Water Cooling Tower — Data Analysis Notes

Background

A cooling tower is a system that rejects waste heat to the atmosphere through the evaporative cooling of a hot water stream. A diagram of an induced draft counterflow cooling tower is shown in Figure 1. In an induced draft configuration, the fan driving the air flow is located near the discharge at the top of the tower. While, in a forced draft configuration, a blower type fan is located at the air intake near the bottom of the tower. Finally, 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). In a counterflow configuration, the air flows in a direction opposite to the water flow. In a crossflow configuration, the air flows perpendicular to the direction of water flow, i.e., the air enters through multiple vertical faces along the height of the tower.

The experimental setup in your laboratory is a forced draft, counterflow type cooling tower. The water path 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,

→ as the water evaporates, its temperature drops,

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

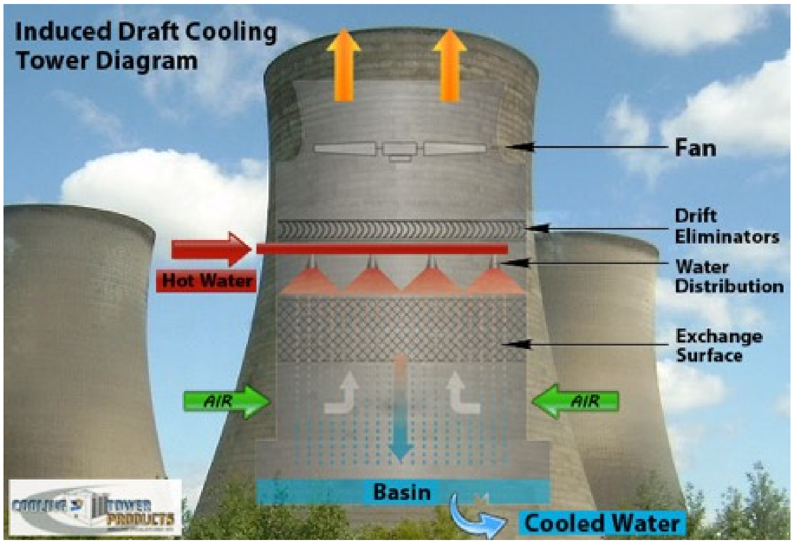

Figure 1: Diagram of a typical induced draft, counterflow cooling tower.

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

Note, because liquid water is lost to water vapor during the evaporation process, fresh water makeup must be added to the basin during normal operation to compensate. The air path 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.

The moisture content of an air–water vapor mixture can be expressed using different quantities. 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 (gm 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.

Performance Characteristics

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. Since the heat transfer process is driven predominantly by evaporation, the humidity as a function of tower height is also an important performance characteristic. The lab handout requires the following plots to be generated:

(i) dry bulb temperature of the air, T_a, as a function of height, z, and water inlet mass flow rate, $\dot{m}_{w_{\text{in}}}$,

(ii) specific humidity, ω, as a function of height, z, and water inlet mass flow rate, $\dot{m}_{w_{\text{in}}}$,

(iii) ratio of water outlet mass flow rate, $\dot{m}_{w_{\text{out}}}$, to water inlet mass flow rate, $\dot{m}_{w_{\text{in}}}$, as a function of water inlet temperature, $T_{w_{\text{in}}}$,

(iv) total rate of heat gain by the air, $\dot{Q}_a$, and total rate of heat lost to the ambient surroundings, $\dot{Q}_{\text{amb}}$, as a function of water inlet temperature, $T_{w_{\text{in}}}$.

Of the plots required, the only quantities that can be measured directly via instrumentation are the dry bulb temperature of the air (T_a), the water inlet temperature ($T_{w_{\text{in}}}$), and the water inlet mass flow rate ($\dot{m}_{w_{\text{in}}}$). All other performance characteristics must be calculated using known relationships or theories, as described below.

Experimental Measurements

In the laboratory, instruments are available for acquiring the following measurements, expressed in their native units:

→ $T_{db_{\text{air}}}$: dry bulb temperature of the air at several heights along the tower including the inlet and outlet [°C],

→ $T_{wb_{\text{air}}}$: wet bulb temperature of the air at several heights along the tower including the inlet and outlet [°C],

→ T_w: water temperature at several heights along the tower including the inlet and outlet [°C],

→ P_{atm}: barometric pressure of the ambient air [mm Hg],

→ ΔP_{air}: differential pressure of the air flow at the air inlets and outlets [mm H_2O],

→ $\dot{m}_{w_{\text{in}}}$: inlet water mass flow rate [gm/sec].

A photograph and schematic of the experimental setup, along with a description of the instrumentation and the measurement locations are provided in the Appendix.

Data Analysis Calculations

We consider the calculations necessary to obtain the performance characteristics of the cooling tower stated above, in the order listed. Note, the height, z, of the measurement locations are known; and, the mass flow rate of the inlet water, $\dot{m}_{w_{\text{in}}}$, is measured directly along with the dry bulb temperature of the air, T_a. Therefore, the only quantities that need to be calculated are the specific humidity, the mass flow rate of the outlet water, and the heat transfer rates.

(i) Specific Humidity, ω

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

$$\omega = \frac{m_v}{m_a}, \tag{1}$$

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 at Salt Lake City. A Psychrometric Chart appropriate for the measurements you acquired in the laboratory is provided in the Appendix.

You can also calculate the specific humidity directly using the procedure outlined below. We start by writing (1) in terms of the density gives,

$$\omega = \frac{m_v}{m_a} = \frac{\rho_v \mathcal{V}}{\rho_a \mathcal{V}} = \frac{\rho_v}{\rho_a}, \tag{2}$$

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,

$$\omega = \frac{\rho_v}{\rho_a} = \frac{P_v/(R_v\,T)}{P_a/(R_a\,T)} = \frac{R_a}{R_v}\frac{P_v}{P_a}, \tag{3}$$

$$\omega = 0.622\frac{P_v}{P_a}, \tag{4}$$

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 (4), 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,

$$P_v = \phi\,P_g, \tag{5}$$

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 air temperature T. Note, this temperature should be the dry bulb temperature of the air. Alternatively, you can use the following empirical relation,

$$P_g = 610.78\,\exp\left(\frac{17.2694\,T}{T+238.3}\right), \tag{6}$$

where P_g is in Pa and T 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). The relative humidity of a gas-vapor mixture can be determined using either a Psychrometric Chart or an empirical relation. Instead of visual inspection on a Psychrometric Chart, the following empirical formula may be used to calculate relative humidity in terms of a percentage,

$$\phi = \frac{\exp\left[1.8096 + \left(\frac{17.2694\,T_{wb}}{237.3+T_{wb}}\right)\right] - 7.866\times10^{-4}\,P_{\text{atm}}\,(T_{db}-T_{wb})\left(1+\frac{T_{wb}}{610}\right)}{\exp\left[1.8096 + \left(\frac{17.2694\,T_{db}}{237.3+T_{db}}\right)\right]}\cdot 100 \tag{7}$$

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

$$P = P_v + P_a \qquad \Longrightarrow \qquad P_a = P - P_v, \tag{8}$$

where P represents the total absolute pressure of the gas-vapor mixture. In the cooling tower experiment, P in (8) is approximately equal to the measured barometric pressure,

$$P \approx P_{\text{atm}}. \tag{9}$$

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 mmHg. For comparison, the atmospheric pressure in Salt Lake City is typically about 655 mmHg. Once the partial pressure of the water vapor P_v is known from (5), we can use (8) along with our atmospheric pressure measurement to determine P_a.

(ii) Water Outlet Mass Flow Rate, $\dot{m}_{w_{\text{out}}}$

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 2. 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

$$\dot{m}_{w_{\text{in}}} + \dot{m}_{v_{\text{in}}} = \dot{m}_{w_{\text{out}}} + \dot{m}_{v_{\text{out}}}, \tag{10}$$

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 (10) yields

$$\dot{m}_{w_{\text{out}}} = \underbrace{\dot{m}_{w_{\text{in}}}}_{\text{measured}} + \underbrace{\dot{m}_{v_{\text{in}}}}_{\text{calculate}} - \underbrace{\dot{m}_{v_{\text{out}}}}_{\text{calculate}}. \tag{11}$$

The water vapor mass flow rates in (11) can be calculated as described below.

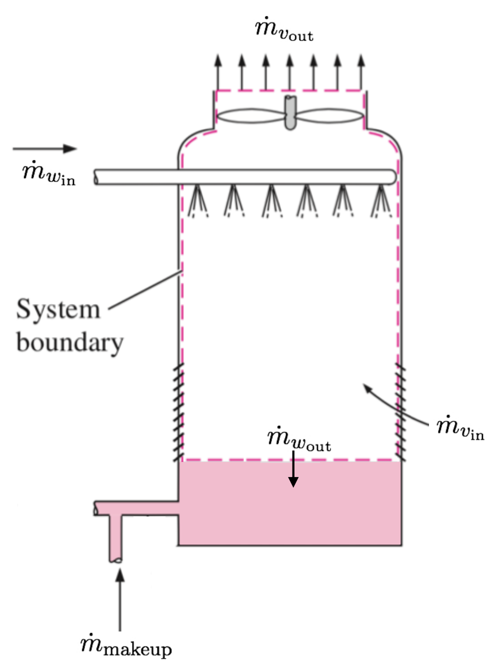

Figure 2: Diagram for calculating the mass conservation of water in the cooling tower system.

→ 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.,

$$\dot{m}_v = \omega\,\dot{m}_a, \tag{12}$$

where ω is the specific humidity calculated from part (i) 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 into and out of the cooling tower.

→ Mass Flow Rate of Dry Air

The pressure difference (ΔP) measured from the pressure taps mounted on the side wall of the cooling tower and connected to the inclined manometer can be used to calculate the mass flow rate of dry air at these locations. The manufacturer has already performed a calibration to this effect and has supplied the relevant conversion equation,

$$\dot{m}_a = 0.0137\sqrt{\frac{\Delta P}{(1+\omega)\,v_a}} \tag{13}$$

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.

Note, the specific volume of dry air, v_a, may be obtained from the Psychrometric Chart given measurements of the dry bulb and wet bulb temperatures at the same location. Once $\dot{m}_a$ is known from (13), we can determine $\dot{m}_v$ from (12) and then $\dot{m}_w$ from (11), 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. Typical 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

$$\dot{m}_{\text{makeup}} = \dot{m}_{w_{\text{in}}} - \dot{m}_{w_{\text{out}}}. \tag{14}$$

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 recirculating, versus the percentage that is lost through the top of the tower to the atmosphere.

(iii) Rate of Heat Gain by 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 dry 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,

$$\dot{Q}_a = \dot{m}_a(h_{a_{\text{out}}} - h_{a_{\text{in}}})\,, \tag{15}$$

where h_a denotes the specific enthalpy of the 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 (13).

(iv) 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 3. In this system, the liquid water remains entirely within the system boundary, i.e., no liquid water crosses the system boundary. Furthermore, we only consider the dry air as the working fluid. In other words, the rate of heat transfer to the water vapor is included as part of the heat lost to the surroundings. Note, in order to calculate the rate of heat lost to the water vapor, we would need to integrate the differential heat transfer along the height of the tower, because the water vapor mass flow rate continuously changes with height (i.e., increasing, as the rising moist air becomes more and more humid). Since the system does no shaft work, the simplified energy balance can be written as

$$\dot{Q}_{\text{in}} + \dot{Q}_{a_{\text{in}}} = \dot{Q}_{a_{\text{out}}} + \dot{Q}_{\text{amb}}. \tag{16}$$

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 dry air by the change in specific enthalpy between the inlet and outlet as calculated in (15). Therefore the above equation can be written as

$$\dot{Q}_{\text{amb}} = \dot{Q}_{\text{in}} + \dot{m}_a(h_{a_{\text{out}}} - h_{a_{\text{in}}})\,. \tag{17}$$

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 heat is added from the pump that serves to recirculate the water. Therefore, $\dot{Q}_{\text{in}} = 1.6$ kW, for the experiments that you ran in the laboratory.

Appendix — Experimental Setup

The experimental setup used in the lab is shown in Figure 4. Because of the counterflow nature of the cooling tower, location A represents the inlet for the air, but the outlet for the water. Similarly, location B represents the outlet for the air, but the inlet for the water. Type K thermocouples are used to measure the wet and dry bulb temperatures throughout. An inclined manometer is used to measure differential air pressure at the locations A and B, which can then be converted to mass flow rate using a modified Bernoulli's equation with the specified orifice constant, as provided by the manufacturer. Locations of the thermocouples are listed in Table 1.

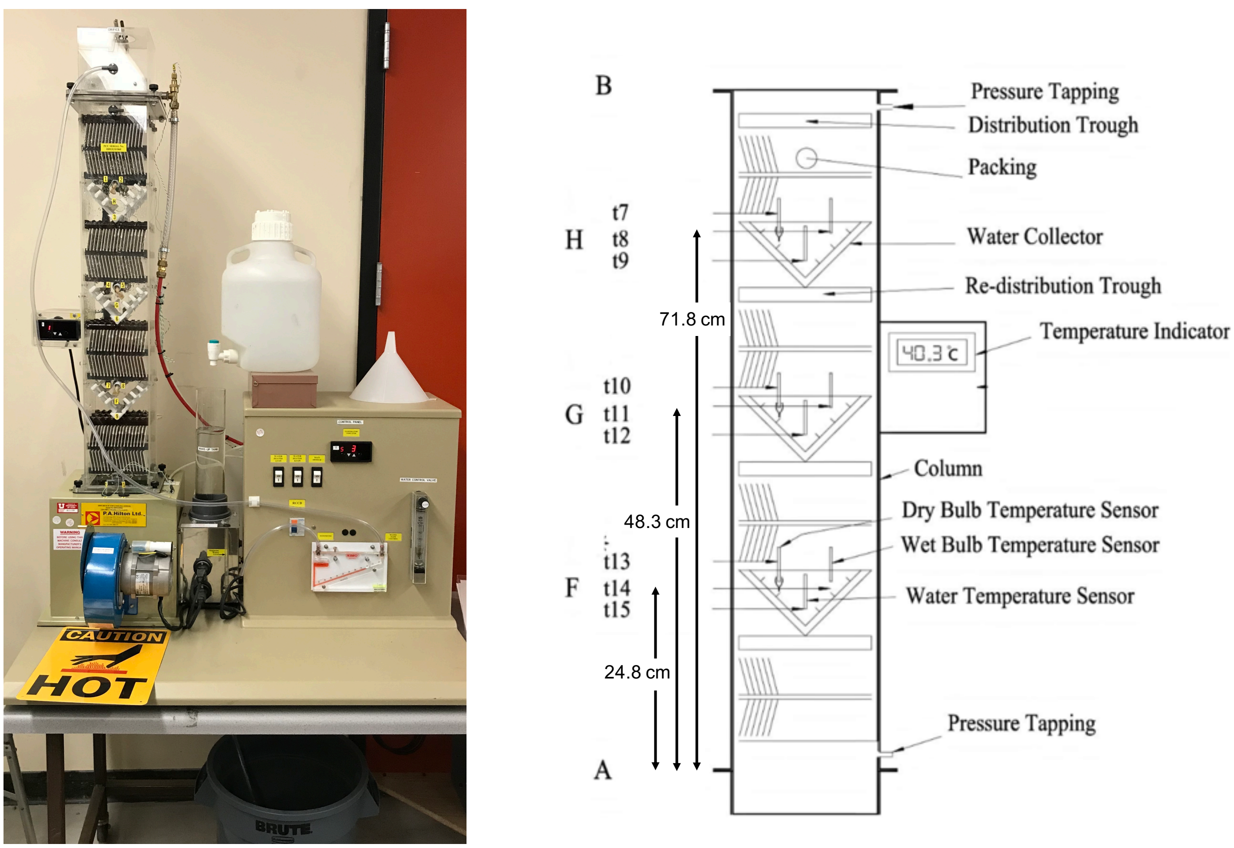

Figure 4: Experimental setup to measure the performance of a water cooling tower in the laboratory.

Table 1: Location of the temperature measurements.

Main Display Unit

Channel	Symbol	Position	Temperatures
1	T_1	Air inlet (A)	Dry-bulb temperature
2	T_2		Wet-bulb temperature
3	T_3	Air outlet (B)	Dry-bulb temperature
4	T_4		Wet-bulb temperature
5	T_5	Water inlet	Water temperature
6	T_6	Water outlet	Water temperature

Side Display Unit

Channel	Symbol	Position	Temperatures
1	t_1	H (H_t = 71.8 cm)	Air, wet-bulb
2	t_2		Air, dry-bulb
3	t_3		Water
4	t_4	G (H_t = 48.3 cm)	Air, wet-bulb
5	t_5		Air, dry-bulb
6	t_6		Water
7	t_7	F (H_t = 24.8 cm)	Air, wet-bulb
8	t_8		Air, dry-bulb
9	t_9		Water

Appendix — Psychrometric Chart and MATLAB Function

A Psychrometric Chart appropriate for measurements made at an altitude of 1500 m (consistent with the location of our laboratory) is provided in Figure 5. See the lecture notes for help on how to read these types of charts.

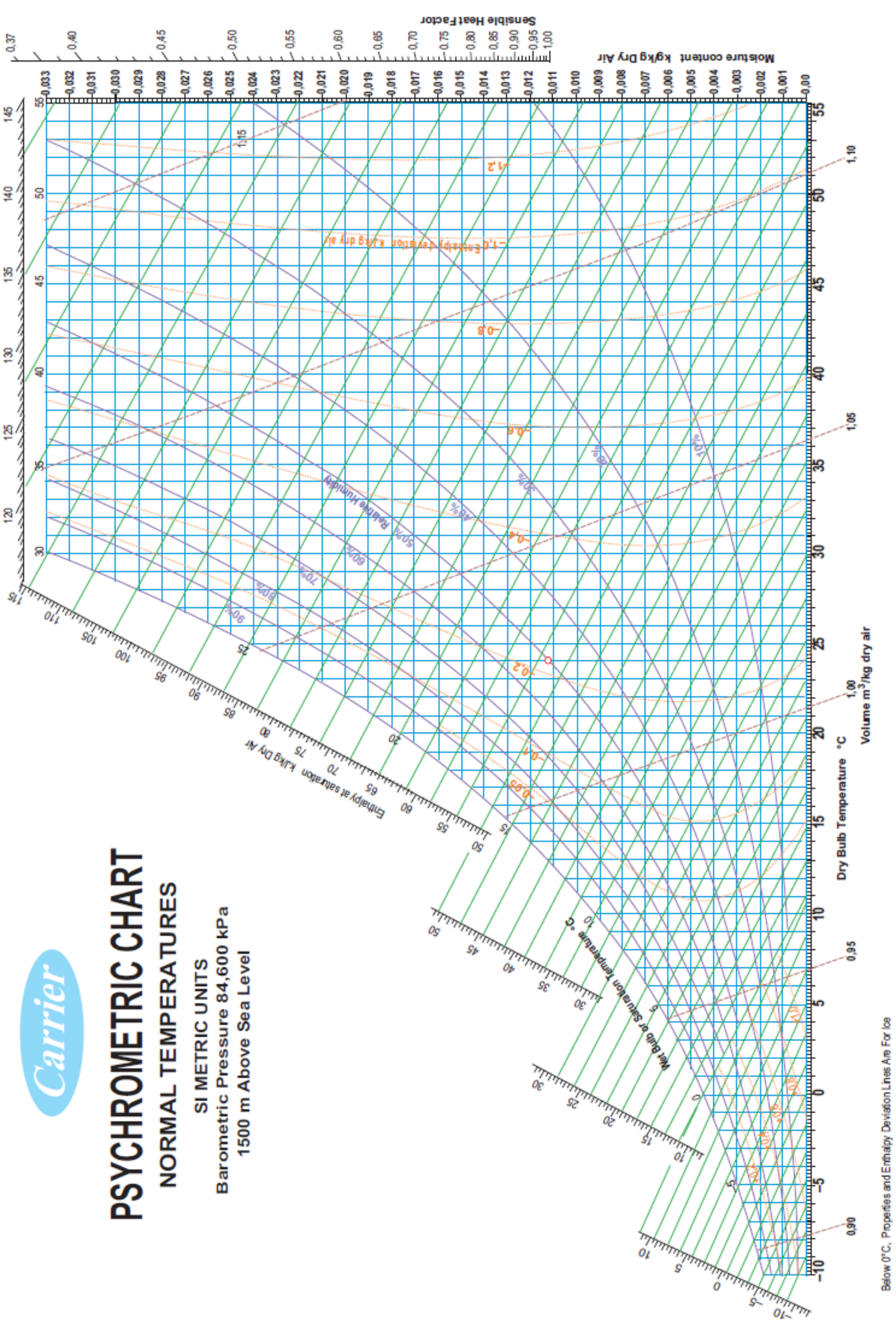

Figure 5: Psychrometric Chart appropriate for use in analyzing the data acquired in our laboratory.

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);
```