Cooling Tower Performance

Purposes

1. Student has deep understanding on principles of cooling tower
2. Student can use the psychrometric chart for determining the specific humidity, specific enthalpy, relative humidity
3. Student can calculate effectiveness of the cooling tower, t range, t approach
4. Student can plot the relevant data for seeking the relation of air and water flow-rates; and the effectiveness

Theory

What a cooling tower is

A special kind of heat exchanger which allows air and water to come in contact to lower the temperature of hot water. During the contact, some part of the water evaporates and decreases the temperature of left water.

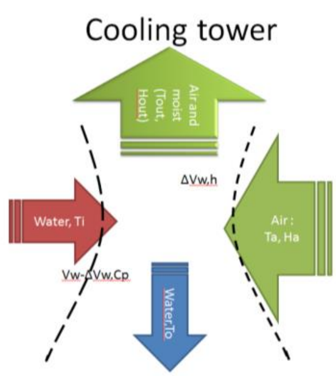


Figure 1. Principle of cooling tower system

The components of cooling tower

Figure 2 mentions the typical components of cooling tower.

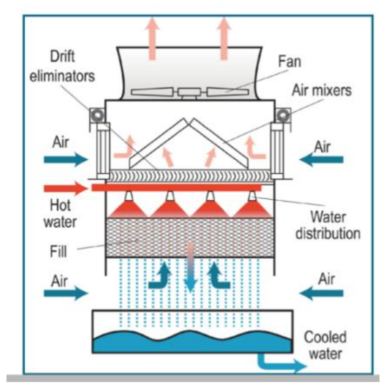


Figure 2. Component of cooling tower (https://www.scribd.com/document/336968645/waterfs-coolingtowers-pdf)

Type of cooling tower

Type of cooling tower is determined primarily by the direction of the air flow when it contacts with the water and the way of creating air flow. If the air contacts the water in crossing direction, the cooling tower will be called as crossflow. If the water contacts the air flow in opposite direction, the cooling tower is classified as counterflow cooling tower. If the air flow is a natural flow (buoyancy flow), the cooling tower is natural draft type. And when air flow is a force flow, it will be called as mechanical draft.

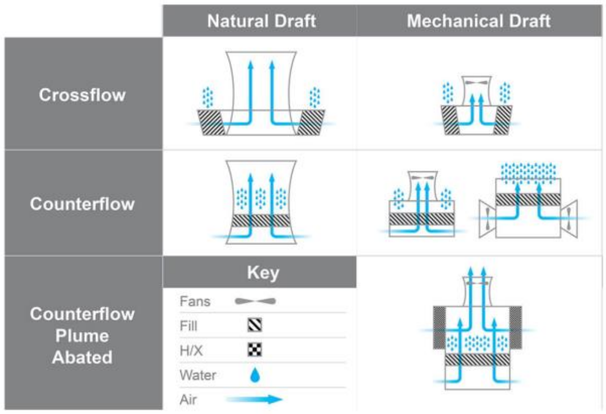


Figure 3. Types of cooling tower (http://www.coolingtowerproducts.com/blog/how-cooling-towers-work-diagram-pictures-2015.htm)

Psychrometric chart

A psychometric chart is a method to represent psychrometric process that is a thermodynamic process in mixture of air and vapor. In a psychrometric chart, relations among thermodynamic properties can easily to determine. A typical psychrometric chart of 1 atm pressure is provided at Figure 4.

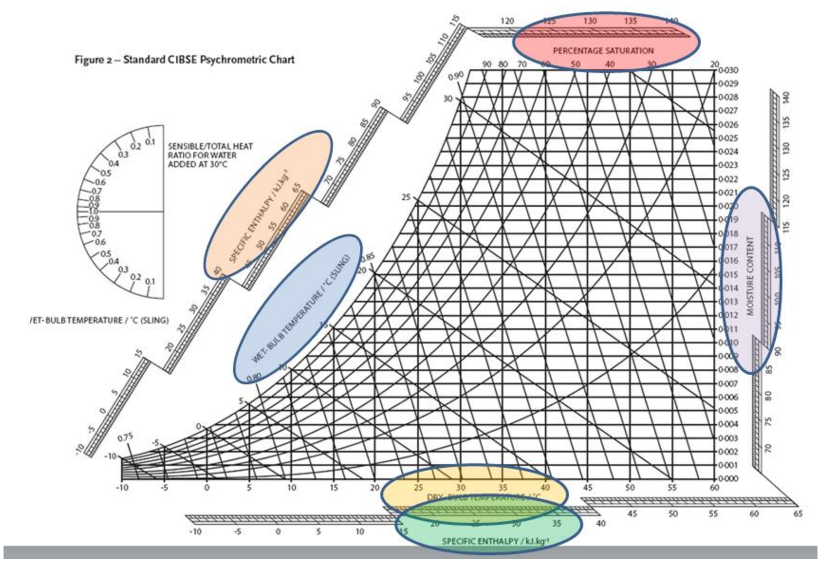


Figure 4. A typical psychrometric chart where ellipses show the parameters of psychrometric process axes.

An example of determining parameters on a psychrometric process with t_dry = 20°C and t_wet = 13°C can be referred in the following picture. The crossing point of the t_dry (temperature of dry bulb) and t_wet (temperature of wet bulb) was used for determining the other parameters. They are specific volume, specific enthalpy, absolute humidity (the vapor content of air), and percentage humidity.

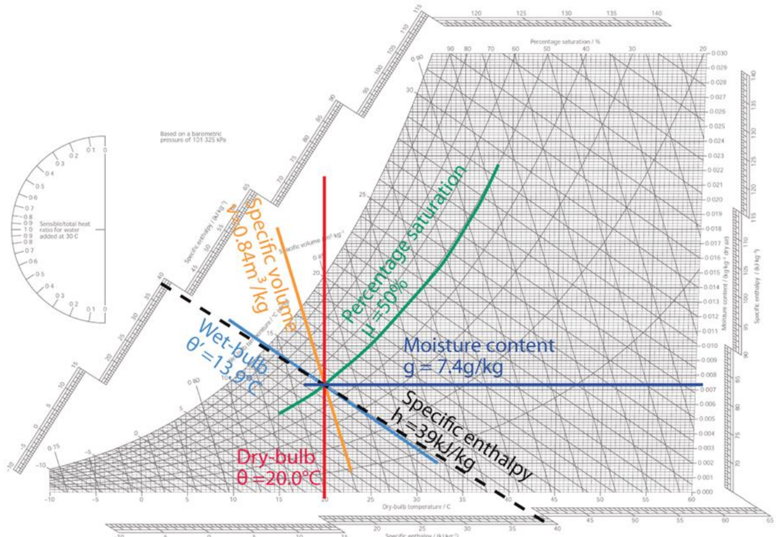
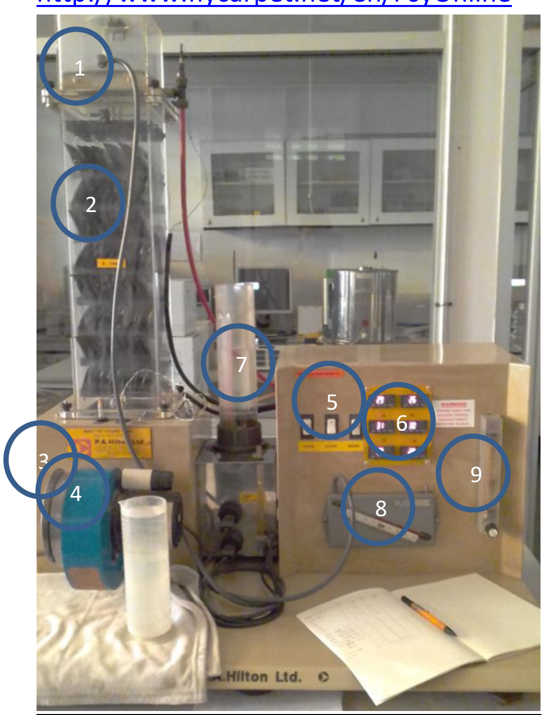


Figure 5. Example of taking values on psychrometric chart
(http://www.cibsejournal.com/cpd/modules/2009-08/, accessed March 16th 2017)

Some links that students can access for free:
http://psychrometricchart.net/psychrometric_chart_software.php
http://www.flycarpet.net/en/PsyOnline



1. drift eliminator
2. fill
3. damper
4. air pump
5. switches
6. temperature display
7. make-up water tank
8. manometer
9. flow-rate water level

Manual of laboratory activities

1. To start operating the cooling tower

- Make sure that all heaters are switched-off.
- Open the air damper and water flow valve
- Turn on the main switch and check the air and water flows.
- Check the temperature displays.
- Add water for wet bulbs
- Add make-up water
- When everything is running well, start the experiment through adding heat load.

2. To stop operation of cooling tower

- Turn-off all the heaters.
- Keep the air and water flows until the water outlet and inlet temperature are equal and constant.
- Turn-off the main switch for shutting down the pump.
- Close the damper and plug the power out.

3. Some basic safety principles

- Do not let the temperature of load to exceed 70^{o}C. If the temperature of the load > 70^{o}C degree, the hot water pump may get into trouble. (Shut down the system and check the pump)
- Check the load water. The water should be in range. Lack of water will break the heaters. Add the make-up water before the water surface reach minimum level.

4. Collecting data

- Collect the data (t1, t2, t3, t4, t5, t6, manometer, water make up) for the next variation condition

Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Load	1.5 kW	1.5 kW	1 kW	1 kW	1 kW	1 kW	1.5 kW	1.5 kW
Water flow	g/s	g/s	g/s	g/s	g/s	g/s	g/s	g/s
Damper	Fully open	Half open	Fully open	Half open	Fully open	Half open	Fully open	Half open

- For every run, calculate air flow, specific humidity inlet, specific humidity outlet, specific enthalpy inlet, specific enthalpy outlet

- Procedures for collecting data
    1. Before starting the first run, take the position of manometer
    2. Set the make-up water to be zero position
    3. Do starting procedure
    4. Set conditions to be 1st run, take note on manometer
    5. Wait around 5 minutes until the cooling tower steady
    6. Take data of water make-up, t1, t2, t3, t4, t5, t6,
    7. Add the water make-up and take note its level position
    8. Set the condition for the next run and repeat activities from the step 5th .
    9. During waiting the cooling tower reaching steady, determine specific humidity inlet, specific humidity outlet, specific enthalpy inlet, specific enthalpy outlet by plotting the data of the preceding run.
    10. Calculate effectiveness, t approach and t range of the preceding run.
    11. Do stopping procedure after all data are collected.

Properties	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Water flow rate (g/s)								
Damper position	Half Opened		Fully Opened		Half Opened		Fully Opened	
Manometer								
Cooling load (kW)	1.5	1	1.5	1	1.5	1	1.5	1
Dry bulb temperature of inlet; t1 (^oC)								
Wet bulb temperature of inlet; t2 (^oC)								
Dry bulb temperature of outlet; t3 (^oC)								
Wet bulb temperature of outlet; t4 (^oC)								
Input water temperature; t5 (^oC)								
Output water temperature; t6 (^oC)								
Make-up water consumption (cm)								
Specific enthalpy of air inlet, h_{in} (kJ/kg)								
Specific humidity of air inlet, ωin (g/kg dry air)								
Specific enthalpy of air outlet, h_{out} (kJ/kg)								
Specific humidity of air outlet, ω_{out} (g/kg dry air)								
Cooling range = t5 – t6 (^oC)								
Temperature approach, $t_{approach}$ = t6-t2 (^oC)								
Effectiveness of cooling tower; η=(t5-t6)/(t5-t2)								
air flow rate; $\dot{m} = 0.0137\sqrt{\frac{\Delta pressure}{\gamma_B}}$								

γ_B = specific volume of air Manometer at zero air flow rate :

Personal assignments:

Every student must submit a fully report after the coming week of the class. The report should contain.

- The cover
- Abstract
- Introduction
- Experiment procedure
- Result
- Discussion
- Conclusions
- Appendix
- Literature Cited

The Report should contain;
- Plot 2 graphs (plot the relation of water or air flow-rates, cooling range and the effectiveness).
- Determine the specific volume, specific enthalpy, absolute humidity (the vapor content of air) and percentage humidity from a psychrometric chart from one of your collecting data.
- Answer of questions.

Literature Cited;
- Sufficient and appropriate sources cited. Sources are cited appropriately in the text (Author, Year). All references are formatted appropriately according to APA format.
Spelling and grammar - All grammar and spelling correct and very well-written.
Readability - Excellent handwriting and readable.

Questions:

What is the effect of increasing water flow rate to cooling load?
What is the effect of cooling load to cooling range?
What is the effect of increasing water flow rate to T approach?
What is the effect of increasing water flow rat to effectiveness?

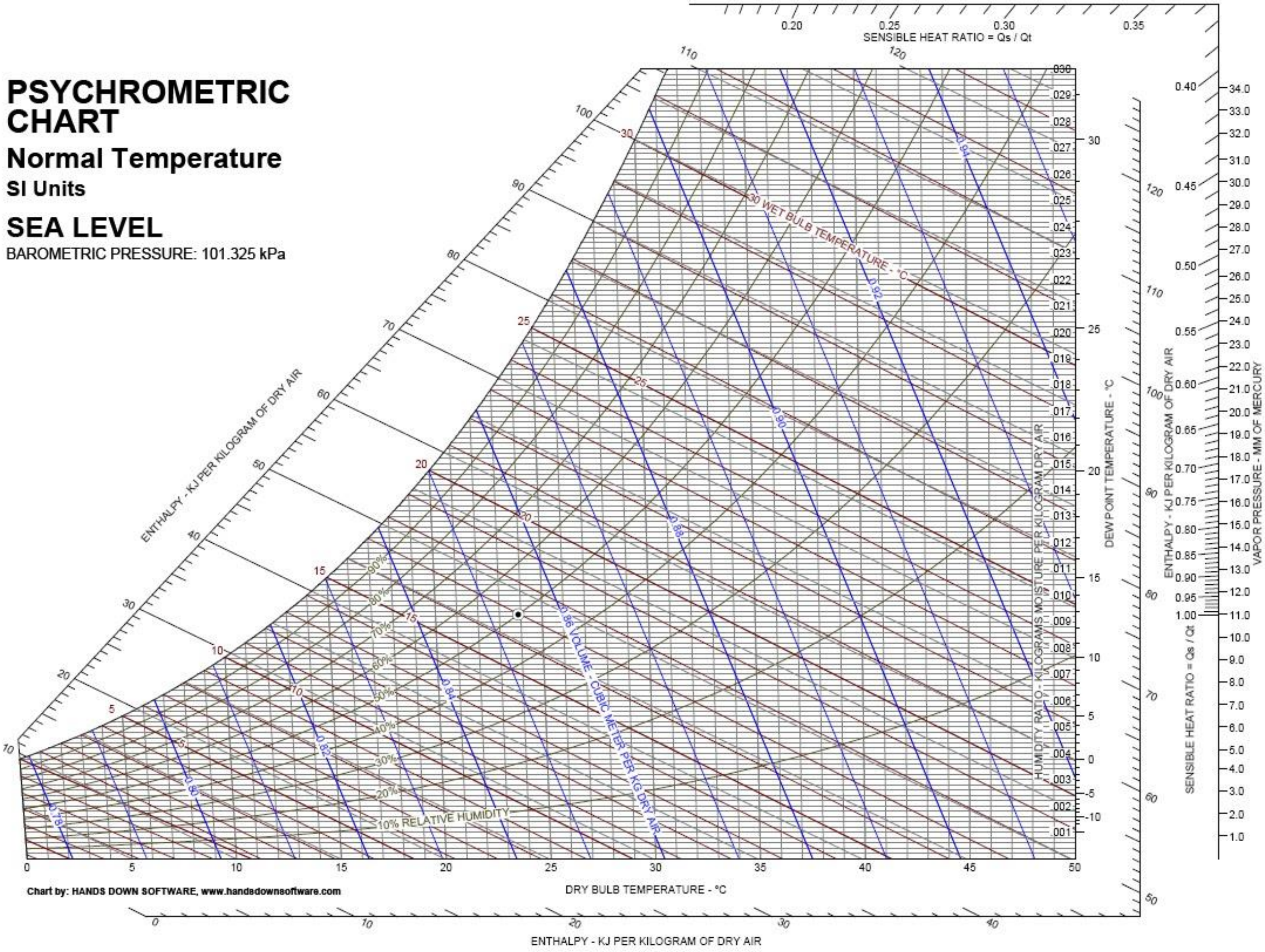
PSYCHROMETRIC CHART

Normal Temperature

SI Units

SEA LEVEL

BAROMETRIC PRESSURE: 101.325 kPa



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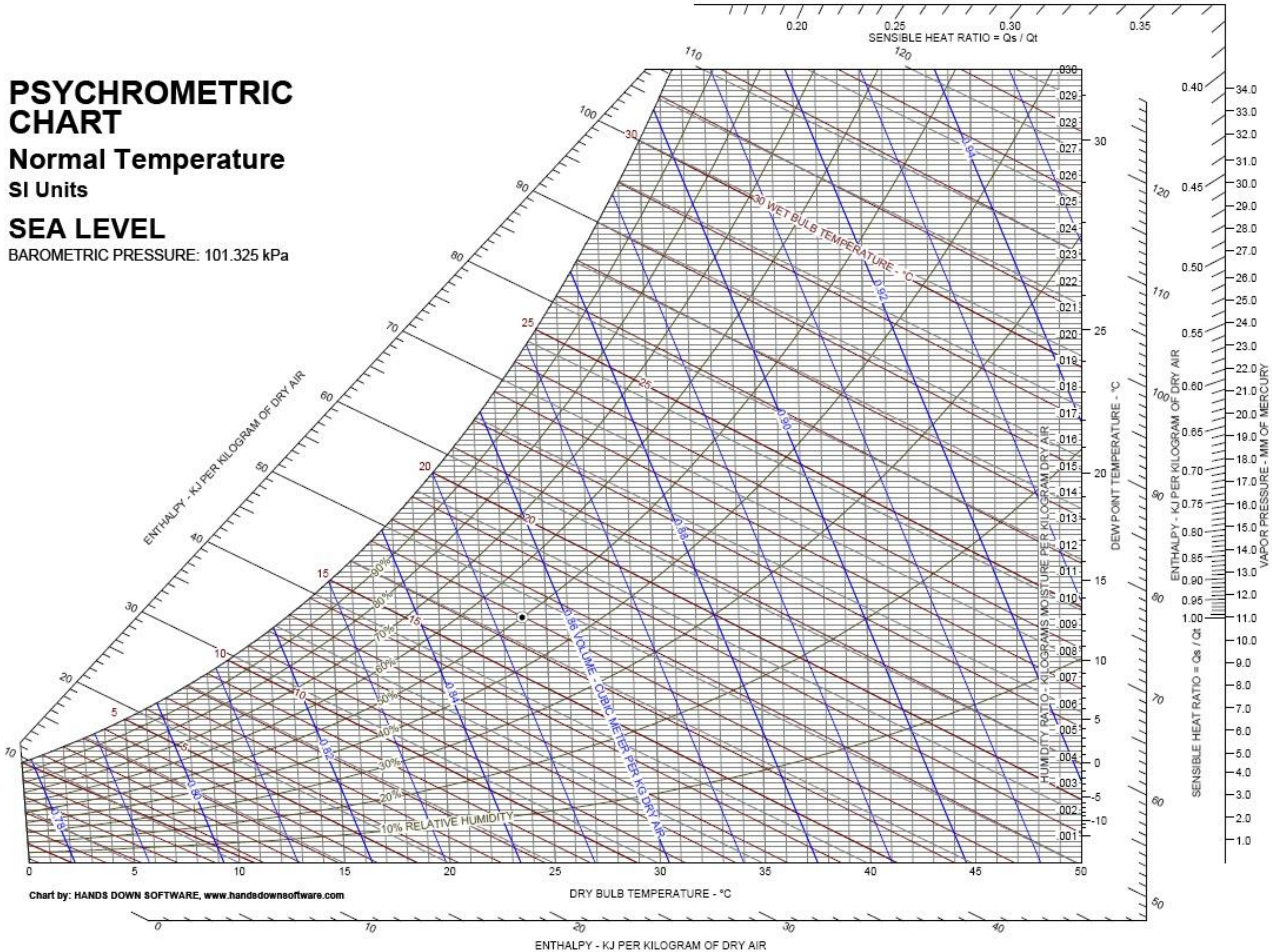


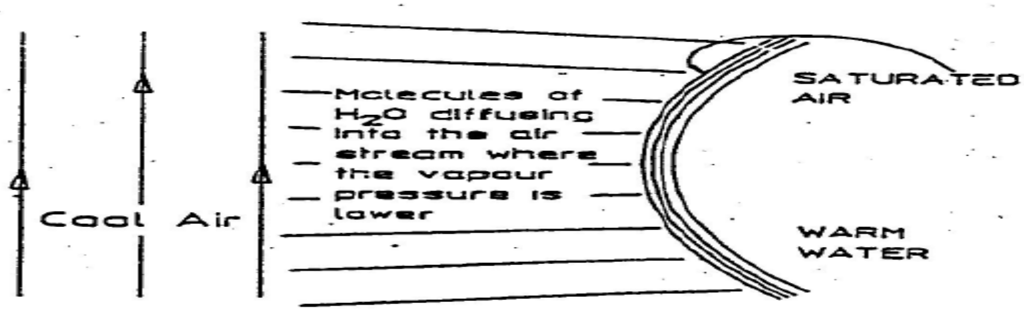
Appendix : Theory

Cooling Tower Terms

Cooling Range	The difference between the water temperature at entry to and exit from the tower.
Cooling Load	The rate at which heat is removed from the water. This may be expressed in kW, Btu/h or k Cal/h.
Make-up	The quantity of fresh water which must be supplied to the water circuit to make good the losses due to evaporation and other causes.
Drift Or Carry Over	Droplets of water which are entrained by the air stream leaving the tower.
Packing or Fill	The materials over which the water flows at it fall through the tower, that a large surface area is presented to the air stream.
Approach to Wet Bulb	The difference between the temperature of water leaving the tower and the wet bulb temperature of the air entering.
Drain Down	Water deliberately removed from the water system to prevent the excessive concentration of dissolved solids due to evaporation and sludge due to impurities from the atmosphere.

Basic Principles

Consider the surface of a warm water droplet or film in contract with an air stream



Assuming that the water is hotter than the air, it will be cooled.

(i) By radiation – This effect is likely to be very small at normal conditions and may be neglected.
(ii) By conduction and convention – This will depend on the temperature difference, the surface area, air velocity, etc.
(iii) By evaporation – This is by far the most important effect. Cooling takes place as molecules of H_2O diffuse from the surface into the surrounding air. These molecules are then replaced by others from the liquid (evaporation) and the energy required for this is from the remaining liquid.

Evaporation from a Wet Surface

The rate of evaporation from a wet surface into the surrounding air is determined by the difference between the vapour pressure at the liquid surface, i.e. the saturation pressure corresponding with the surface temperature, and the vapour pressure in the surrounding air. The latter is determined by the total pressure of the air and its absolute humidity,

In an enclosed space, evaporation can continue until the two vapour pressure are equal, i.e. until the air is saturated and at the same temperature as the surface. However, if unsaturated air is constantly circulated, the wet surface will reach an equilibrium temperature at which the cooling effect due to the evaporation is equal to the heat transfer to the liquid by conduction and convection from the air, which under these conditions, will be at the higher temperature.

The equilibrium temperature reached by the surface under adiabatic conditions, i.e. in the absence of external heat gains or losses, is the "wet bulb temperature", well known in connection with hygrometry.

In a cooling tower of infinite size and with an adequate air flow, the water leaving will be at the wet bulb temperature of the incoming air.

For the reason, the difference between the temperature of water leaving a cooling tower and the local wet bulb temperature is an indication of the effectiveness of the cooling tower.

The "Approach to Wet Bulb" is one of the important parameters in the testing, specification, design and selection of cooling towers.

Conditioning within a cooling tower packing are complex due to the changing air temperature, humidity and water temperature as the two fluids pass through the tower – usually in a contra flow fashion.

Cooling Tower Performance

The following factors affect the performance of a cooling tower:

(i) The air flow rate
(ii) The water flow rate
(iii) The water temperature
(iv) The air temperature and humidity at inlet (particularly the wet bulb temperature)
(v) The type of packing used
(vi) The area and volume of the packing

The Bench Top Cooing Tower enables these factors to be varied so that an overall appreciation of cooling tower characteristics can be obtained.

<u>Thermodynamics Properties</u>

Water

The specific enthalpy of saturated water is assumed to be zero at the triple point (0.01 °C and 0.00611 bar (611Nm^2), which is taken as datum.
Thermodynamic table give the specific enthalpy of saturated water (h_f) at a range of temperatures above the datum conditions, e.g. from the tables (Ref.7, Page 54) at 20 °C, the value of (h_f) is 83.9 kJ Kg^{-1} ,the saturated pressure is 0.02337 bar (2.337kN m^{-2}) and the specific volume is 0.001 m^{3}kg^{-1}.
Water is the Bench Top Cooling Tower is at atmosphere pressure, usually about 1.013 bar (101.3 kN m^{-2}), and if the water is at say 20°C it must be "compressed liquid", as its pressure is above the saturation pressure.
The specific enthalpy of compressed liquid is given by $h = h_f + v_f\left(p - p_{sat}\right)$
So that water at 20°C and 101.3 kN m^{-2} has a specific enthalpy of

$$h = 83.9 \times 10^3 + 0.001(101300 - 2337)\ \text{J kg}^{-1}$$
$$h = 83.9 \times 10^3 + 99\ \text{J kg}^{-1}$$
$$h = 84\ \text{kJ kg}^{-1}$$

It will be seen that at the conditions likely to be encountered in a cooling tower, $h = h_f$ at the given temperature, i.e. the correction of pressure is insignificant.

Specific Heat Capacity (Cp)
If water is cooled from say 50°C to 20°C at atmospheric pressure, its specific enthalpy will fall from 209.3 to 83.9 kJ kg^{-1}, i.e. a decrease of 125.4 kJ kg^{-1}
This is an average change $\frac{\Delta h}{\Delta t}$ of $\frac{125.4}{30}$ = 4.18 kJ kg^{-1}
The rate of change of enthalpy with respect to temperature, (i.e. $\frac{dt}{dh}$) is given symbol Cp (often called the specific heat at constant pressure).
Over the range of temperatures likely to be used in Bench Top Cooling Tower, we may therefore use for water, $\Delta h = Cp\Delta t$) where Cp = 4.18 kJ kg^{-1} and $h = Cpt$

Dalton's and Gibbs Laws

Air is a mixture of "dry air" (oxygen, nitrogen and other gases) and water vapour.

The behavior of such a mixture is set out in the laws of Dalton and Gibbs from which the following may be deduced:

(i) The total pressure of the air is equal to the sum of the pressures which the "dry air" and the water vapour each and alone would exert if they were occupy the volume of the mixture at the temperature of the mixture.
(ii) The dry air and the water vapour respectively obey their normal property relationships at their partial pressures.
(iii) The enthalpy of the mixture may be found by adding together the enthalpies which the dry air and water vapour each would have as the sole occupant of the space occupied by the mixture and at the same temperature.

The water "water vapour" "steam" or "moisture" content of the air is denoted by its "HUMIDTY".

<u>"Absolute or Specific Humidity"</u> (ω) is the ratio $\frac{Mass\ of\ Water\ Vapour}{Mass\ of\ Dry\ Air}$ (i)

<u>"Relative humidity"</u> ($\emptyset$) is the ratio

$$\frac{Partial\ Pressure\ of\ Water\ Vapour\ in\ the\ Air}{Saturation\ Pressure\ of\ Water\ Vapour\ at\ the\ same\ Temperature} \qquad \text{(ii)}$$

"Percentage Saturation" is the ratio

$$\frac{Mass\ of\ Water\ Vapour\ in\ a\ given\ volume\ of\ Air}{Mass\ of\ same\ volume\ of\ Saturated\ Water\ Vapour\ at\ the\ same\ Temperature} \qquad \text{(iii)}$$

It can be shown that at the conditions within a cooling tower, i.e. at high humidities, there is very little difference between the "Relative Humidity" and the "Percentage Saturation" and for convenience, they will be regarded as equal in the following.

Hygrometer are instruments for measuring the H_2O content of the atmosphere.

Many different types of the hygrometer are available but the Bench Top Cooling Tower uses the well known "wet" and "dry" bulb type for which a large amount of data is available.

In this hygrometer, the wet bulb thermometer bulb is enclosed by a water wetted fabric sleeve.

Evaporation from this sleeve causes the temperature indicated by the wet bulb thermometer to be lower than that indicated by the "dry" bulb temperature. (see page 15)

Observation of these temperatures in conjunction with published tables or charts enables the humidity and other properties of the air to be determined.

Alternatively, the pressure of the water vapour in the atmosphere may be obtained by substitution in the equation (due originally to Regnault, August and Apjohn).

$$p_s = p_{satw} - 6.666x10^{-4} p_t (t_0 - t_w)$$

Where p_s is the pressure of the water vapour in the air/(mbar)

p_{satw} is the saturation pressure of water vapour at the temperature of wet bulb/(mbar)

p_t is the total air pressure (normally atmospheric pressure)/(mbar)

t_0 is the temperature of dry bulb/°C

t_w is the (sling) temperature of wet bulb/°C

Effect of Air Velocity on the Indicated Wet Bulb Temperature

The "sling" wet bulb temperature used by the psychometric charts and tables is that indicated by a wet bulb sensor placed in an air stream having a velocity of 3.5 m s^{-1} or more

At high relative humidities, there is little error if the sensor is placed in a stream having a lower velocity , but at low relative humidities an appreciable error may occur.

At outlet from the Bench Top Cooling Tower the sensors are placed in air with a very high relative humidity and where the air velocity is high. The wet bulb temperature indicated will therefore be accurate.

The wet bulb sensor in the air chamber is in a region-where the velocity is lower and where the relative humidity is much lower. It is therefore advisable to confirm the wet bulb reading as follows:

(i) Ease the bung securing the wet bulb sensor from the top of the air chamber.
(ii) Draw the sensor upward until the air escapes between the socket and the sleeve. The air velocity over the sleeve will now be about 10 m/s and the "sling" temperature will quickly be indicated by the sensor.
(iii) Compare the "sling" reading with that previously indicated – any discrepancy can be allowed for in subsequent observations at the same conditions.

The application of the foregoing Laws and relationships and the evaluation of properties is best illustrated by a worked example as follows.