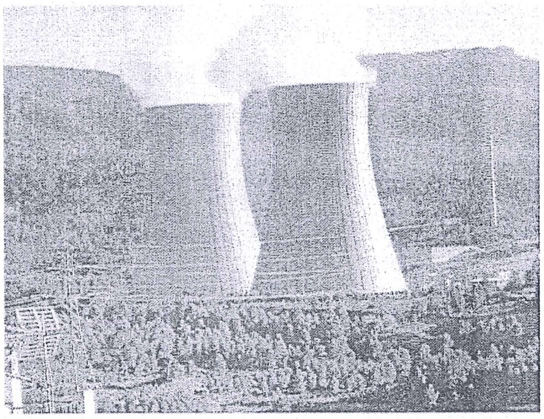
COOLING TOWERS

1. INTRODUCTION

When a relatively warm liquid is brought into direct contact with the gas that is unsaturated, some of the liquid is vaporized. The liquid temperature will drop mainly because of the latent heat of vaporization. This direct contact of a gas with a pure liquid occurs most often in contacting air with water.

This is done for the following purposes; **humidifying air** for control of moisture content of air in drying, **air-conditioning**, **dehumidifying air** and **water cooling**.

In a typical water-cooling tower, warm water flows countercurrent to an air stream. The warm water enters the top of a packed tower and cascades down through the packing, leaving at the bottom. Air enters at the bottom of tower and flows upward through descending water. The flow of air can be induced by buoyancy of warm air in the tower (natural draft) or by the action of a fan.[1]



Natural draft designs use very large concrete chimneys to introduce air through the media. Due to the tremendous size of these towers, they are generally used for water flow rates above 45000 m^3/hr. Usually these types of towers are only used by utility power stations. Mechanical draft cooling towers are much more widely used. These towers utilize large fans to force air through circulated water. The water falls downward over fill surfaces that help increase the contact time between the water and the air. This helps maximize heat transfer between

In humidification and dehumidification, intimate contact between the gas phase and liquid phase is needed for large rates of mass transfer and heat transfer. The gas-phase resistance controls the rate of transfer. Spray or packed towers are used to give large interfacial areas and to promote turbulence in the gas phase.[1]

The heat-transfer process involves two mechanisms;

- latent heat transfer owing to vaporization of a small portion of the water
- sensible heat transfer owing to the difference in temperature of water and air.

Approximately 80% of this heat transfer is due to latent heat and 20% to sensible heat.[3]

The driving force for the evaporation of water is approximately the difference between vapor pressure of water and the vapor pressure it would have at the wet bulb temperature of air.[1] Wet bulb temperature shortly is an indication of the moisture content of the air[3] and it is explained in detail in page 8. Thus the water can be cooled only to the wet bulb temperature and in practice it is cooled to about 3K or more above this.[1] This is because practically, the cold-water temperature approaches but does not equal the air wet bulb temperature in a cooling tower; since it is impossible to contact all the water with fresh air as the water drops through the wetted fill surface to the basin.

The magnitude of approach to the wet bulb temperature is dependent on tower design. Important factors are air-to-water contact time, amount of fill surface, and breakup of water into droplets. Theoretical possible heat removal per pound of air circulated in a cooling tower depends on the temperature and moisture content of air.[3]

In the cooling tower equipment provided in our laboratory, understanding of the construction, design and operative characteristics of a modern cooling system by evaporating water is aimed. This unit is a good example of "open system" through which two currents of fluids (water and air) flow and where a transfer of material from one phase to another takes place.[4]

2. THEORY

COOLING and HUMIDIFICATION

In a number of seperation processes and transport processes, it is required to comment on the properties of mixtures of water vapor and air. Therefore, knowledge of the concentration of water vapor in air under various conditions of temperature and pressure, thermal properties of these mixtures and the changes occurring when these mixtures are brought into contact with water or with wet solids in drying is required.

Humidification involves the transfer of water from the liquid phase into a gaseous mixture of air and water vapor. Dehumidification involves the reverse transfer whereby water vapor is transferred from the vapor state to the liquid state. Humidification and dehumidification can also refer to vapor mixtures of materials such as benzene but most practical applications occur with water. To better understand humidity, it is first necessary to discuss the vapor pressure of water. Pure water can exist in three different physical states: solid ice, liquid and vapor. Figure 1 below illustrates the various physical states of water and the pressure-temperature relationship at equilibrium.[1]

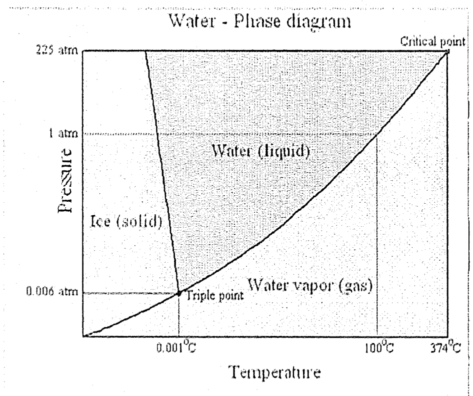


Figure 1: Phase diagram of water[1]

Along the line from the triple point to the critical point seen on Figure 1, liquid and vapor coexist in equilibrium which is also called the vapor-pressure line for water.[1]

PROPERTIES OF WATER

Variation of specific enthalpy with temperature

Water in a cooling tower has the atmospheric pressure, that uses to be 1.013 bares (101,3 kN m^{-2}), and if water is, for example, to 20 °C it must be compressed liquid since its pressure is higher than saturation pressure.

Specific enthalpy of the compressed liquid is given by:

$$h = h_f + v_f (p - p_{sat})$$ Eq. 1[4]

Calorific capacitance Cp.

Quite the opposite, specific enthalpy of water is strongly affected by the same temperature. For example, if water cools down from 50°C to 20°C to an atmospheric pressure, its specific enthalpy will decrease from 209,3 kJ/kg to 83,9 kJ/Kg, that is, a drop of 125,4 kJ/Kg. The average variation of enthalpy by °C is known specific heat to constant pressure $Cp=\Delta H/\Delta T$. According to the anterior calculation, it is had that Cp=125,4/30 = 4.18 kJ/KgK, from where variation of specific enthalpy of water can be obtained from the following formula:

$$\Delta h = Cp\Delta T$$ Eq. 2[4]

Dalton and Gibbs law

Behaviour of air, composed of a mixture of "dry air" (oxygen, nitrogen and other gases) with steam, can be explained through Gibbs laws, from where the following conclusions can be reached:

- Pressure of air is equal to the sum of pressures of dry air and steam.
- Dry air and steam, respectively, follow their normal relations of partial pressure.
- Enthalpy of the mixture can be obtained by adding the enthalpies of dry air and of steam if each one took up the whole space occupied by the mixture, being both to the same temperature.[4]

Hygrometers

Hygrometers are instruments for measuring the amount of water in air. In our case, the cooling tower has the well known hygrometer of wet and dry bulb. In this hygrometer, the wet bulb is wrapped in a scabbard made of cotton fabric which is connected to a tank with distilled water. Evaporation originated in the scabbard makes to the temperature of the thermometer be inferior than the one of the dry bulb. Observation of this temperature, together with the psychometric map allows to determine humidity and other properties of air.

Vapour pressure in atmosphere can be obtained through Regnault, August and Apjohn equation, that is:

$$p_s = p_{sat} - 6.666x10^{-4}\, p_t\,(T_S - T_H) \qquad \text{Eq. 3}^4$$

where:

p_s is the pressure of steam in air.
P_{sat} is the saturation pressure of steam to the temperature of the wet bulb.
P_t is the total pressure of the air (mbar)
T_S is the temperature of the dry bulb (°C)
T_H is the temperature of the wet bulb (°C).

PROPERTIES OF HUMID AIR

A convenient chart of the properties gas-vapor mixtures at 1.0 atm abs pressure is the humidity chart also called the psychrometric chart.[1] On a humidity chart, several properties of a gas-vapor mixture are cross-plotted. The most common of these charts is the one for air-water vapor system at 1 atm and it is used extensively in the analysis of humidification, drying and air-conditioning processes.[5]

For the air-water vapor system at 1 atm, a humidity chart in SI units is given in Appendix A3 and a second chart in American engineering units is given in Appendix A4.

Absolute humidity, h_a : The absolute humidity of an air-water vapor mixture is defined as the kg water vapor contained in 1 kg of dry air[1] and it is also called the moisture content of air[4]. This value is calculated by Eq. 4 given below.

$$h_a = \frac{kg_{H_2O\,(v)}}{kg_{DA}} \qquad \text{Eq. 4}^5$$

Please realize that absolute humidity can be used to easily calculate the mass fraction of water vapor.

The humidity so defined depends only on the partial pressure P_A of water vapor in air and on the total pressure P and it can also be calculated by Eq. 5 given below.

$$h_a = \frac{18.02}{28.97}\frac{P_A}{P-P_A} \quad (in \frac{kg_{H_2O(v)}}{kg_{DA}})$$ Eq. 5[5]

For saturated air, the partial pressure of the water vapor in the water vapor-air is equal to the vapor pressure P_{AS} of pure water at the given temperature.[1]

Relative humidity, h_r : Relative humidity represents the ratio of partial pressure of water vapor to vapor pressure of water at the system temperature, given by Eq. 6 below.

$$h_r = 100 * \frac{p_{H_2O}}{p^*_{H_2O}(T)}$$ Eq. 6[5]

Curves on humidity chart correspond to specified values of h_r such as 100%, 90%, 80%, etc. The curve that forms the left boundary of the chart is the 100% relative humidity curve also known as the saturation curve.[5]

Humid heat of an air-water vapor mixture, c_s : This is the amount of heat in J (or kJ) required to raise the temperature of 1 kg of dry air plus water vapor present by 1 K. the heat capacity of air and water vapor can be assumed constant over the temperature ranges usually encountered at 1.005 kJ/kg dry air*K and 1.88 kJ/kg water vapor*K , respectively.

Total enthalpy of an air-water vapor mixture, H_Y : If T_0 is the datum temperature chosen or both components, the total enthalpy is the sensible heat of the air-water vapor mixture plus the latent heat λ_0 in J/kg water vapor of the water vapor at T_0.[1]

Specific enthalpy of saturated air, H : The diagonal scale above the saturation curve on the humidity chart shows the enthalpy of a unit mass (1 kg or 1 lbm) of dry air plus the water vapor it contains at saturation. The reference states are liquid water at 1 atm and 0^0C and dry air at 1 atm and 0^0C.

Humid volume, V_H : The humid volume is the volume occupied by 1 kg of dry air plus the water vapor that accompanies it. It is also explained in Eq.7 below. [5]

$$V_h = \frac{m^3}{kg\ DA} \qquad \text{Eq. } 7^5$$

Dew point, T_{dp} : The temperature at which air becomes saturated if a given air-water mixture is cooled at constant pressure[4] or in other words it is the temperature at which air would be saturated.[1]

Dry-bulb temperature, T_{db} : This is the air temperature as measured by a thermometer, thermocouple or other temperature-measuring instrument as shown in Figure 2.[5]

Wet-bulb temperature, T_{wb} : This is the steady-state non-equilibrium temperature reached when a small amount of water is contacted under adiabatic conditions by a continuous stream of gas.[1] This quantity is best defined in terms of how it is measured which is also shown in Figure 2. A porous material like cloth or cotton is soaked in water and wrapped around the bulb of a thermometer to form a wick and the thermometer is placed in a stream of flowing air. Evaporation of water from the wick into flowing air is accompanied by a transfer of heat from the bulb, which in turn causes a drop in the bulb temperature and hence in the thermometer reading. Provided that the wick remains moist, the bulb temperature falls to a certain value and remains there. The final temperature reading is the wet bulb temperature of the air flowing past the wick. The wet-bulb temperature of humid air depends on both the dry-bulb temperature and the moisture content of the air. If air is saturated (100% relative humidity), no water evaporated from the wick and the wet-bulb & dry-bulb temperatures are the same. The lower the humidity, the greater the difference between two temperatures. [5]

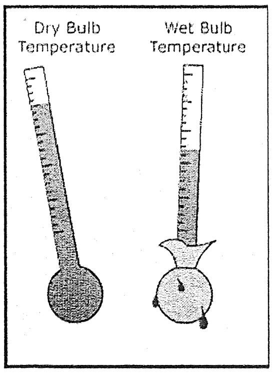


Figure 2: Illustration of measuring devices for dry bulb and wet bulb temperatures[6]

HEAT TRANSFER IN COOLING TOWERS

The most generally accepted theory of the cooling-tower heat-transfer process is that developed by Merkel which is based upon **enthalpy potential difference** as the driving force. Each particle of water is assumed to be surrounded by a film of air, and the enthalpy difference between the film and surrounding air provides the driving force for the cooling process. In the integrated form the Merkel equation is

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{dT}{h' - h} \qquad \text{Eq.8}^3$$

where

K = mass-transfer coefficient, kg water/(s×m^2);

a = contact area,m^2/m^3 tower volume;

V = active cooling volume, m^3/m^2 of plan area;

L = water rate, kg/(s×m^2);

h' = enthalpy of saturated air at water temperature, kJ/kg;

h = enthalpy of air stream, kJ/kg;

T_1 and T_2 = entering and leaving water temperatures, K.

The right-hand side of Eq. 8 is entirely in terms of air and water properties and is independent of tower dimensions.

DESIGN OF COOLING TOWERS

Objectives:

- Find the minimum required air rate to obtain particular water temperature

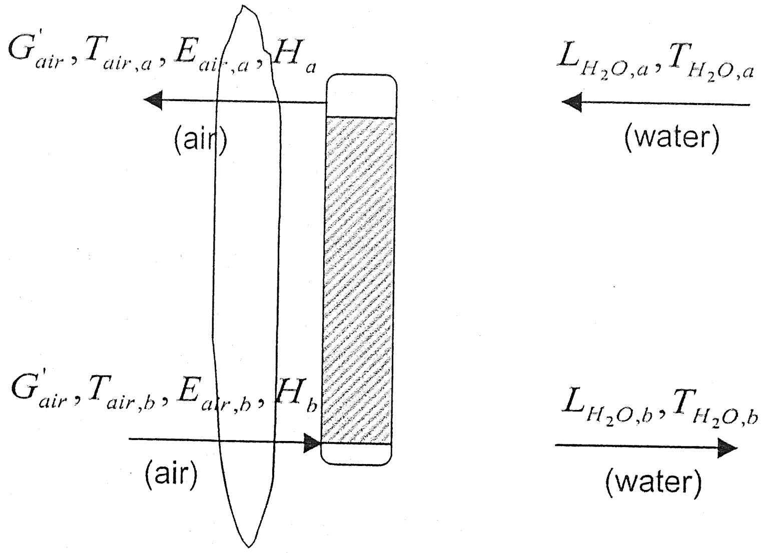


Figure 3: Water Cooling Tower[6]

Overall Energy Balance:

$$G'_{air}(E_{air,a} - E_{air,b}) = L_{H_2O}c_{H_2O}(T_{H_2O,a} - T_{H_2O,b}) \qquad \text{Eq. } 9^{10}$$

G'_{air} vapour free mass flow rate of air

$L_{H_2O,a} \approx L_{H_2O,b} \equiv L_{H_2O}$ mass flow rate of water

Figure 4 illustrates water and air relationships and the driving potential which exist in a counter flow tower, where air flows parallel but opposite in direction to water flow. An understanding of this diagram is important in visualizing the cooling-tower process.

The **water operating line** is shown by line *AB* and is fixed by the inlet and outlet tower water temperatures. The **air operating line** begins at *C*, vertically below *B* and at a point having an enthalpy corresponding to that of the entering wet-bulb temperature. Line *BC* represents the initial driving force (*h' - h*). The liquid-gas ratio *L/G* is the slope of the operating line. The cooling range is the projected length of line *CD* on the temperature scale. The cooling-tower approach is shown on the diagram as the difference between the cold-water temperature leaving the tower and the ambient wet-bulb temperature. The integral is represented by the area *ABCD* in the diagram. This value is known as the **tower characteristic,** varying with the *L/G* ratio. For example, an increase in entering wet-bulb temperature moves the origin *C* upward, and the line *CD* shifts to the right to maintain a constant *KaV/L*. If the cooling range increases, line *CD* lengthens.

In order to predict tower performance it is necessary to know the required tower characteristics for fixed ambient and water conditions. The tower characteristic *KaV/L* can be determined by integration.[3]

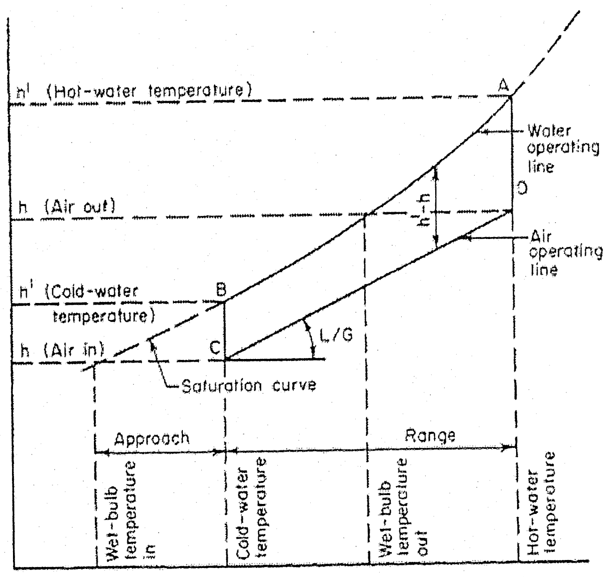


Figure 4: Approach and Range in Cooling Towers[3]

This is operating line:

$$\frac{E_{air,a} - E_{air,b}}{T_{H_2O,a} - T_{H_2O,b}} = \frac{L_{H_2O} c_{H_2O}}{G'_{air}}$$ Eq 10[10]

The important parameters, from the point of determining the performance of cooling towers, are:

- **Range** : This is the difference between water inlet and outlet temperatures in the cooling tower.
- **Approach** : This is the difference between outlet cold water temperature and ambient wet bulb temperature in the cooling tower.

Although, both range and approach should be monitored, the `Approach' is a better indicator of cooling tower performance.

Cooling tower effectiveness (in percentage) is the ratio of range, to the ideal range, i.e., difference between cooling water inlet temperature and ambient wet bulb temperature, or in other words it is = Range / (Range + Approach).

Cooling capacity is the heat rejected in kCal/hr , given as product of mass flow rate of water, specific heat and temperature difference.

Evaporation loss is the water quantity evaporated for cooling duty.

Cycles of concentration (C.O.C). : This is the ratio of dissolved solids in circulating water to the dissolved solids in make up water.[9] As pure water is evaporated, minerals are left behind in the recirculating water which eventually can lead to saturated conditions. The term *cycles of concentration* compares the level of solids in the recirculating cooling tower to the level of solids in the original raw make up water.[10] As the cycles of concentration increase the water may not be able to hold the minerals in solution. When the solubility of these minerals have been exceeded they can precipitate and cause fouling and heat exchange problems in the cooling tower. To overcome these situations, in addition to treating the circulating cooling to minimize scaling and fouling, the water should also be filtered and dosed with biocides and algaecides to prevent growths that could interfere with the continuous flow of the water.[11] Another very important reason for using biocides in cooling towers is to prevent the growth of *Legionella*, including species that cause *Legionnaires' disease*. Common sources of *Legionella* include cooling towers used in open recirculating evaporative cooling water systems, domestic hot water systems.[12]

3. EXPERIMENTAL SECTION

Experimental Set Up :

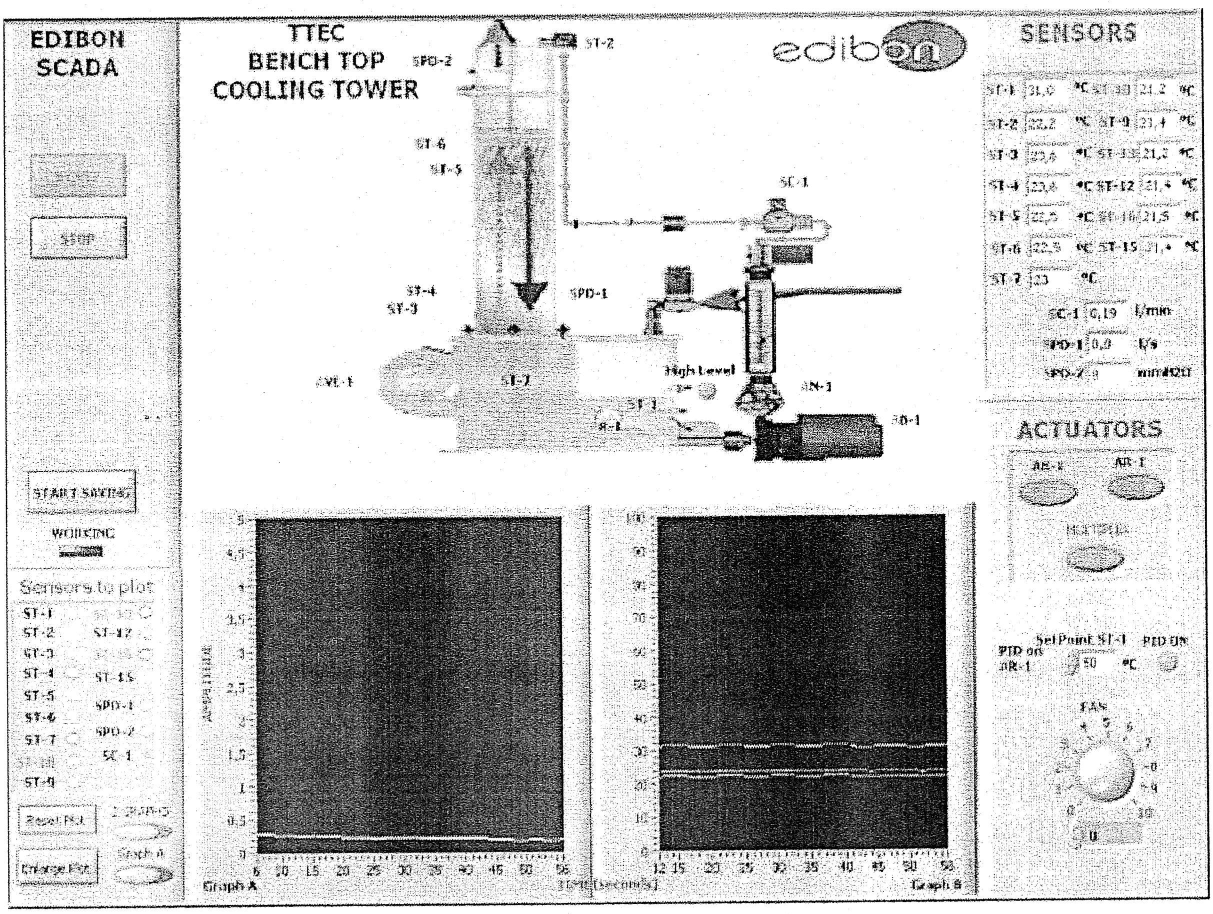


Figure 5: Description of main control elements[4]

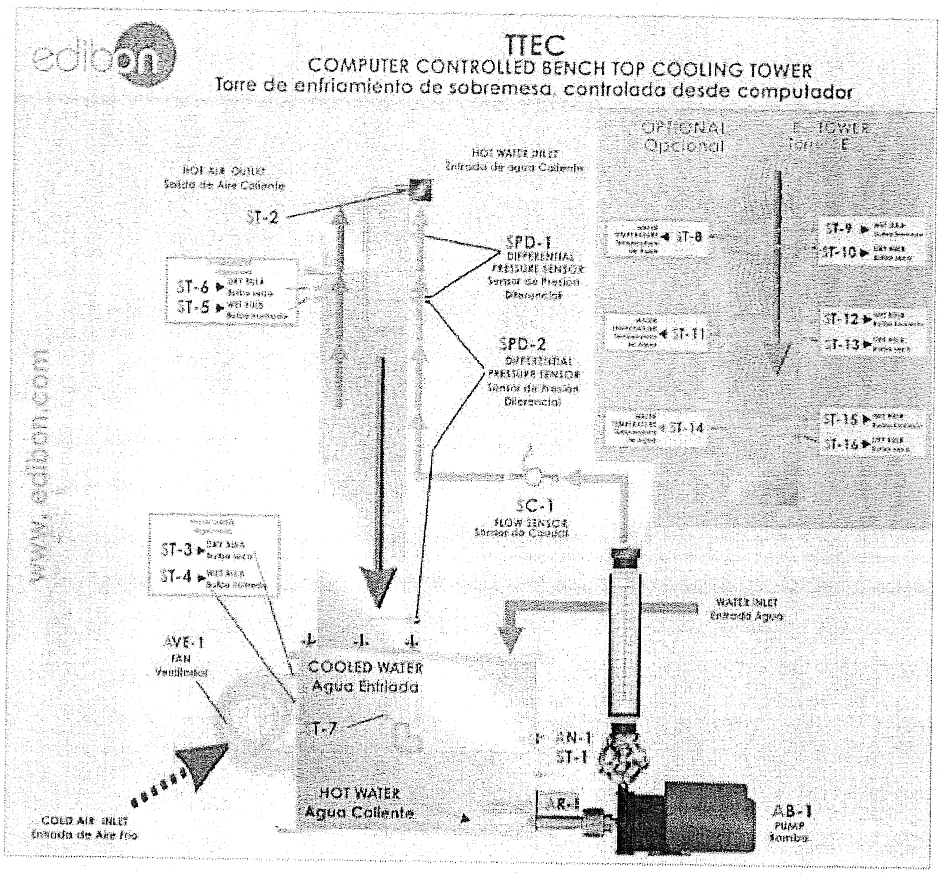


Figure 6: Description of experimental set-up[4]

Following, specifications of the elements of the equipment will be detailed:

Water propeller pump, made of PVC thermally protected. This pump provides a maximum flow of water of 120 l/h.

Air propeller. The fan set in the equipment is regulated from the computer, allowing an exact control of the flow of air inserted in the tower. A differential pressure sensor complements the PID control measuring the flow of air at the output of the tower.

A tank of water with water level gauge.

A level switch (On/Off) for filling the tank.

Two solenoid valves; one normally closed and other one normally open.
Flow sensor.
Interface.

Experimental Procedure:

1. Start the fan
2. Start water pump and adjust the flow rate to a desired value.
3. Start the water heater and set the inlet temperature to a desired value.
4. Measure wet bulb temperature and dry bulb temperature of outlet water.
5. Wait till the steady state is obtained. The attainment of the steady state is confirmed by the constancy in the outlet temperature.
6. Measure air velocity.
7. Measure inlet temperature and outlet temperature of air.
8. Repeat steps 2 to 7 by changing water flow rate or inlet temperature of water.

Part 1: The air in the tower is heated up to different temperatures. Wet and dry bulb temperatures are measured to examine

- the physical properties of air
- the determination the evaporation velocity.
- the balance of matter. Use of psychometric maps.
- the balance of energy.

Part 2: The air in the tower is heated up to set value by using second tower. Wet and dry bulb temperatures are measured to

- find the minimum required air rate to obtain particular water temperature

4. CALCULATIONS

- Use of psychometric maps for Part 1:

Find the humidity, saturation humidity, dew point, humid volume, humit heat, relative humidity and percentage humidity of the air by means of physometric charts.

- Balance of Matter. Use of psychometric maps.

The following experiment will be filled, by using the psychometric map, that is, with the readings of the input and output hygrometers and using the psychometric table, the amount of steam in a Kg of dry air will be determined. If the airflow inserted in the tower and its pressure is known, the inserted amount of Kg of dry air can be known, and by the amount of final humidity at the outlet of the tower, the steam gained by the air when passing through the tower can be calculated. Integrating this amount into the time of the experiment, the total evaporated water can be calculated, and it should be equal to the measure of the water tank.

- Balance of energy.

To determine the given or dragged energy by the air, the psychometric map should be used again. This heat gained by the airflow must be equal to the given heat by the mass of water against the air.

- The tower design for Part 2:

The tower design is done using the following steps.

1. The enthalpy of saturated air H_{y1} is plotted versus T_i on an H versus T plot. This enthalpy is calculated by using the saturation humidity from the humidity chart for a given temperature, with 0°C (273K) as a base temperature. Calculated values are tabulated in Appendix A2.
2. Knowing the entering air conditions T_{G1} and H_1, the enthalpy of this air H_{y1} is calculated. The point H_{y1} and T_{L1} (desired leaving water temperature) is plotted as one point on the operating line. The operating line is plotted with a slope Lc_L/G and ends at point T_{L2}, which is the entering water temperature. This gives H_{y2}.
3. Sketch the operating line with maximum slope then find the minimum value of the air flow rate.

5. NOMENCLATURE

a	: contact area,m^2/m^3 tower volume
c_s	: Humid heat of an air-water vapor mixture
E	: The enthalpy of air
h'	: Enthalpy of saturated air at water temperature
h	: Enthalpy of air stream
h_a	: Absolute humidity
h_r	: Relative humidity
H_Y	: Total enthalpy of an air-water vapor mixture
H_A %	: Percentage Humidity
H_R %	: Relative Humidity
H_S	: Saturation Humidity
K	: mass-transfer coefficient
L	: water flow rate
P_A^o	: Partial Pressure
P_A	: Vapor Pressure
p_s	: Pressure of steam in air.
P_{sat}	: Saturation pressure of steam to the temperature of the wet bulb
P_t	: Total pressure of the air
T_1 and T_2	: entering and leaving water temperatures
T_S	: Adiabatic Saturation Temperature
T_{dew}	: Dew Point Temperature
T_S	: Temperature of the dry bulb (°C)
T_H	: Temperature of the wet bulb (°C)
T_{dp}	: Dew point
T_{db}	: Dry-bulb temperature
T_{wb}	: Wet-bulb temperature
V_H	: Humid Volume
V	: active cooling volume, m^3/m^2 of plan area

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DATA SHEET

Name/Surname: Date:

Group No:

Assistant:

System 1: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6

System 2: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6

System 3: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6

System 4: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6

6. APPENDIX

A.1 Steam Table

Vapor Pressure of Water

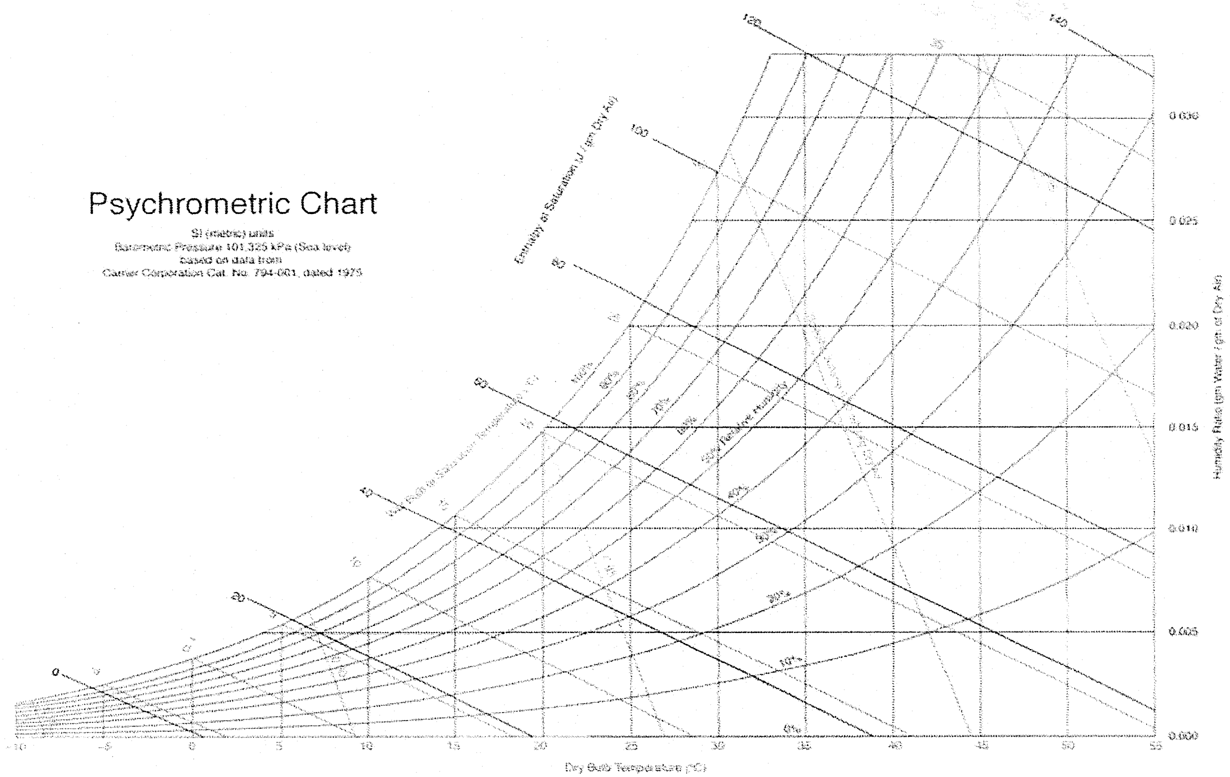
Temperature		Vapor Pressure		Temperature		Vapor Pressure	
K	°C	kPa	mm Hg	K	°C	kPa	mm Hg
273.15	0	0.611	4.58	323.15	50	12.333	92.51
283.15	10	1.228	9.21	333.15	60	19.92	149.4
293.15	20	2.338	17.54	343.15	70	31.16	233.7
298.15	25	3.168	23.76	353.15	80	47.34	355.1
303.15	30	4.242	31.82	363.15	90	70.10	525.8
313.15	40	7.375	55.32	373.15	100	101.325	760.0

Source: Physikalish-technishe, Reichsansalt, Holborn, Scheel, and Henning, *Warmetabellen*, Brunswick, Germany: Friedrich Viewig and Son, 1909.

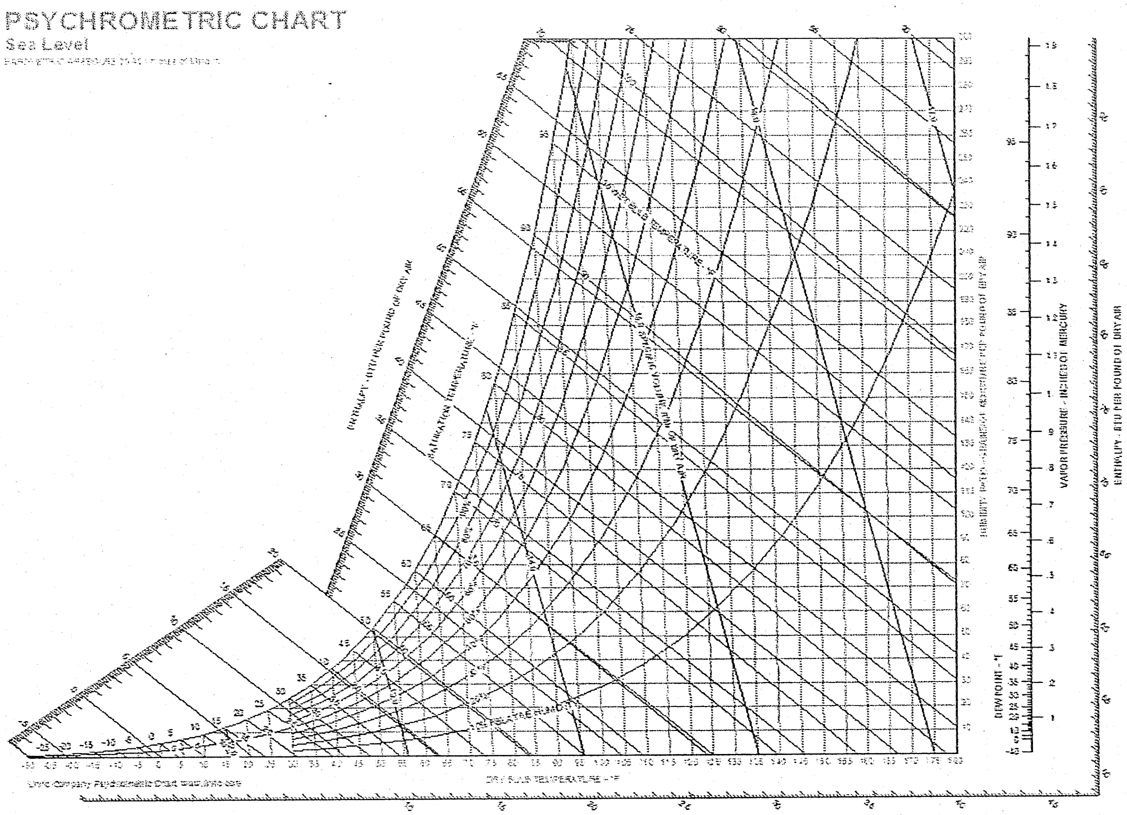
A.2 Enthalpies of Saturated Air-Water Vapor Mixtures

T_L		H_y		T_L		H_y	
		btu	J			btu	J
°F	°C	lb_m dry air	kg dry air	°F	°C	lb_m dry air	kg dry air
60	15.6	18.78	43.68×10^3	100	37.8	63.7	148.2×10^3
80	26.7	36.1	84.0×10^3	105	40.6	74.0	172.1×10^3
85	29.4	41.8	97.2×10^3	110	43.3	84.8	197.2×10^3
90	32.2	48.2	112.1×10^3	115	46.1	96.5	224.5×10^3
95	35.0	55.4	128.9×10^3	140	60.0	198.4	461.5×10^3

A3: Humidity Chart For Air-Water Vapor System In SI Units[7]



Appendix A4: Humidity Chart For Air-Water Vapor System In American Engineering Units[8]



SAMPLE CALCULATION

System 1: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6	H_i	H_o	Hs_i	Hs_o	$(T_d)_i$	$(T_d)_o$	Cs_i	Cs_o	Vh_i	Vh_o	$\%H_i$	$\%H_o$

System 2: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6	H_i	H_o	Hs_i	Hs_o	$(T_d)_i$	$(T_d)_o$	Cs_i	Cs_o	Vh_i	Vh_o	$\%H_i$	$\%H_o$

System 3: Air Velocity: Water Velocity:

t	ST2	ST7	ST3	ST4	ST5	ST6	H_i	H_o	Hs_i	Hs_o	$(T_d)_i$	$(T_d)_o$	Cs_i	Cs_o	Vh_i	Vh_o	$\%H_i$	$\%H_o$

-Material Balance

System	Vair (kg/s)	ST3	ST4	ST5	ST6	H_i Input (kg/kg)	H_o Output (kg/kg)	Steam (kgs/kg)
1								
2								
3								

-Energy Balance

System	Vair (kg/s)	Vwater (kg/s)	$Enthalpy_A$ (kJ/kg)	$Enthalpy_B$ (kJ/kg)	ST2	ST7	ΔEair	ΔEwater	Qlost
1									
2									
3									

where:

$\Delta Hair = m_a (E_B - E_A)$

$\Delta Hwater = m_{water} Cp (ST7-ST2)$ Cp:4.18 kJ/kg