, and another in Albuquerque, New Mexico. The ambient air temperature at these two locations may be similar, but the relative humidity in Albuquerque on average will be much lower than that of Atlanta. Therefore, a cooling tower located in Albuquerque will be able to extract more heat from the water, and will run at a cooler temperature, because the dry desert air has a greater capacity to absorb the water vapor created through evaporation.

The process of evaporation occurs when the vapor pressure of the water, P_v, is less than the saturation pressure of the liquid water, P_g, at the given temperature. Based on (8), we know that this criterion will always be satisfied for water vapor in air, as long as the relative humidity of the air is less than 100%. Evaporation is a molecular process. When a liquid molecule near the surface of the liquid-vapor interface absorbs enough energy (via intermolecular collisions with its neighbors) to overcome the vapor pressure, it will change phase and enter the surrounding air as water vapor. Energy released during the phase change (namely, the latent heat of vaporization) reduces the temperature of the liquid, resulting in evaporative cooling. Therefore, the rate of heat rejected during the evaporation process, $\dot{Q}_e$, can be calculated as

$$\dot{Q}_e = \dot{m}_e \, h_e, \tag{26}$$

where $\dot{m}_e$ is the mass flow rate at which liquid water is evaporated (in kg/s) and h_e is the latent heat of vaporization. For water, $h_e = 2256$ kJ/kg. In the cooling tower experiment, $\dot{m}_e$ is equal to the makeup water flow rate, $\dot{m}_{\text{makeup}}$. Based on your data, you should find that $\dot{m}_e \approx 0.4$ g/s at steady state. Plugging this into the above equation gives an estimate of $\dot{Q}_e = 0.9$ kW, meaning that almost 1 kW of power can be dissipated by the cooling tower facility. This is quite impressive, given the relatively small size of the tower.