Chemical Engineering Operations

Humidification and water cooling

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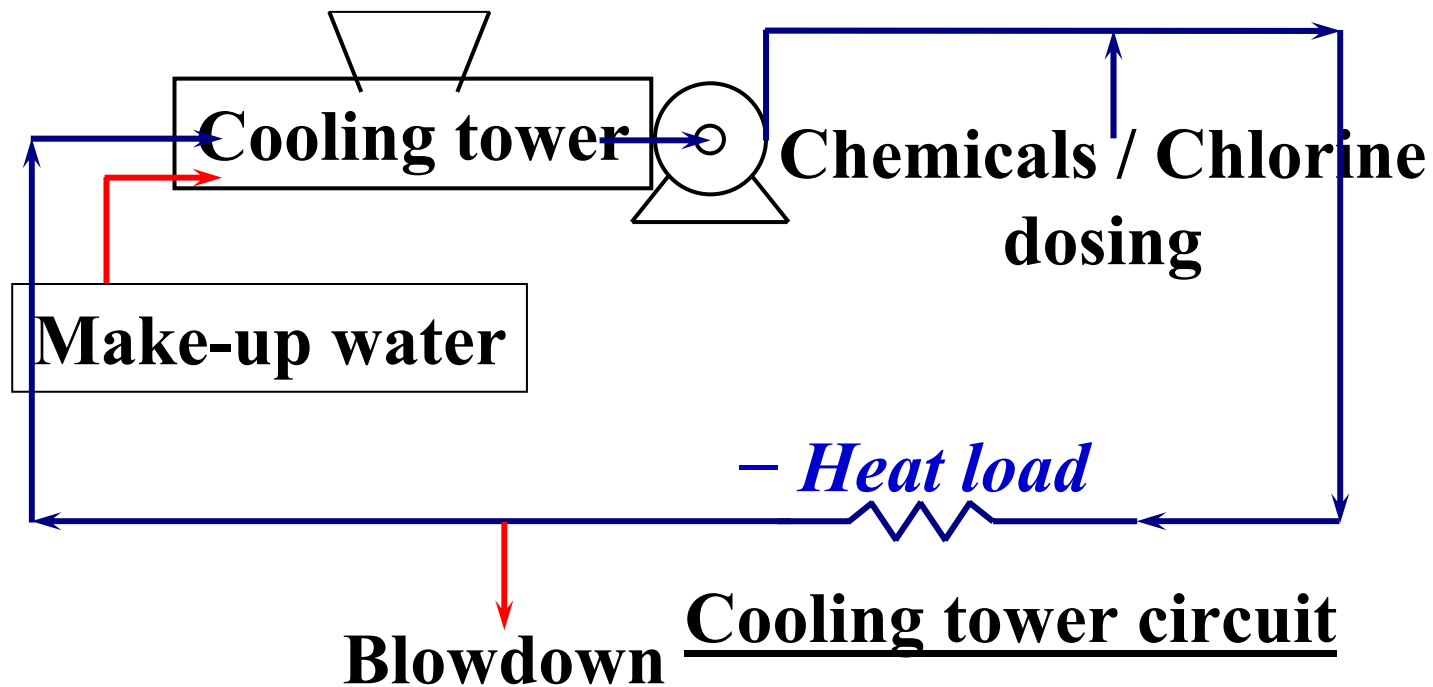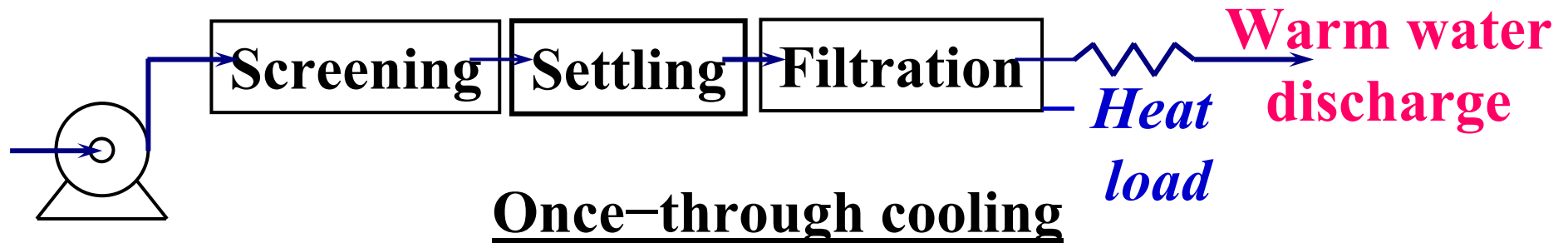**Nathalal M. Parikh Road**
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Water Cooling

- **Heat exchangers, condensers, and other types of coolers.**

- **Cooling water: to remove unusable heat from process streams.**

- **Cooling water has 2 types: (i) raw water, (ii) treated water.**

- **Raw water: from rivers, lakes, tube wells.**

- **Treated water: from water treatment plant in which the hardness and dissolved substances are removed from raw water.**

- **With treated water, the problems of fouling (scale formation) and corrosion of heat transfer surfaces are minimised.**

- **If raw water is available unlimited, then once-through cooling can sometimes be used. However, the hot water cannot always be discharged into natural water bodies.**

- **Conservation of water: by cooling the hot (warm) water, and reusing it.**

Cooling Water Systems

Screening → **Settling** → **Filtration** → *Heat load* → **Warm water discharge**

Once−through cooling

Cooling tower → **Chemicals / Chlorine dosing**

Make-up water

− *Heat load*

Blowdown **Cooling tower circuit**

- **Warm water from heat exchangers (cooling water), reactors (exothermic heat removal and/or cooling) is reused after evaporative cooling.**

- **Evaporative cooling: done by direct contact with air in cooling towers. Latent heat.**

- **In evaporative cooling, the latent heat of vaporisation is supplied mostly by the water to be cooled.**

- **Main losses of water are due to evaporative cooling (cooling by 540 kcal $\equiv$ 1 kg water evaporated) $\Rightarrow$ Small quantity of make-up water is necessary.**

Humidification:

- **To increase the amount of vapour present in a gas stream.**

- **Vapour content may be increased by passing the gas over a liquid which then evaporates into the gas stream.**

- **This transfer takes place by diffusion, and at the interface simultaneous heat and mass transfer take place.**

Dehumidification:

- **To reduce the vapour present in a gas stream.**

- **Partial condensation must be effected and the condensed vapour is removed.**

- **This transfer takes place by diffusion, and at the interface simultaneous heat and mass transfer take place.**

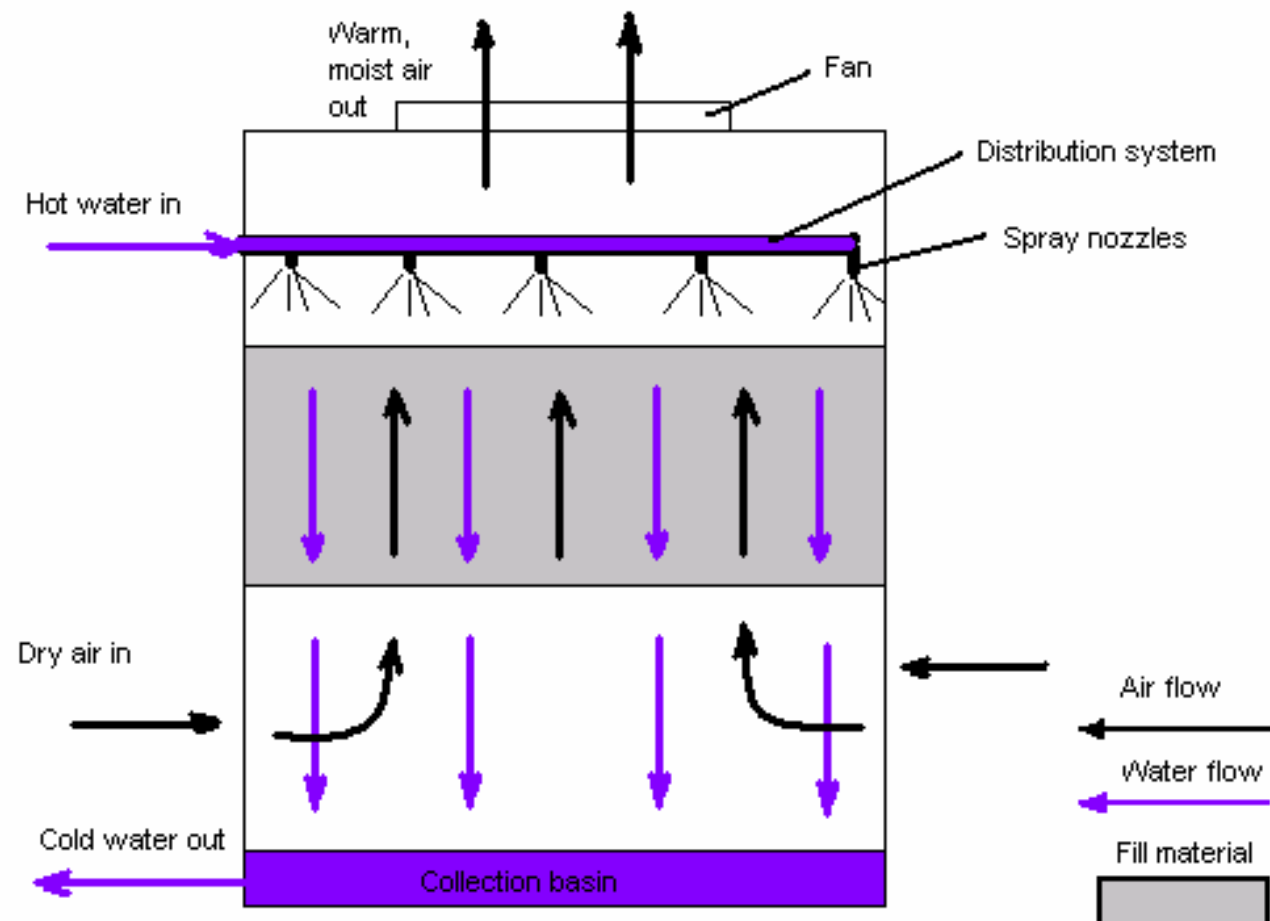# Examples of humidification and dehumidification

- **Drying of wet solids (humidification of air); however, reduction of the moisture content of the solids is the main objective.**

- **Air conditioning: dehumidification.**

- **Removal of moisture from wet Cl_2 (otherwise severely corrosive for steel equipment): dehumidification.**

- **Drying of gases used in the manufacture of sulphuric acid: if the gases are passed through concentrated H_2SO_4, it is "absorption". Alternatively, dehumidification (by water condensation) can be used.**
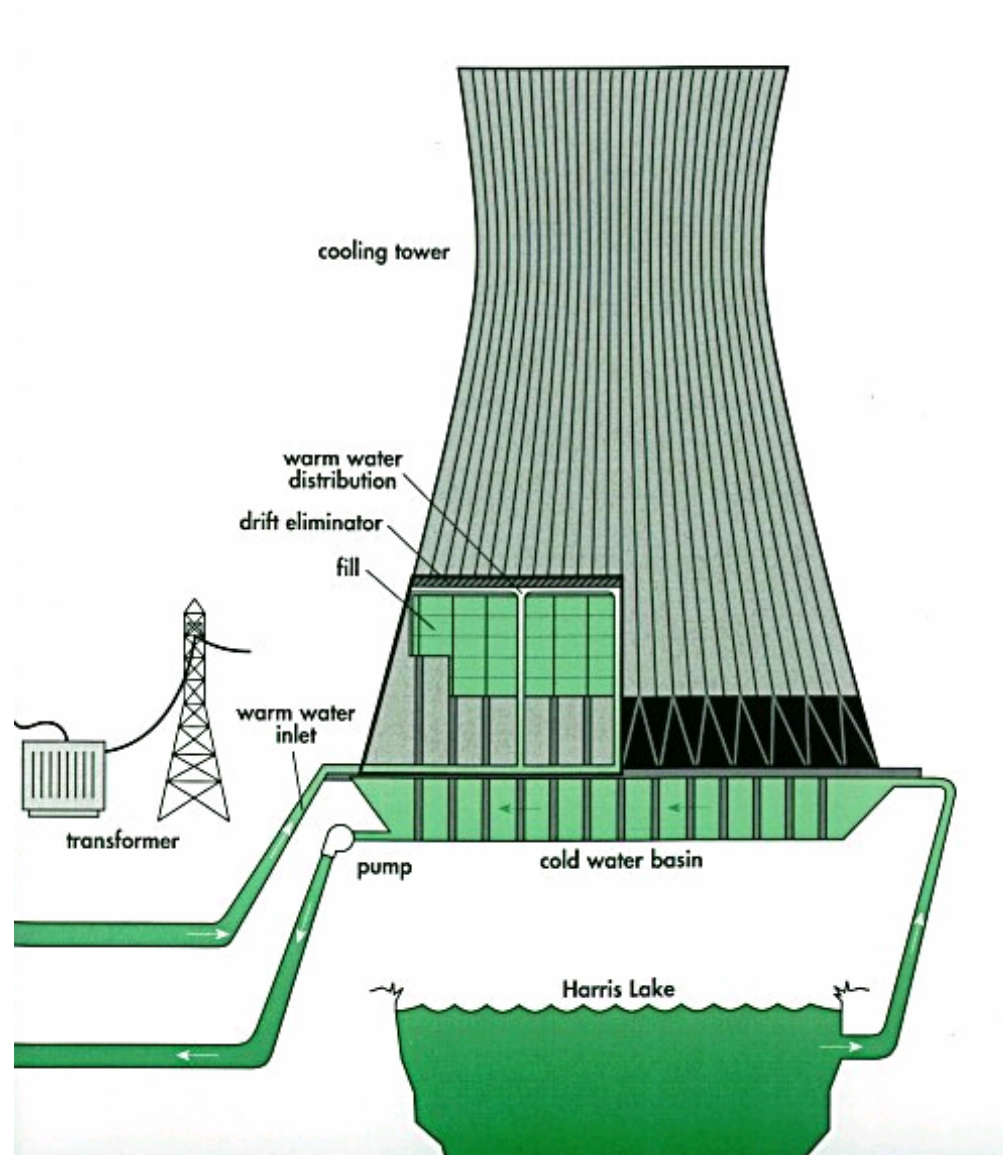
- **Example 5: ???**

- **Example 6: ???**

- **Example 7: ???**

- **Example 8: cooling of hot water returning from condensers / coolers. The main purpose is to cool water so that the same can be reused as cooling water, but the effect is humidification of air: cooling towers.**
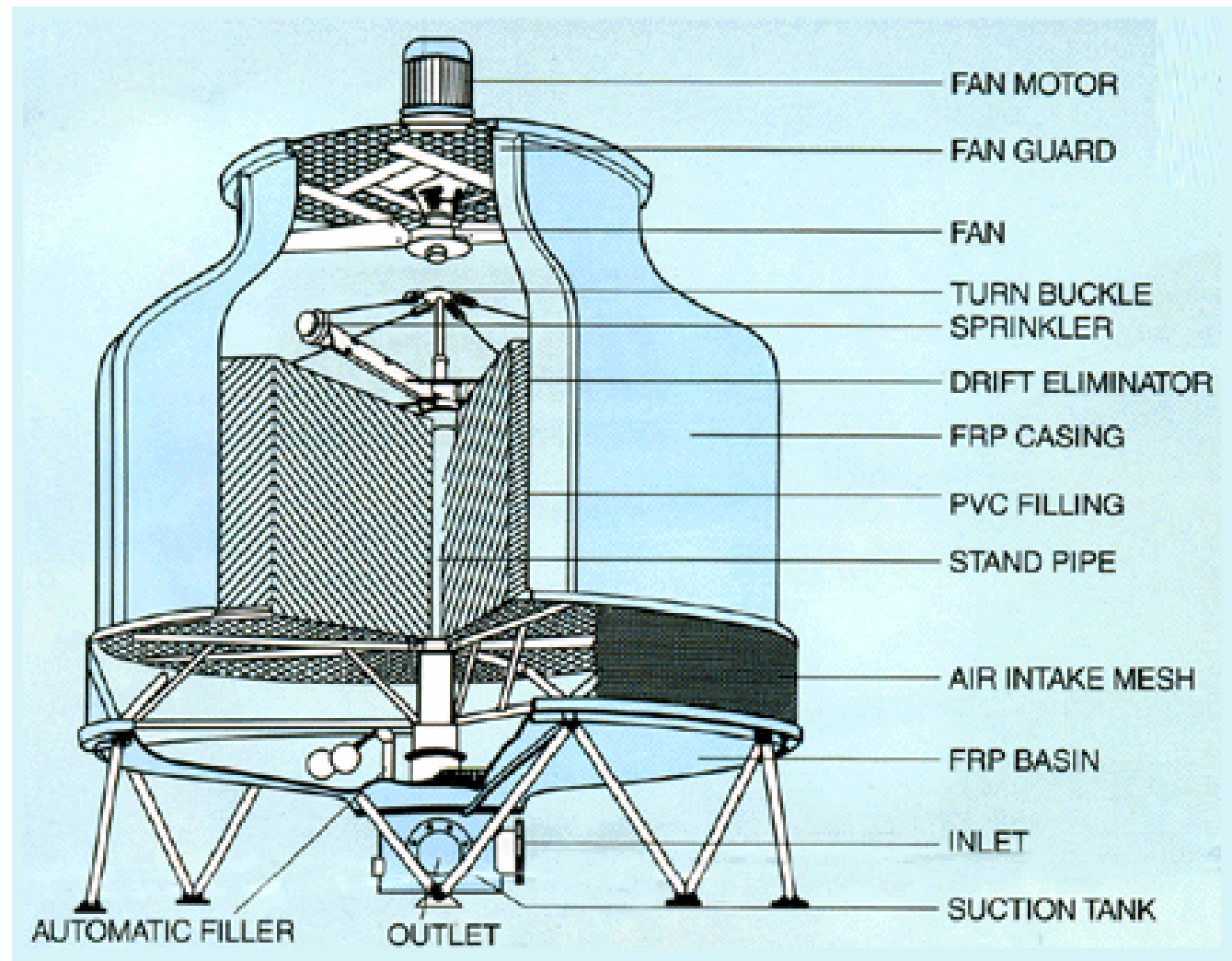
Natural draught water cooling tower

Counterflow type design

cooling tower

warm water
distribution

drift eliminator

fill

warm water
inlet

transformer

pump

cold water basin

Harris Lake

FAN MOTOR

FAN GUARD

FAN

TURN BUCKLE
SPRINKLER

DRIFT ELIMINATOR

FRP CASING

PVC FILLING

STAND PIPE

AIR INTAKE MESH

FRP BASIN

INLET

SUCTION TANK

AUTOMATIC FILLER

OUTLET

DRIFT
ELIMINATOR

MOTOR

FAN

CEPL

NOZZLE

INLET
PIPE

FILL

AIR INLET

FLOAT
VALVE

OVERFLOW

DRAIN

SUCTION

PULTRUDED FRP COOLING TOWER

Air

E   D

Fan

Demister

C   Warm Water

Water Distributor

Process Heat Exchange
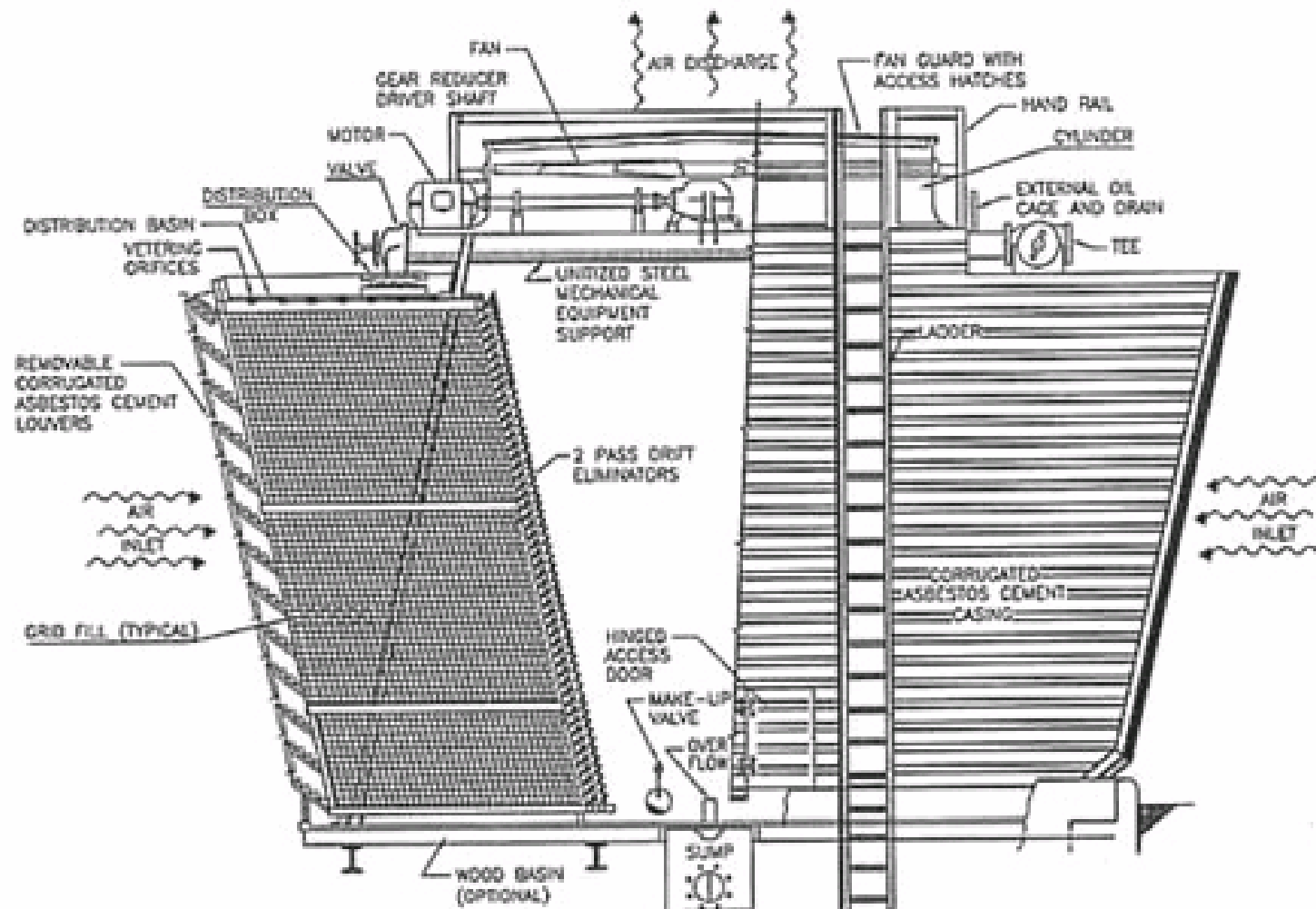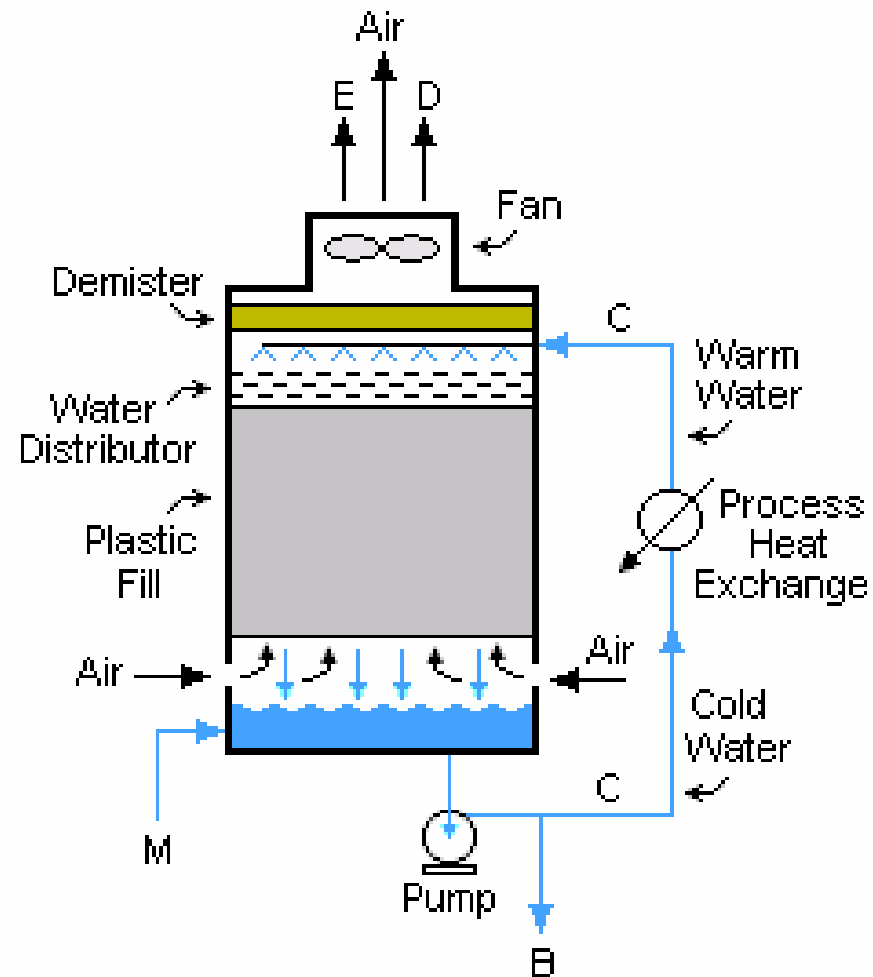
Plastic Fill

Air   Air

Cold Water

M

C

Pump

B

C = Circulating cooling water
M = Makeup water
E = Evaporated water
D = Drift or windage water loss
B = Blowdown or drawoff water

Humidification and water cooling

- **If hot water from a condenser / cooler is to be re-used, it is generally cooled by direct contact with air stream.**

- **The equipment is of the form of a tower in which the hot water enters at the top and flows downwards over a packing with a countercurrent flow of air entering at tower bottom.**

- **Let us first consider basic definitions of various quantities involved in humidification: wet-bulb temperature and adiabatic saturation temperature and also the way in which humidity data are presented on charts and graphs.**

- **While the present discussion is devoted to the very important air-water system, which is in some ways unique, the same principles may be applied to other liquids and gases.**

Vapour pressure of water and humidity

- Many times, it is necessary to make calculations involving the properties of mixtures of water vapour and air.

- These calculations involve knowledge of the concentration of water vapour in air under various conditions of T and P, the thermal properties of these mixtures, and the changes occurring when this mixture is brought into contact with water or with wet solids in drying.

- **Humidification involves the transfer of water from the liquid phase into a gaseous mixture of air and water vapour.**

- **Dehumidification involves the reverse transfer, whereby water vapour is transferred from the vapour state to the liquid state.**

- **Humidification and dehumidification can also refer to vapour mixtures of materials such as benzene, but most practical applications occur with water.**

Vapour pressure of water and physical states

- **Pure water can exist in three different physical states: solid ice, liquid, and vapour. The physical state in which it exists depends on the pressure and temperature.**

- **The Figure on the next slide illustrates the various physical states of water and the pressure-temperature relationships at equilibrium.**

- **The regions of the solid, liquid, and vapour states are shown.**

- **Along the line AB, the phases liquid and vapour coexist.**

- Along line **AC**, the phases ice and liquid coexist.

- Along line **AD**, ice and vapour coexist.

- If ice at **point (1)** is heated at constant pressure, the temperature rises and the physical condition is shown moving horizontally.

- As the line crosses **AC**, the solid melts, and on crossing **AB** the liquid vaporises.

- Moving from **point (3) to (4)**, ice sublimes (vaporises) to a vapour without becoming a liquid.

- Liquid and vapour coexist in equilibrium along the line **AB**, which is the vapour pressure line of water.

- **Boiling occurs when the vapour pressure of the water is equal to the total pressure above the water surface.**

- **For example, at 100 ^{0}C (212 ^{0}F) the vapour pressure of water is 101.325 kPa (1.0 atm), and hence it will boil at 1 atm pressure.**

- **At 65.6 ^{0}C (150 ^{0}F), the vapour pressure of water is 25.7 kPa (3.72 psia). Hence, at 25.7 kPa and 65.6 ^{0}C, water will boil.**

- **If a pan of water is held at 65.6 ^{0}C in a room at 101.325 kPa abs pressure, the vapour pressure of water will again be 25.7 kPa.**

- **Vapour pressure of water is not influenced by the presence of an inert gas such as air.**

- **That is, the vapour pressure of water is essentially independent of the total pressure of the system.**

Phase diagram for water
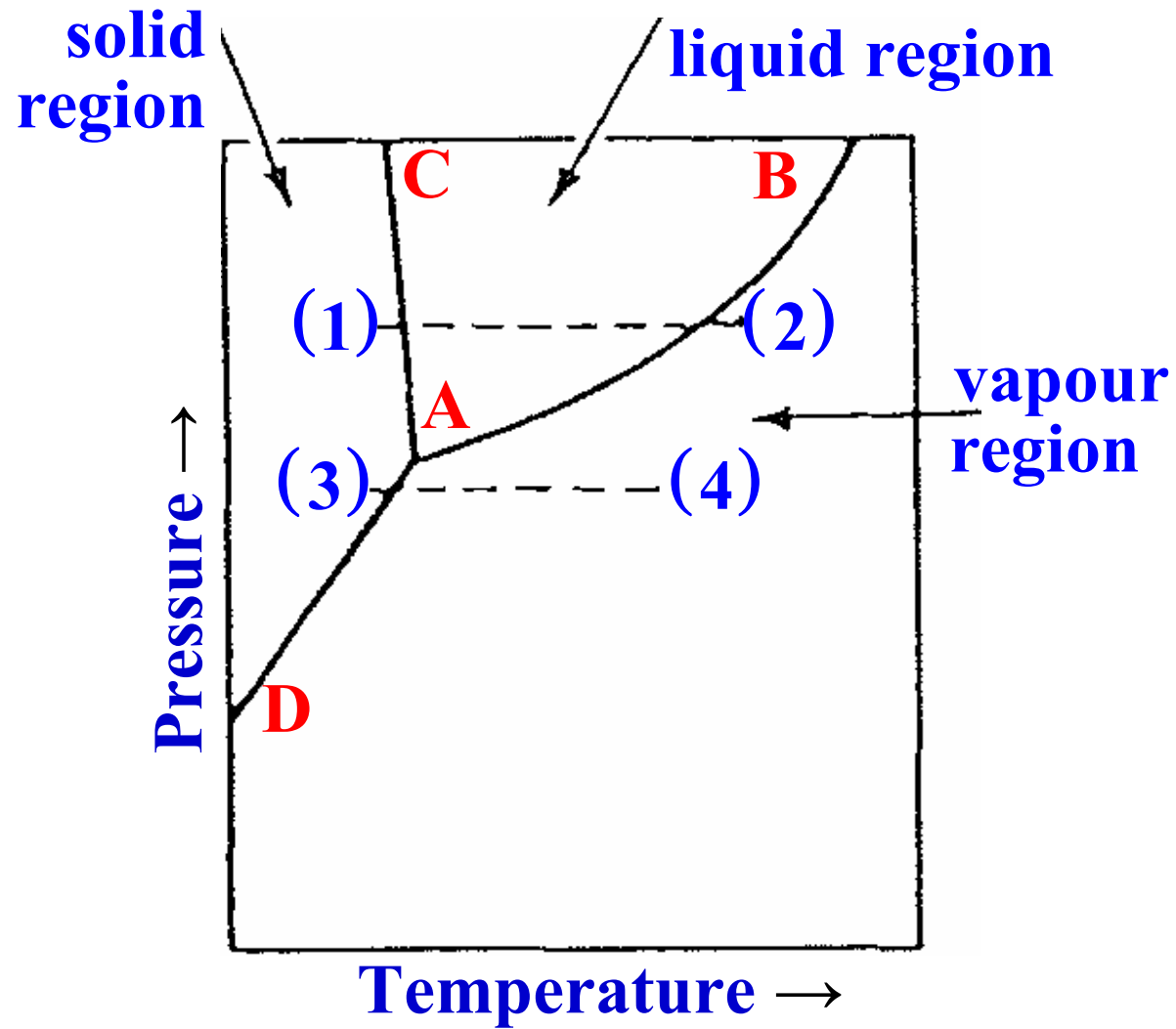
Humidity and Humidity Chart:

- **Definition of humidity**: The humidity **H** of an air-water vapour mixture is defined as the kg of water vapour contained in 1 kg of dry air.

- The humidity depends only on the **partial pressure** p_A of water vapour in the air and on the **total pressure P** (assumed to be 101.325 kPa, 1.0 atm abs, 760 mm Hg).

- Using the molecular weight of water (A) as **18.02** and of air as **28.97**, the humdiity **H** in **kg H_2O per kg dry air** is as follows:

$$\left(\underbrace{H}_{\dfrac{\text{kg } H_2O}{\text{kg DRY air}}} \right) = \left(\dfrac{\overbrace{\dfrac{p_A}{P - p_A}}}{\text{kmol } H_2O} \right) \left(\dfrac{\overbrace{\dfrac{(MW)_A}{(MW)_B}}}{\dfrac{\text{mol wt of } H_2O}{\text{mol wt of DRY air}}} \right)$$

$$\Rightarrow \left(\underbrace{H}_{\dfrac{\text{kg } H_2O}{\text{kg DRY air}}} \right) = \left(\dfrac{\overbrace{\dfrac{p_A}{P - p_A}}}{\dfrac{\text{kmol } H_2O}{\text{kmol DRY air}}} \right) \left(\dfrac{\overbrace{\dfrac{18.02}{28.97}}}{\dfrac{\text{mol wt of } H_2O}{\text{mol wt of DRY air}}} \right)$$

$$\Rightarrow \boxed{H = \left(\dfrac{18.02}{28.97} \right) \dfrac{p_A}{P - p_A}} \dfrac{\text{kg } H_2O}{\text{kg DRY air}}$$

- **Saturated air: Air in which the water vapour is in equilibrium with liquid water at the given conditions of P and T.**

- **In this mixture, the partial pressure of the water vapour in the air-water mixture is equal to the vapour pressure P_{AS} of pure water at the given T.**

- **Hence, the saturation humidity H_S is given by,**

$$H_S = \left(\frac{18.02}{28.97}\right)\frac{p_{AS}}{P - p_{AS}}$$

- **Percentage humidity H_P is given by,**

$$H_P = 100 \frac{H}{H_S}$$

- **Percentage relative humidity H_R is given by,**

$$H_R = 100 \frac{p_A}{p_{AS}}$$

$$H_P = 100\frac{H}{H_S} = 100\frac{\left(\dfrac{18.02}{28.97}\right)\left(\dfrac{p_A}{P-p_A}\right)}{\left(\dfrac{18.02}{28.97}\right)\left(\dfrac{p_{AS}}{P-p_{AS}}\right)}$$

$$\Rightarrow H_P = 100\frac{\left(\dfrac{p_A}{P-p_A}\right)}{\left(\dfrac{p_{AS}}{P-p_{AS}}\right)} \Rightarrow \boxed{H_P = 100\frac{p_A\left(P-p_{AS}\right)}{p_{AS}\left(P-p_A\right)}}$$

$$\Rightarrow \boxed{H_P \neq H_R}$$

Example: Humidity from vapour pressure data

- The air in a room is at **26.7 ^{0}C** and a pressure of **101.325 kPa** and contains water vapour with a partial pressure **p_A = 2.76 kPa**. Calculate the following:

- Humidity, **H**.

- Saturation humidity, **H_S**; percentage humidity **H_P**.

- Percentage relative humidity, **H_R**.

- **Given**: Vapour pressure of water at **26.7 ^{0}C = p_{AS} = 3.50 kPa**.

- $p_A = 2.76$ kPa; $P = 101.325$ kPa; $p_{AS} = 3.5$ kPa

<u>Humidity:</u>

$$H = \left(\frac{18.02}{28.97}\right)\frac{p_A}{P - p_A} = \left(\frac{18.02}{28.97}\right)\frac{2.76}{101.325 - 2.76}$$

$$\Rightarrow \boxed{H = 0.017418 \ \frac{\text{kg H}_2\text{O}}{\text{kg DRY air}}}$$

Saturation Humidity:

$$H_S = \left(\frac{18.02}{28.97}\right)\frac{p_{AS}}{P - p_{AS}} = \left(\frac{18.02}{28.97}\right)\frac{3.5}{101.325 - 3.5}$$

$$\Rightarrow \boxed{H_S = 0.022255 \ \frac{\text{kg H}_2\text{O}}{\text{kg DRY air}}}$$

Percentage Humidity:

$$H_P = 100\frac{H}{H_S} = 100\frac{0.017418}{0.022255} \Rightarrow \boxed{H_P = 78.27}$$

Percentage Relative Humidity:

$$H_R = 100 \frac{p_A}{p_{AS}} = 100 \frac{2.76}{3.5} \Rightarrow \boxed{H_R = 78.86}$$

Dew point of air-water vapour mixture:

- **Dew point**: The temperature at which a given mixture of air and water vapour would be saturated is called the dew point temperature or the dew point.

- For example, at **26.7 ^{0}C**, the saturation vapour pressure of water is **p_{AS} = 3.50 kPa**.

- Hence, the dew point of a mixture containing water vapour having a partial pressure of **3.50 kPa is 26.7 ^{0}C**.

- **If an air-water vapour mixture is at $37.8\ {}^0C$ (often called the dry bulb temperature, since this is the actual temperature a dry thermometer bulb would indicate in this mixture) and contains water vapour of $p_A = 3.50\ \text{kPa}$, the mixture would not be saturated.**

- **On cooling to $26.7\ {}^0C$, the air would be saturated, that is, at the dew point. On further cooling, some water vapour would condense, since the partial pressure cannot be greater than the saturation vapour pressure.**

Humid heat of air-water vapour mixture:

- ## Humid heat c_S:

- **The humid heat c_S is the amount of heat in J (or kJ) required to raise the temperature of 1 kg of dry air plus the water vapour present by 1 K or 1 ^{0}C. The heat capacity of air and water vapour can be assumed constant [at 1005 J/(kg dry air.K) and (1880 J/kg water vapour.K, respectively] over the temperature ranges usually encountered. In SI units,**

$$\dfrac{\underbrace{c_S}_{kJ}}{\left(\begin{array}{c}\text{kg dry air}\\\text{with water vapour}\end{array}\right)(K)} = 1.005 + 1.880\,(H)$$

where, $\boxed{H = \left(\dfrac{18.02}{28.97}\right)\dfrac{p_A}{P - p_A}}\ \dfrac{\text{kg } H_2O}{\text{kg DRY air}}$

Humid volume of air-water vapour mixture:

- **Humid volume**: The humid volume v_H is the total volume in m^3 of **1 kg of dry air PLUS the water vapour** it contains at **101325 Pa (1.0 atm)** absolute pressure and the given temperature.

- Using ideal gas law,

$$\frac{v_H\left[\dfrac{}{}\right]}{m^3} \middle/ \binom{\text{kg dry air}}{\text{with water vapour}} = \frac{22.414}{273.15}\left(\frac{1}{28.97} + \frac{H}{18.02}\right)\frac{(T)}{K}$$

$$\Rightarrow \quad \underbrace{v_H}_{\dfrac{m^3}{\left(\substack{\textbf{kg dry air} \\ \textbf{with water vapour}}\right)}} = \left(0.002832 + 0.004554\,H\right)\underbrace{(T)}_{K}$$

- In the case of <u>air saturated with water vapour</u>, replace H by H_S, and v_H will be saturated volume.

Total enthalpy of air-water vapour mixture:

- **Total enthalpy: The total enthalpy of 1 kg of air plus its water vapour is H, J/kg.**

- **If T_0 is the datum temperature chosen for both components, the total enthalpy is the sensible heat of the air-water mixture PLUS the latent heat λ_0 (J/kg water vapour) at T_0.**

$$\Rightarrow \quad \underbrace{H_y}_{\frac{kJ}{\left(\substack{kg\ dry\ air \\ with\ water\ vapour}\right)}} = c_S\left(T - T_0\right) + H\lambda_0$$

$$\Rightarrow \quad \underbrace{H_y}_{\left(\dfrac{kJ}{\substack{\text{kg dry air} \\ \text{with water vapour}}}\right)} = \left[1.005 + 1.880\,(H)\right]\left(T - T_0\right) + (H)\lambda_0$$

- If the datum temperature is 0 ^{0}C, then the above equation becomes,

$$\Rightarrow \quad \underbrace{H_y}_{\left(\dfrac{kJ}{\substack{\text{kg dry air} \\ \text{with water vapour}}}\right)} = \left[1.005 + 1.880\,(H)\right](T) + 2501.4\,(H)$$

Humidity chart of air-water vapour mixture:

- A convenient chart of the properties of air-water vapour mixtures at **1.0 atm abs pressure** is the humidity chart (see Figure on the next slide).

- In this Figure, the humidity **H is plotted versus the actual T** of the air-water vapour mixture (dry bulb temperature).

Humidity chart for air and water vapour mixtures at 101325 Pa (1 atm)

percentage humidity

adiabatic saturation curve

100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 5% 2%

Humidity H, (kg water vapour/kg dry air) →

Temperature T, ^{0}C →
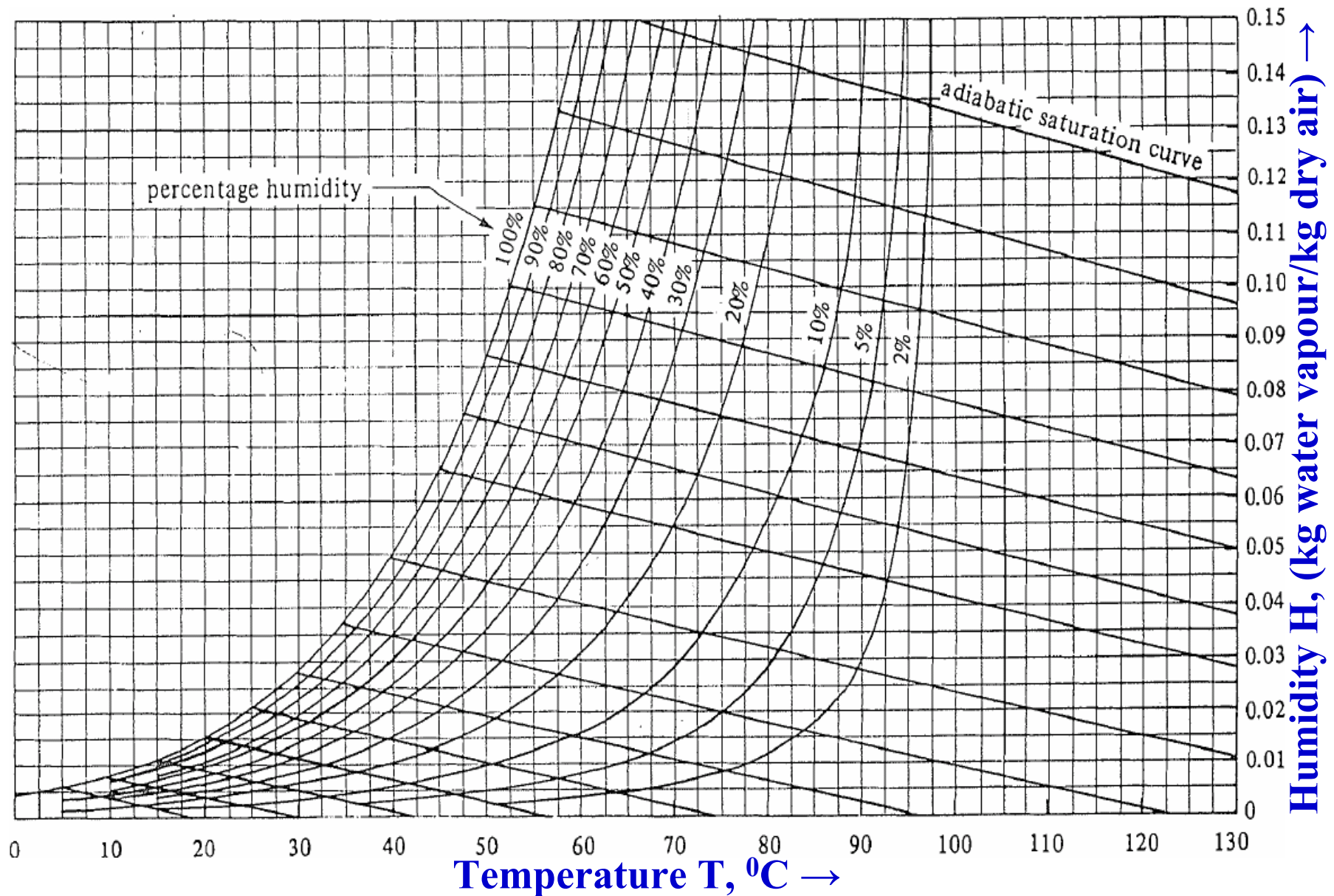
- **The curve marked 100% gives the saturation humidity H, as a function of T.**

- **Any point below the saturation line represents unsaturated air-water vapour mixtures.**

- **The curved lines below the 100% saturation line and running upward to the right represent unsaturated mixtures of definite percentage humidity H_P.**

- **Going downward vertically from the saturation line at a given temperature, the line between 100% saturation and zero humidity H (the bottom horizontal line) is divided evenly into 10 increments of 10% each.**

- **All the percentage humidity lines (H), and the saturation humidity line (H_S) can be calculated from the data of vapour pressure of water.**

Example: Use of Humidity Chart

- Air entering a dryer has a temperature (dry bulb temperature) of **60 ^{0}C** and a dew point of **26.7 ^{0}C**. Using the humidity chart, determine the actual humidity **H**, percentage humidity **H$_P$**, humid heat **c$_S$**, and the humid volume **v$_H$**.

- The dew point of **26.7 ^{0}C** is the temperature at which the mixture is **100%** saturated.

- Starting at **26.7 ^{0}C**, on the Humidity Chart (see next slide), draw a vertical line till it intersects the **100%** saturation curve.

- This gives **H = 0.0225 kg water / kg dry air** (with water vapour).

Humidity chart for air and water vapour mixtures at 101325 Pa (1 atm)
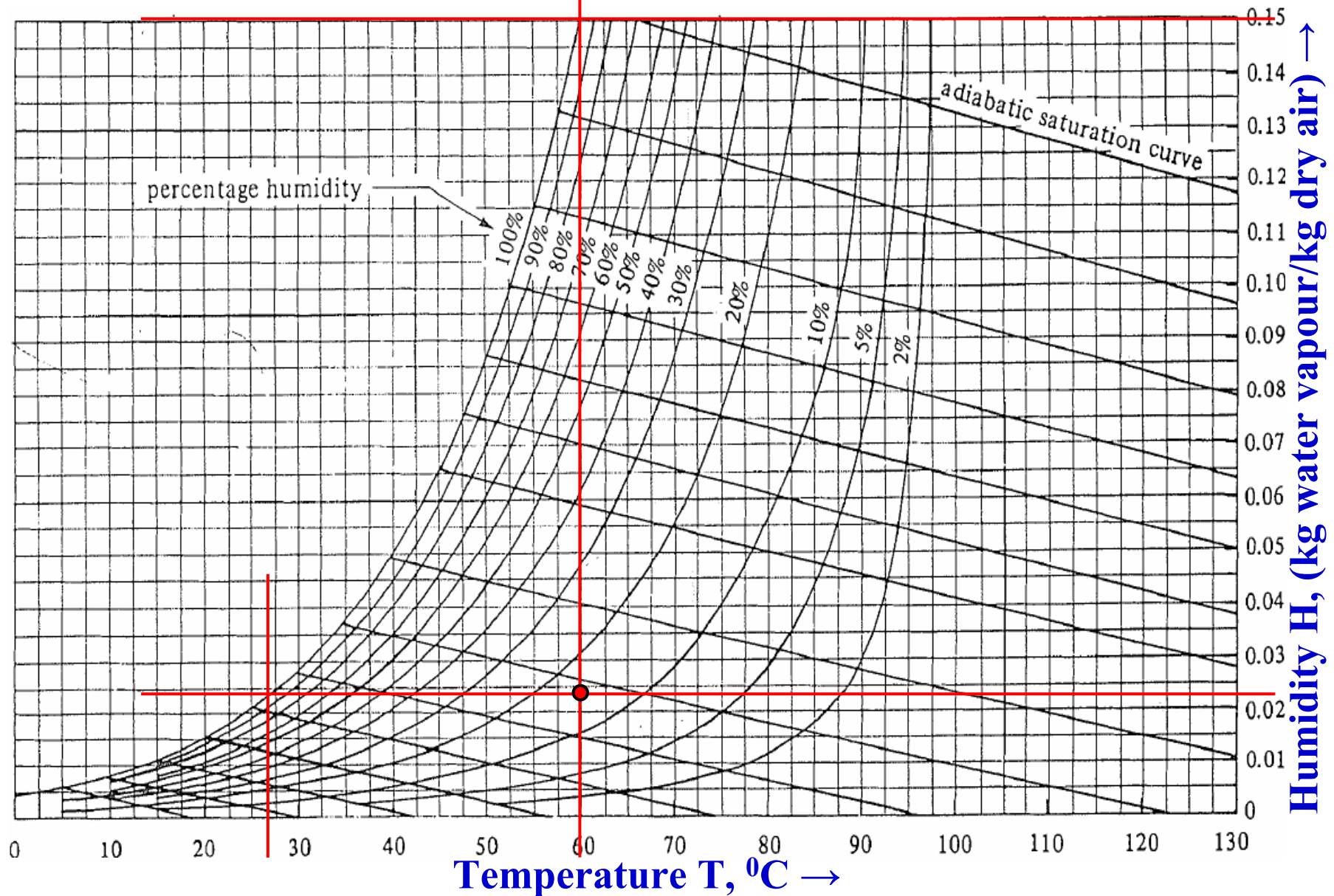
- This is the **actual humidity** of air at **60 ⁰C**.

- **Locating this point (H = 0.0225, T = 60 ⁰C) on the Humidity Chart, the Percentage Humidity (H_P) is found to be ≈ 15% (using linear interpolation vertically between 10% curve and 20% curve).**

- **The Humid Heat for H = 0.0225 is calculated from,**

$$c_S = 1.005 + 1.880(H) \Rightarrow c_S = 1.005 + 1.880(0.0225)$$

$$\Rightarrow c_S = 1.005 + 1.880(0.0225)$$

$$\Rightarrow c_S = 1.0473 \; \frac{kJ}{\left(\begin{array}{c} kg \; dry \; air \\ with \; water \; vapour \end{array}\right)(K)}$$

- **The Humid Volume for $H = 0.0225$ is calculated from,**

$$v_H = \frac{22.414}{273.15}\left(\frac{1}{28.97} + \frac{H}{18.02}\right)\frac{(T)}{K}$$

$$\Rightarrow v_H = \frac{22.414}{273.15}\left(\frac{1}{28.97} + \frac{0.0225}{18.02}\right)(T)$$

$$\Rightarrow v_H = 0.9778 \ \frac{m^3}{\left(\begin{array}{c}kg\ dry\ air \\ with\ water\ vapour\end{array}\right)}$$

Adiabatic saturation temperatures:

- **Consider a process shown (see Figure on next slide), where the entering gas of the air-water vapour mixture is contacted with a water-spray.**

- **The gas leaves with a different humidity and T, and consider the process to be adiabatic.**

- **The water is recirculated, with (obviously) some make-up water added.**

Adiabatic air-water vapour saturator
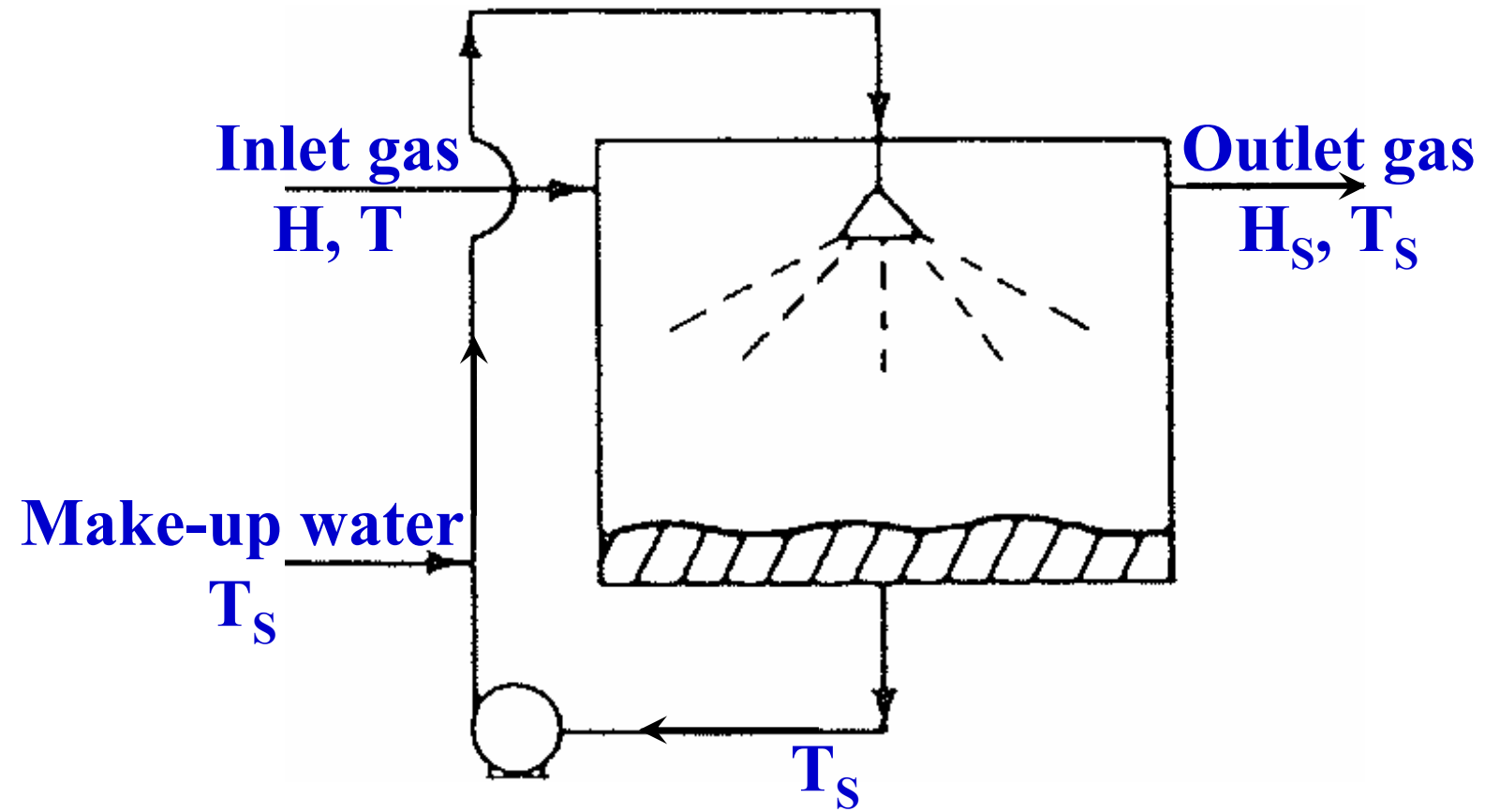
- The temperature of the water being recirculated reaches a <u>steady-state temperature</u> called the <u>adiabatic saturation temperature</u>, T_S.

- If the entering gas at temperature T having a humidity of H is not saturated, T_S will be lower than T.

- If the contact between the entering gas and the spray of droplets is enough to bring the gas and liquid to equilibrium, the leaving air is saturated at T_S, having a humidity H_S.

- **For the sake of convenience, while writing an enthalpy balance (heat balance) over the process, a datum of T_S is used.**

- **The enthalpy of the makeup water is then zero.**

- **This means,**

$$\underbrace{c_S\left(T-T_S\right)+H\lambda_S}_{\substack{\text{total enthalpy of} \\ \text{entering gas mixture}}} = \underbrace{c_S\left(T_S-T_S\right)+H_S\lambda_S}_{\substack{\text{total enthalpy of} \\ \text{leaving gas mixture}}}$$

$$\Rightarrow \frac{\left(H-H_S\right)}{\left(T-T_S\right)} = -\frac{c_S}{\lambda_S} = -\frac{1.005+1.880\left(H\right)}{\lambda_S}$$

$$\frac{(H - H_S)}{(T - T_S)} = -\frac{1.005 + 1.880(H)}{\lambda_S}$$

- This the Equation of an "adiabatic humidification curve".

- This curve passes through the point (T_S, H_S) on the 100% saturation curve, and other points (T, H).

- These series of curves, running upward to the left, are called adiabatic humidification lines or adiabatic saturation lines.

- Since c_S contains the term H, these adiabatic curves are not quite straight.

- If a given gas mixture at (T_1, H_1) is contacted for a sufficiently long time in an adiabatic saturator, it will leave saturated at (T_{S1}, H_{S1}).

- The values of H_{S1} and T_{S1} are determined by following the adiabatic saturation line going through point (T_1, H_1) until it intersects the 100% saturation line.

- If contact is not suflicient, the leaving mixture will be at a percentage saturation less than 100 but on the same line.

Example: Adiabatic Saturation of Air

- An air stream at **87.8 °C** having a humidity **H = 0.030 kg H_2O/kg dry air** is contacted in an adiabatic saturator with water. It is cooled and humidified to **90% saturation**.

- What are the final values of **H and T** ?

- For **100% saturation**, what would be the values of **H and T** ?

- The point (**T = 87.8 °C, H = 0.030**) is located on the humidity chart (see Figure on next slide).

Humidity chart for air and water vapour mixtures at 101325 Pa (1 atm)
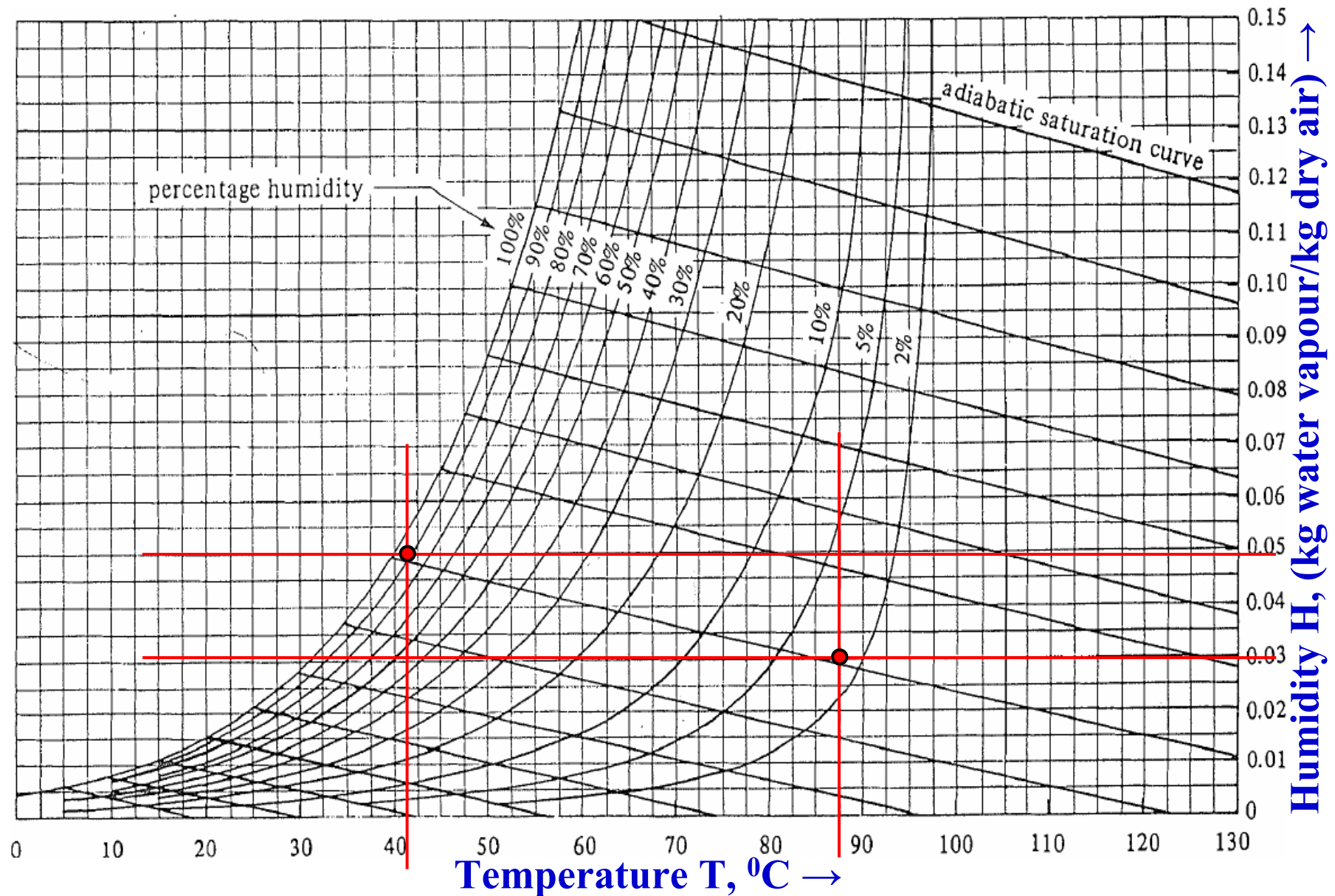
- The adiabatic saturation curve through this point is followed upward to the left until it intersects the **90% line (T ≈ 43 ^{0}C)**, and corresponding **H ≈ 0.048 kg water/kg dry air**.

- For **100% saturation**, the adiabatic saturation curve through the point (**T = 87.8 ^{0}C, H = 0.030**) is followed upward to the left until it intersects the **100% line (T ≈ 41 ^{0}C)**, and corresponding **H ≈ 0.05 kg water/kg dry air**.

Humidity chart for air and water vapour mixtures at 101325 Pa (1 atm)
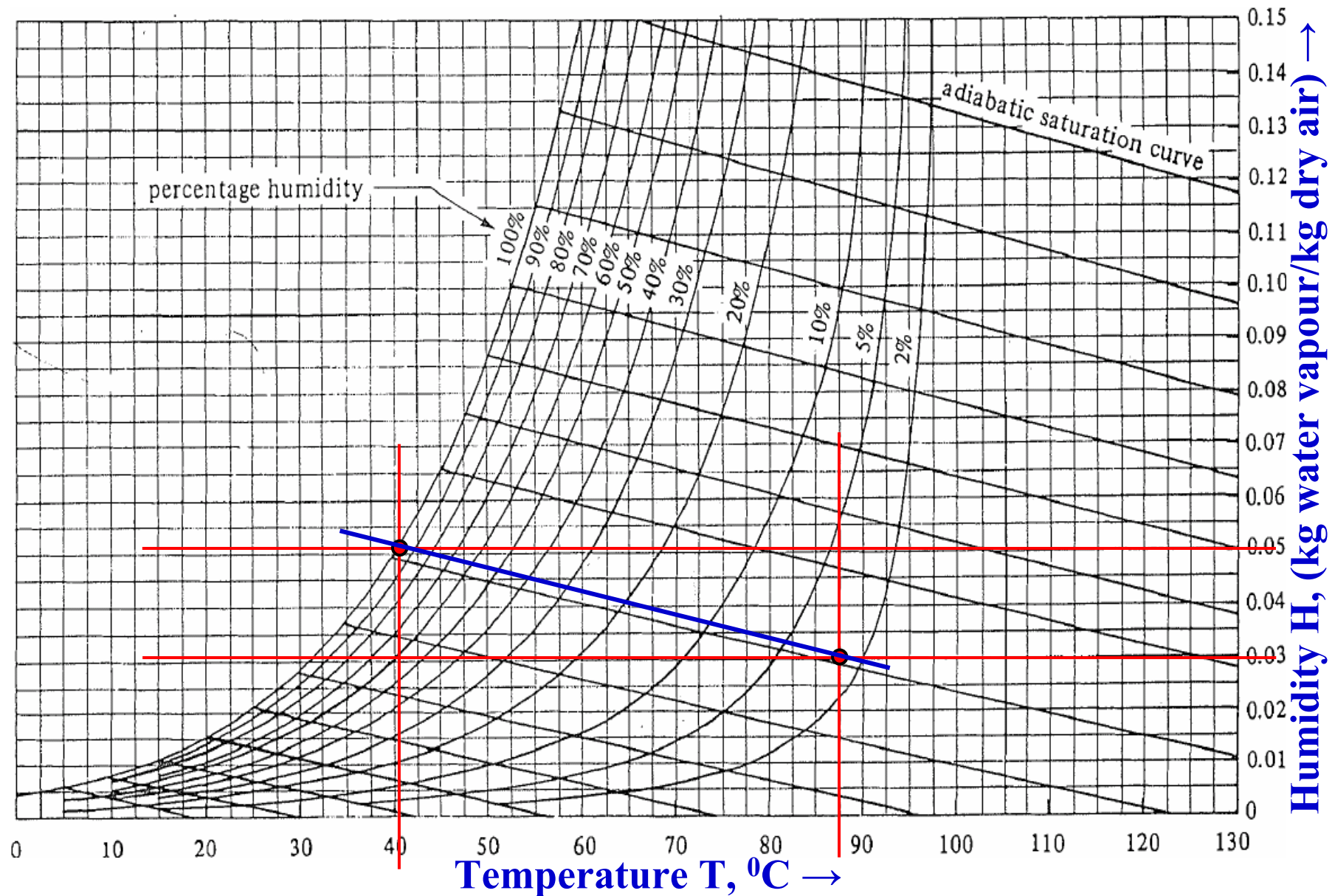
Wet Bulb Temperature:

- **Wet bulb temperature: The <u>steady-state nonequilibrium temperature</u> reached when a <u>small amount of water</u> is contacted under adiabatic conditions by a continuous stream of gas.**

  (The adiabatic saturation temperature is the steady-state temperature attained when a <u>large amount of water</u> is contacted with the entering gas).

- **Since the amount of liquid is small, the <u>T and H of the gas are not changed</u>, contrary to the adiabatic saturation case, where the T and H of the gas are changed.**

Measurement of wet bulb temperature

Thermometer reads T_W

Make-up water T_W

T_W

Gas T, H

Gas T, H
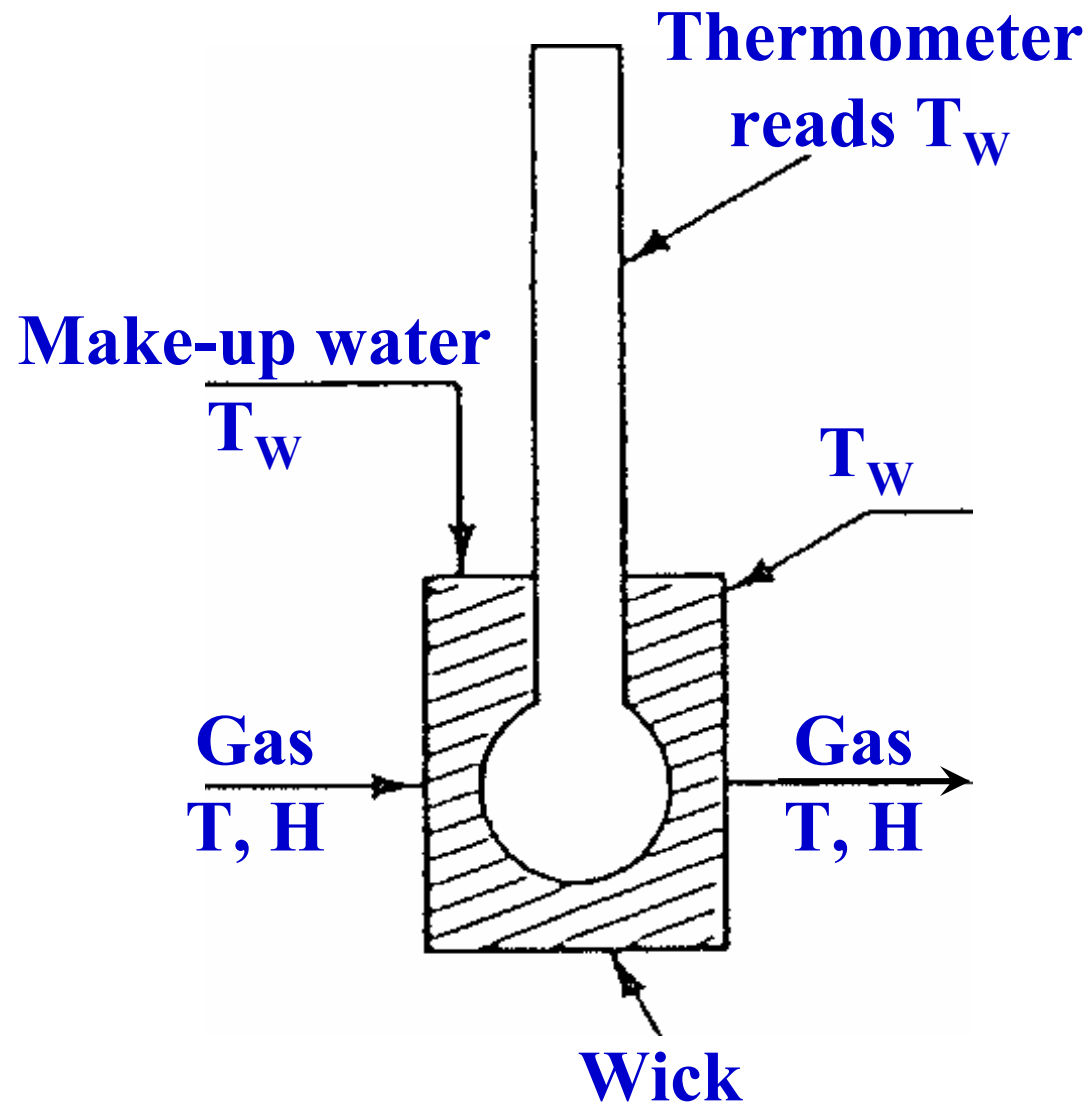
Wick

Measurement of Wet Bulb Temperature:

- **The method used to measure the wet bulb temperature is illustrated in Figure on previous slide.**

- **A thermometer is covered by a wick or cloth.**

- **The wick is kept wet by water and is immersed in a flowing stream of air-water vapour having a temperature of T (dry bulb temperature) and humidity H.**

- At steady state, water is evaporating to the gas stream.

- The wick and water are cooled to T_W, and stay at this constant temperature.

- The latent heat of evaporation is exactly balanced by the convective heat flowing from the gas stream at T to the wick at a lower temperature T_W.

- While taking heat balance on the wick, the datum temperature is taken at T_W.

- **The amount of heat lost by vaporisation, (<u>neglecting the small sensible heat change of the vaporised liquid and radiation</u>), is given by,**

$$\underbrace{Q}_{\dfrac{kJ}{s}} = \left(\underbrace{M_A}_{18.02} \quad \underbrace{N_A}_{\dfrac{kmol\ H_2O\ evaporating}{(s)\left(m^2\right)}} \quad \underbrace{\lambda_A}_{\dfrac{kJ}{kg\ H_2O}} \right) \underbrace{A}_{m^2}$$

$$N_A = k_y \left(y_W - y \right)$$

where,

$y_W = H_2O$ vapour mole fraction at gas-liquid interface

$y = H_2O$ vapour mole fraction in bulk gas phase

Also, since Air does not dissolve in water,
this is a case of diffusion of A through non-diffusing B

$$\Rightarrow N_A = \frac{k'_y}{(1-y)_{iM}}(y_W - y)$$

$$\text{where, } (1-y)_{iM} = \frac{(1-y)-(1-y_W)}{\ln\left[(1-y)/(1-y_W)\right]}$$

using usual notation

- However, for a dilute mixture (such as air-water vapour in this case), $(1-y)_{iM} \approx 1$. Hence, $k_y \approx k'_y$

- **The relation between Humidity (H) and the mole fraction of water vapour in air (y) can be derived as,**

$$y = \frac{\left(H/M_A\right)}{\left(1/M_B\right)+\left(H/M_A\right)} \approx H\frac{M_B}{M_A} \Rightarrow \boxed{y_W \approx H_W\frac{M_B}{M_A}}$$

$$\Rightarrow N_A = k_y\left(y_W - H\frac{M_B}{M_A}\right)$$

$$\Rightarrow Q = \left(M_A\left\{k_y\left(y_W - H\frac{M_B}{M_A}\right)\right\}\lambda_A\right)A$$

$$\Rightarrow Q = \left(M_A \left\{ k_y \left(y_W - H \frac{M_B}{M_A} \right) \right\} \lambda_A \right) A$$

$$\Rightarrow Q = M_A k_y y_W A \lambda_A - M_A k_y H \frac{M_B}{M_A} A \lambda_A$$

$$\Rightarrow Q = M_A k_y y_W A \lambda_A - k_y H M_B A \lambda_A$$

$$\Rightarrow Q = M_B k_y A \lambda_A \left(\frac{M_A}{M_B} y_W - H \right)$$

$$\Rightarrow \boxed{Q = M_B k_y A \lambda_A \left(H_W - H \right)}$$

- **Now, the rate of convective heat transfer from the gas stream (temperature T) to the wick (temperature T_W) is given by,**

$$Q = hA\left(T - T_W\right)$$

$$\Rightarrow M_B k_y A \lambda_A \left(H_W - H\right) = hA\left(T - T_W\right)$$

$$\Rightarrow \frac{\left(H_W - H\right)}{\left(T - T_W\right)} = \frac{h}{M_B k_y \lambda_A} \Rightarrow \frac{\left(H - H_W\right)}{\left(T - T_W\right)} = -\frac{\left(h/M_B k_y\right)}{\lambda_A}$$

$$\left(h/M_B k_y\right) = \text{psychrometric ratio} \approx 0.96 - 1.005$$

- Now, the equation of an "<u>adiabatic humidification curve</u>" is given by,

$$\Rightarrow \frac{\left(H - H_S\right)}{\left(T - T_S\right)} = -\frac{c_S}{\lambda_S} = -\frac{1.005 + 1.880\left(H\right)}{\lambda_S}$$

- The experimental values of "<u>psychrometric ratio</u>", given by $(h/M_B k_y) \approx 0.96$ to 1.005, which is close the value of c_S.

- This means that the adiabatic saturation lines can also be used for "<u>wet bulb temperature lines</u>" without much of an error.

- **Therefore, the "<u>wet bulb temperature lines</u>" is commonly used for the determination of the humidity of air-water vapour mixtures.**

- <u>**This is valid only for air-water vapour mixtures**</u>.

Continuous Humidification Processes:

- **Introduction and Types of Equipment for Humidification**

- When a relatively warm liquid is directly contacted with gas that is unsaturated, some of the liquid is vaporised.

- The liquid temperature will drop mainly because of the latent heat of evaporation.

- 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 the moisture content of air in drying or air conditioning;**

  ✓ **Dehumidifying air, where cold water condenses some water vapour from warm air;**

  ✓ **<u>Water cooling, where evaporation of water to the air cools warm water</u>.**

- **There are many cases in industry in which warm water is discharged from heat exchangers and condensers when it would be more economical to cool and reuse it than to discard it.**

Water cooling towers:

- **In a typical water cooling tower, warm water flows counter-currently to an air stream.**

- **Typically, 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 the tower and flows upward through the descending water.**

- **The tower packing often consists of slats of wood or plastic or of a packed bed.**

- The water is distributed by troughs and overflows to cascade over slat gratings or packing that provide large interfacial areas of contact between the water and air in the form of droplets and films of water.

- The flow of air upward through the tower can be induced by the buoyancy of the warm air in the tower (natural draft) or by a fan.

- The water cannot be cooled below the wet bulb temperature. The water can be cooled only to the wet bulb temperature, and in practice it is cooled to about **3 K or more above this**.

- The driving force for the evaporation of the water is approximately the **vapour pressure of the water MINUS the vapour pressure it would have at the wet bulb temperature**.

- Only a small amount of water is lost by evaporation in cooling water.

- Since the latent heat of vaporisation of water is about 2300 kJ/kg, a typical change of about 8 K in water temperature corresponds to an evaporation loss of about 1.5%.

- Therefore, the total flow of water is usually assumed to be constant in calculations of tower size.

- **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.**

- **Therefore, spray or packed towers are used to give large interfacial areas and to promote turbulence in the gas phase.**

Theory and calculations of water cooling towers:
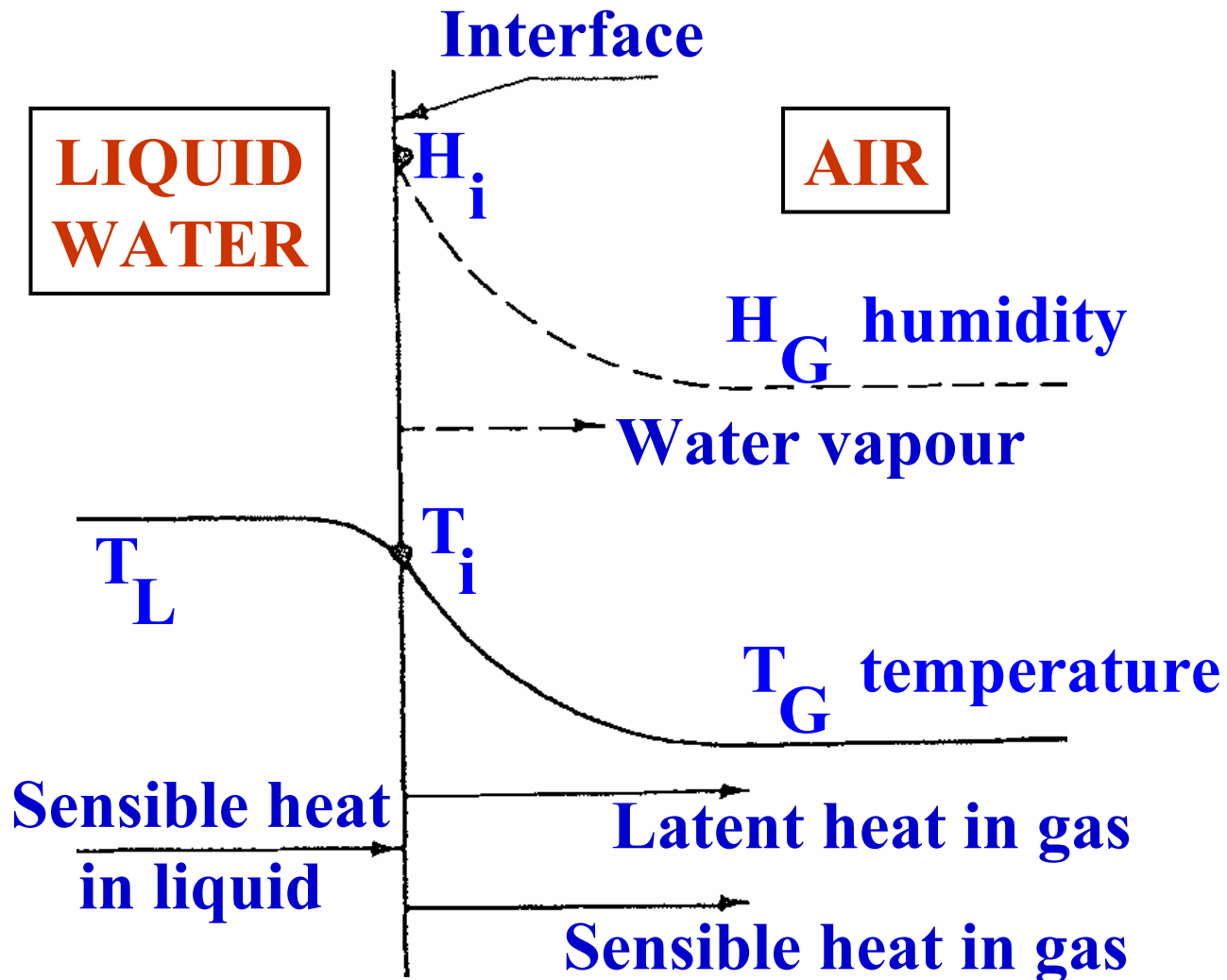
T and H profiles in upper part of cooling tower

THEORY AND CALCULATIONS OF WATER COOLING TOWERS:

- **T and H profiles**: see Figure on the next slide.

- **Water vapour diffuses from the interface to the bulk gas phase with a driving force in the gas phase of $(H_i - H_G)$ kg H_2O/kg dry air.**

- **There is no driving force for mass transfer in the liquid phase, since water is a pure liquid.**

- **The temperature driving force is $(T_L - T_i)$ in the liquid phase and $(T_i - T_G)$ in the gas phase.**

- **Sensible heat flows from the bulk liquid to the interface in the liquid.**

- **Sensible heat also flows from the interface to the gas phase.**

- **Latent heat also leaves the interface and in to the water vapour, which is diffusing to the gas phase.**

- **IMPORTANT: The sensible heat flow from the liquid to the interface equals the sensible heat flow in the gas plus the latent heat flow in the gas.**

- **These conditions (shown in the Figure on the previous slide) occur at the upper part of the cooling tower.**

- **In the lower part of the cooling tower the temperature of the bulk water is higher than the wet bulb temperature of the air but may be below the dry bulb temperature.**

- **Then the direction of the sensible heat flow is reversed.**

Rate equations for heat and mass transfer:

- **Consider a packed tower for water cooling (air flowing upward and water counter-currently flowing downward).**

- **Let specific interfacial area = $\underline{a}$, (m^2 of total interfacial area per m^3 of packed section).**

- **Let gas phase mass transfer coefficient = k_G, kmol/(s. m^2 . Pa) OR kmol/(s. m^2 . atm).**

- **Then $k_G\underline{a}$ = volumetric gas phase mass transfer coefficient, kmol/(s. m^3 . Pa).**

- **Assume: adiabatic process.**

- **See Figure on next slide.**

Continuous counter-current adiabatic water cooling

G_2, T_{G2}, H_2, H_{y2}

Water

L_2, T_{L2}

$G+dG$, T_G+dT_G
$H+dH$, $H_y + dH_y$

$L+dL$, $T_L + dT_L$

dZ

G, T_G, H, H_y

L, T_L

Z

G_1, T_{G1}, H_1, H_{y1} **Air**

L_1, T_{L1}
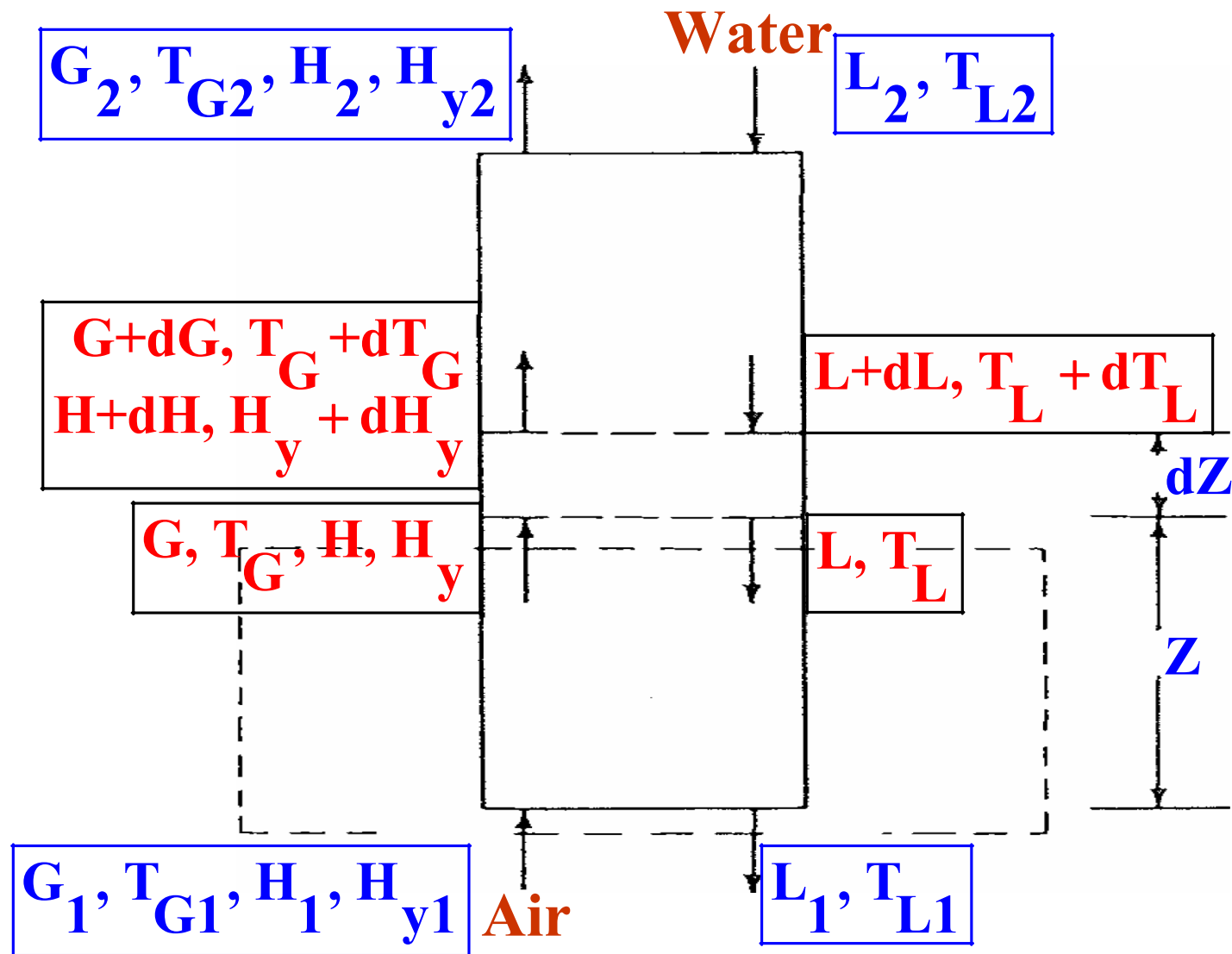
L = water flow, $(\text{kg water})/(\text{s.m}^2)$

T_L = water temperature, K

G = dry air flow, $(\text{kg dry air})/(\text{s.m}^2)$

T_G = air temperature, K

H = air humidity, $(\text{kg water})/(\text{kg dry air})$

H_y = enthalpy of air-water vapour mixture, $\text{J}/(\text{kg dry air})$

- The enthalpy (H_y) is given by (select base temperature = $T_0 = 0\ ^0C$),

$$H_y = c_S\left(T - T_0\right) + H\lambda_0$$

$$\Rightarrow H_y = \left[1005 + 1880(H)\right](T - 0) + H\left(2501 \times 10^3\right)$$

- Find out the operating line by taking <u>generalised heat balance</u> across the control volume.

$$\underbrace{G\left(H_y - H_{y1}\right)}_{J/\left(s\ m^2\right)} = \underbrace{L\ c_L\left(T_L - T_{L1}\right)}_{J/\left(s\ m^2\right)}$$

$$c_L = \text{heat capacity of liquid} = 4187\ \frac{J}{(Kg)(K)}$$

- We assume that **L** is **constant**, because only a very small amount of liquid is evaporated.

- When plotted on a chart of $\underline{H_L \text{ versus } T_L}$ is a straight line with a slope of $\underline{Lc_L/G}$.

- Taking **overall heat balance** across the cooling tower gives,

$$G\left(H_{y2} - H_{y1}\right) = L\, c_L \left(T_{L2} - T_{L1}\right)$$

- Heat balance for a differential column height **dZ** gives,

$$G\, dH_y = L\, c_L\, dT_L$$

- **Total sensible heat transfer from the bulk liquid to the interface is given by,**

$$G \, dH_y = L \, c_L \, dT_L = h_L \, \underline{a} \, dZ \left(T_L - T_i \right)$$

where,

$$h_L \, \underline{a} = \text{liquid phase volumetric heat transfer coefficient}$$

$$\equiv \frac{J}{s \, m^2 \, K} \frac{m^2}{m^3} = \left(\frac{J}{s \, m^3 \, K} \right)$$

- **Please see the schematic diagram on the next slide for quick reference.**
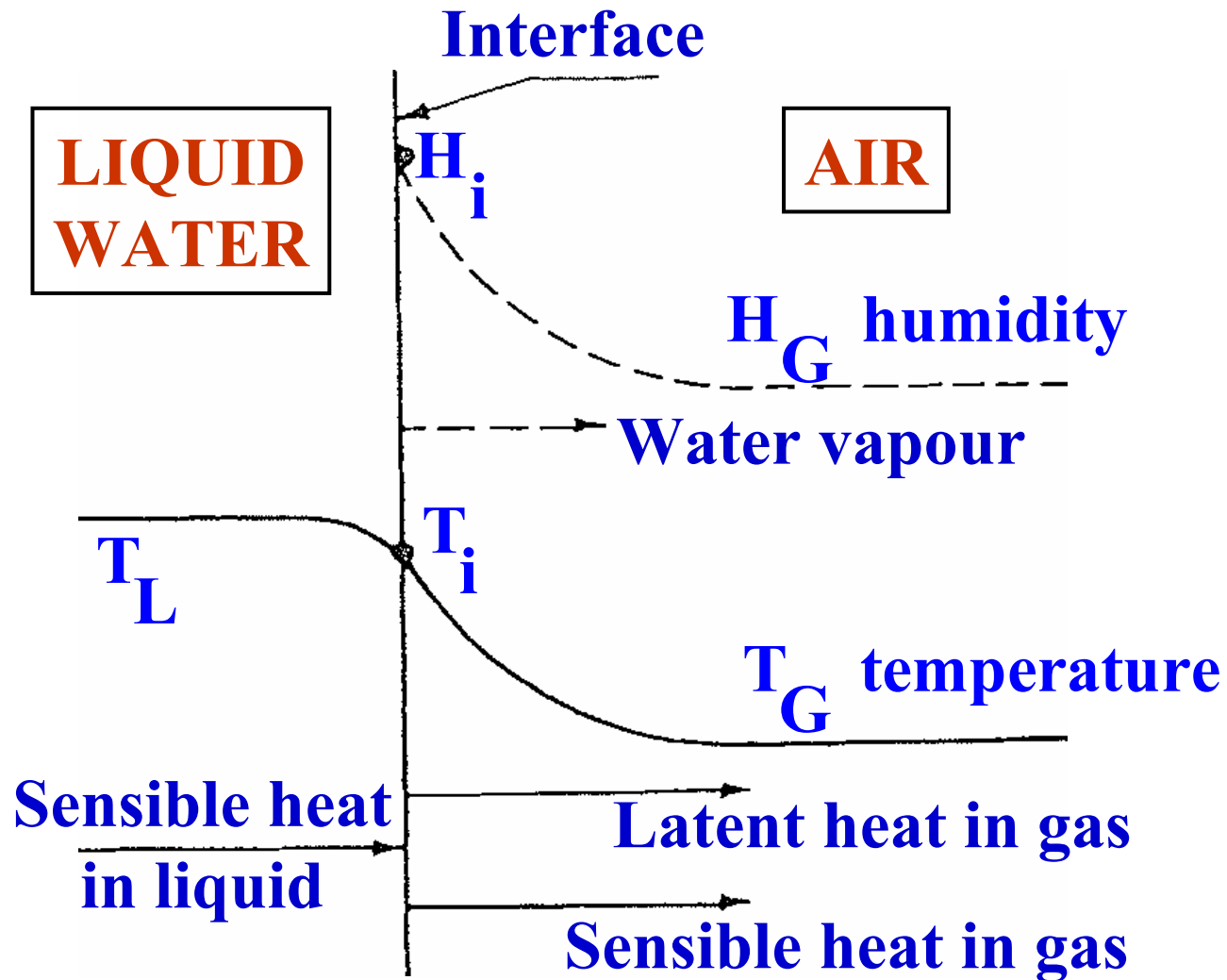
T and H profiles in upper part of cooling tower

- **For adiabatic mass transfer, the heat transfer rate (latent heat in water vapour being transferred) for a differential volume SdZ is obtained as follows:**

Heat Flux due to latent heat of evaporation

$$= q_\lambda = \left(\text{mass flux of water evaporation}\right)$$

$$\times\left(\text{latent heat of evaporation}\right); \quad \frac{J}{(s)\left(m^2 \text{of interfacial area}\right)}$$

$$\Rightarrow q_\lambda = \left(M_A\right)\times\left(\text{molar flux of water evaporation}\right)$$

$$\times\left(\text{latent heat of evaporation}\right)$$

$$\Rightarrow q_\lambda = \left(M_A\right)\left[k_y\left(y_i - y\right)\right]\left(\lambda_0\right)$$

$$\Rightarrow q_\lambda = \left(M_A\right) \times k_y\left(H_i\frac{M_B}{M_A} - H_G\frac{M_B}{M_A}\right)\left(\lambda_0\right)$$

$$q_\lambda = \left(M_B\right)k_y\left(H_i - H\right)\left(\lambda_0\right)$$

$$\Rightarrow q_\lambda = \left(M_B\right)\left[\left(k_G P\right)\left(H_i - H_G\right)\right]\left(\lambda_0\right)$$

Hence, heat rate per unit packed volume due to

latent heat of evaporation is,

$$\Rightarrow q_\lambda \left(\underline{a}\right) = \left(M_B\right)\left(k_G P\right)\left(H_i - H_G\right)\left(\lambda_0\right)\left(\underline{a}\right)$$

Hence, heat rate per differential packed volume

of height dZ and cross-sectional area S

due to latent heat of evaporation is,

$$\Rightarrow q_\lambda \left(\underline{a}\right)\left(SdZ\right) = \left(M_B\right)\left(k_G P\right)\left(H_i - H_G\right)\left(\lambda_0\right)\left(\underline{a}\right)\left(SdZ\right)$$

$$\Rightarrow Q_\lambda = \left(M_B\right)\left(k_G \underline{a}\right)\left(P\right)\left(H_i - H_G\right)\left(\lambda_0\right)\left(SdZ\right)$$

$$\Rightarrow \frac{Q_\lambda}{S} = \left(M_B\right)\left(k_G \underline{a}\right)\left(P\right)\left(H_i - H_G\right)\left(\lambda_0\right)\left(dZ\right)$$

$$\Rightarrow \boxed{\frac{Q_\lambda}{S} = M_B \left(k_G \underline{a} \right) (P) \left(\lambda_0 \right) \left(H_i - H_G \right) dZ}$$

where,

M_B = molecular weight of air, $\dfrac{kg}{kmol}$

$k_G \underline{a}$ = volumetric mass transfer coefficient, $\dfrac{kmol}{s\, m^3\, Pa}$

P = atmospheric pressure, Pa

λ_0 = latent heat of water, J/kg

H_i = humidity of gas at interface, kg water/kg dry air

H_G = humidity of gas in bulk gas, kg water/kg dry air

- **For adiabatic mass transfer, the heat transfer rate (sensible heat) for a differential volume SdZ is given by,**

$$\Rightarrow Q_s = \left(h_G \underline{a} \right)\left(T_i - T_G \right)\left(SdZ \right)$$

$$\Rightarrow \frac{Q_s}{S} = \left(h_G \underline{a} \right)\left(T_i - T_G \right)dZ$$

where,

$h_G \underline{a}$ = gas phase volumetric

heat transfer coefficient, $\dfrac{J}{m^3\ K}$

- **Now,**

  Total sensible heat transfer from the liquid bulk to the interface

  = <u>latent heat</u> **gone to gas with the vaporised liquid +** <u>sensible heat</u> **change in the gas**

- **Therefore,**

$$G\ S\ dH_y = M_B \left(k_G \underline{a}\right)(P)\left(\lambda_0\right)\left(H_i - H_G\right)\ S\ dZ$$

$$+\left(h_G \underline{a}\right)\left(T_i - T_G\right)\ S\ dZ$$

$$\Rightarrow \boxed{\begin{array}{l} G\ dH_y = M_B \left(k_G \underline{a}\right)(P)\left(\lambda_0\right)\left(H_i - H_G\right)dZ \\[2mm] +\left(h_G \underline{a}\right)\left(T_i - T_G\right)dZ \end{array}}$$

$$\left(\frac{h_G}{M_B k_y} \right) = \left(\frac{h_G \underline{a}}{M_B k_y \underline{a}} \right) \approx c_S \quad \dots \quad \left(c_S = \text{humid heat} \right)$$

$$\Rightarrow \frac{h_G \underline{a}}{M_B \left(k_G \underline{a} \right) (P)} \approx c_S \Rightarrow \boxed{h_G \underline{a} \approx c_S M_B \left(k_G \underline{a} \right) (P)}$$

- **Substituting the above expression for $h_G \underline{a}$ into the following equation.**

$$G \, dH_y = M_B \left(k_G \underline{a} \right) (P) \left(\lambda_0 \right) \left(H_i - H_G \right) dZ$$

$$+ \left(h_G \underline{a} \right) \left(T_i - T_G \right) dZ$$

$$\Rightarrow G dH_y = M_B \left(k_G \underline{a} \right) (P) \left(\lambda_0 \right) \left(H_i - H_G \right) dZ$$

$$+ c_S M_B \left(k_G \underline{a} \right) (P) \left(T_i - T_G \right) dZ$$

$$\Rightarrow G dH_y = M_B k_G \underline{a} P \lambda_0 dZ \left(H_i - H_G \right)$$

$$+ c_S M_B k_G \underline{a} P dZ \left(T_i - T_G \right)$$

$$\Rightarrow G dH_y = M_B k_G \underline{a} P dZ \lambda_0 H_i - M_B k_G \underline{a} P dZ \lambda_0 H_G$$

$$+ c_S M_B k_G \underline{a} P dZ T_i - c_S M_B k_G \underline{a} P dZ T_G$$

$$\Rightarrow GdH_y = M_B k_G \underline{a} P dZ \left(\lambda_0 H_i - \lambda_0 H_G \right)$$

$$+ M_B k_G \underline{a} P dZ \left(c_S T_i - c_S T_G \right)$$

$$\Rightarrow GdH_y = M_B k_G \underline{a} P dZ \left(c_S T_i - c_S T_G + \lambda_0 H_i - \lambda_0 H_G \right)$$

$$\Rightarrow GdH_y = M_B k_G \underline{a} P dZ \left(\begin{array}{c} c_S T_i - c_S T_0 - c_S T_G \\ + c_S T_0 + \lambda_0 H_i - \lambda_0 H_G \end{array} \right)$$

$$\Rightarrow \boxed{GdH_y = M_B k_G \underline{a} P dZ \left\{ \begin{array}{c} \left[c_S \left(T_i - T_0 \right) + \lambda_0 H_i \right] \\ - \left[c_S \left(T_G - T_0 \right) + \lambda_0 H_G \right] \end{array} \right\}}$$

Substitute,

$$c_S\left(T_i - T_0\right) + \lambda_0 H_i = H_{yi} = \text{Gas enthalpy at interface}$$

$$c_S\left(T_G - T_0\right) + \lambda_0 H_G = H_y = \text{Gas enthalpy in bulk}$$

$$\Rightarrow G\,dH_y = M_B\, k_G\, \underline{a}\, P\left(H_{yi} - H_y\right) dZ$$

$$\Rightarrow \int_0^Z dZ = \int_{H_{y1}}^{H_{y2}} \frac{G}{M_B\, k_G\, \underline{a}\, P\left(H_{yi} - H_y\right)} dH_y$$

$$\Rightarrow \int_0^Z dZ = \left(\frac{G}{M_B\, k_G\, \underline{a}\, P}\right) \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{\left(H_{yi} - H_y\right)}$$

Now,

$$G \, dH_y = L \, c_L \, dT_L = h_L \, \underline{a} \, dZ \left(T_L - T_i \right)$$

Also,

$$G dH_y = M_B \, k_G \, \underline{a} \, P \left(H_{yi} - H_y \right) dZ$$

$$\Rightarrow \frac{\left(H_{yi} - H_y \right)}{\left(T_L - T_i \right)} = \frac{h_L \, \underline{a}}{M_B \, k_G \, \underline{a} \, P}$$

$$\Rightarrow \boxed{\frac{\left(H_{yi} - H_y \right)}{\left(T_i - T_L \right)} = - \left(\frac{h_L \, \underline{a}}{M_B \, k_G \, \underline{a} \, P} \right)}$$

Design of water cooling tower using film mass transfer coefficients:

The following steps are involved in the design:

- The enthalpy of saturated air H_{yi} is plotted versus T_i on H *versus* T plot.

- This enthalpy (H) is computed with the following equation using the saturation humidity from the humidity chart for a given T, with $0\ ^0C$ (273.15 K) as base Temperature.

$$\underbrace{H_y}_{\dfrac{kJ}{\binom{kg\ dry\ air}{with\ water\ vapour}}} = c_S\left(T - T_0\right) + H\lambda_0$$

$$\Rightarrow \quad H_y = \left[1.005 + 1.880(H)\right]\left(T - T_0\right) + (H)\lambda_0$$

- **Computed values are plotted in the following table.**

Enthalpies of saturated _Air + Water Vapour_ mixtures
(base temperature = 0 ^{0}C)

T_L, ^{0}C	H_y, J/kg dry air	T_L, ^{0}C	H_y, J/kg dry air
15.6	43.68×10^3	37.8	148.2×10^3
26.7	84.0×10^3	40.6	172.1×10^3
29.4	97.2×10^3	43.3	197.2×10^3
32.2	112.1×10^3	46.1	224.5×10^3
35.0	128.9×10^3	60.0	461.5×10^3

- **Knowing the entering air condition (T_{G1}, H_1), the enthalpy H_{y1} is obtained from the same previous equation (given below):**

$$\Rightarrow \boxed{H_y = \left[1.005 + 1.880(H)\right]\left(T - T_0\right) + (H)\lambda_0}$$

- **The point (T_{L1}, H_{y1}) (desired leaving water temperature) is plotted in the Figure as one point on the operating line.**

- **The operating line is plotted with a slope L_{cL}/G and ends at point T_{L2}, which is the entering water temperature. This gives. H_{y2}.**

- **Alternatively, H_{y2} is obtained from the following equation:**

$$G\left(H_{y2} - H_{y1}\right) = L\,c_L\left(T_{L2} - T_{L1}\right)$$

- **Knowing $h_L\underline{a}$ and $k_G\underline{a}$, lines (slope = $-h_L\underline{a}/k_G\underline{a}\,M_B P$) are plotted. Point P represents (T_L, H_y) on the operating line, and point M represents (T_{Li}, H_{yi}), that is, the interface conditions.**

- **Therefore, line MS or $H_{yi}-H_y$ represents the driving force.**

$$\frac{\left(H_{yi} - H_y\right)}{\left(T_i - T_L\right)} = -\left(\frac{h_L\,\underline{a}}{M_B\,k_G\,\underline{a}\,P}\right)$$
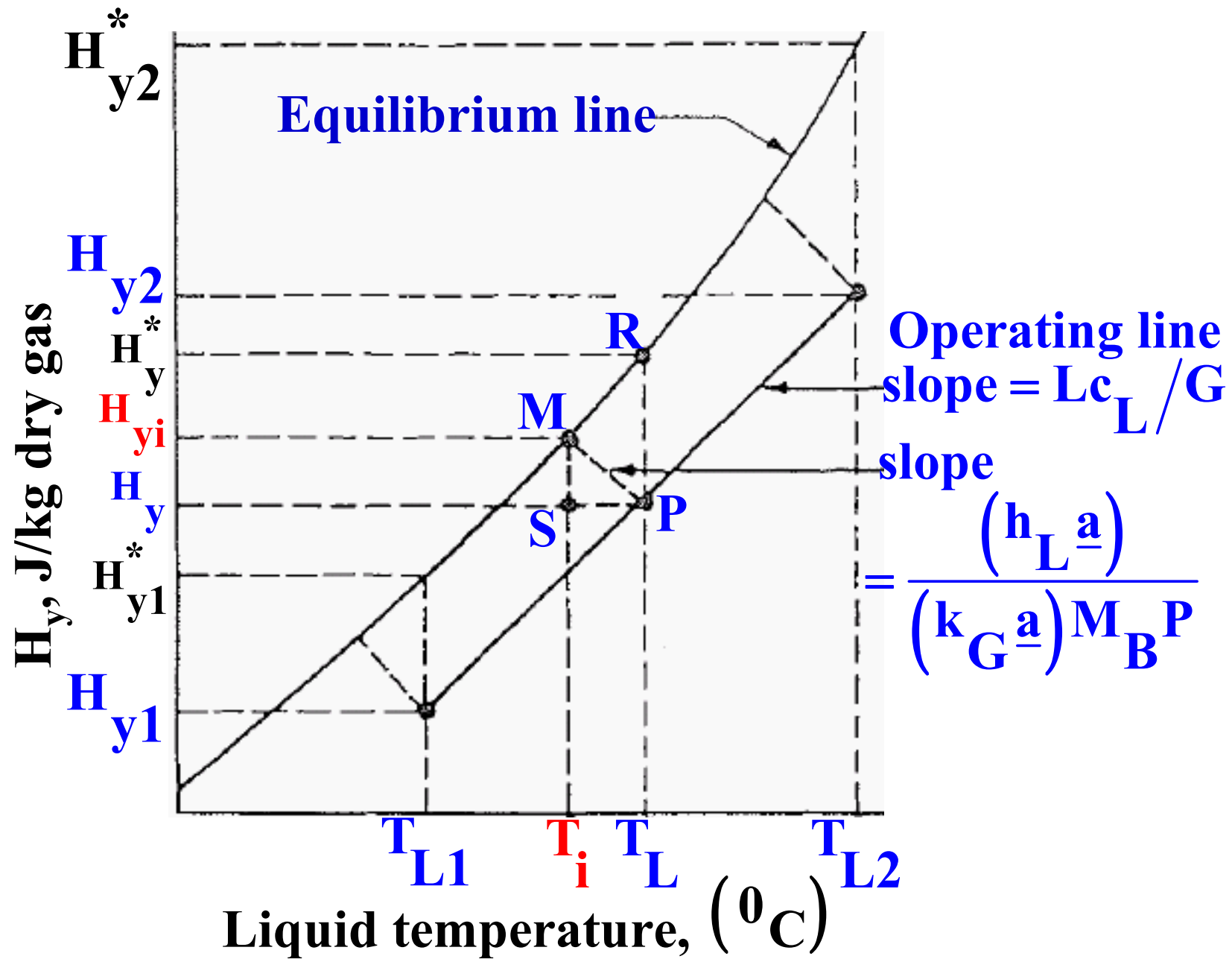
- **The driving force $(H_{yi} - H_y)$ is computed for various values of T_L between T_{L1} and T_{L2}.**

- **Then by plotting $1/(H_{yi} - H_y)$ *versus* H_y (from H_{y1} to H_{y2}), a graphical integration is performed to obtain the value of the integral in the following equation.**

$$\int_0^Z dZ = \left(\frac{G}{M_B \, k_G \, \underline{a} \, P} \right) \int_{H_{y1}}^{H_{y2}} dH_y$$

- **EXAMPLE: A packed counter-current water cooling tower using an air flow rate of 1.356 kg dry air/(s m^2) and a water flow rate of 1.356 kg water/(s m^2) is to cool the water from T_{L2} = 43.3 ^{0}C to T_{L1} = 29.4 ^{0}C. The entering air at 29.4 ^{0}C has a wet bulb temperature of 23.9 ^{0}C. The mass transfer coefficient $k_G\underline{a}$ = 1.207×10^{-7} kmol/(s m^3 Pa) and $h_L\underline{a}/k_G\underline{a}M_BP$ = 4.187×10^4 J/(Kg K). Calculate the height of packed tower. The tower operates at a pressure of 101325 Pa absolute.**

- **Step (1): The values of H_y (enthalpy of saturated air + water vapour) are plotted versus liquid temperature T_L, ^{0}C.**

- **Step (2)**: The inlet air is at $T_{G1} = 29.4\ ^0C$, with a wet bulb temperature of **23.9 ^0C**. Find out the actual humidity of this entering air from the humidity chart = $H_1 \approx 0.017$ **kg water/kg dry air**.

$$H_y = [1.005 + 1.880(H)](T - T_0) + (H)\lambda_0$$

$$\Rightarrow H_{y1} = [1.005 + 1.880(0.017)](T - 0) + (0.017)(2501.4)$$

$$\Rightarrow H_{y1} = 73.010 \ \frac{kJ}{kg\ dry\ air}$$

$$\Rightarrow \boxed{H_{y1} = 73010 \ \frac{kJ}{kg\ dry\ air} = \text{enthalpy of air entering}}$$

- Therefore, the first point on the operating line, that is $(T_{L1}, H_{y1}) = (29.4\ ^0C, 73010\ J/kg)$ is plotted.

- **Enthalpy of outlet is computed using overall material balance, as follows:**

$$\boxed{G\left(H_{y2} - H_{y1}\right) = L\, c_L\left(T_{L2} - T_{L1}\right)}$$

$$\Rightarrow 1.356\left(H_{y2} - 73010\right) = (1.356)(4187)(43.3 - 29.4)$$

$$\Rightarrow \boxed{H_{y2} = 131210 \ \frac{kJ}{kg \ dry \ air} = \text{enthalpy of air leaving}}$$

- **Therefore, the other point on the operating line, that is $(T_{L2}, H_{y2}) = (43.3\ ^0C, 131210\ J/kg)$ is plotted.**

- Now, plot the lines with the slope =

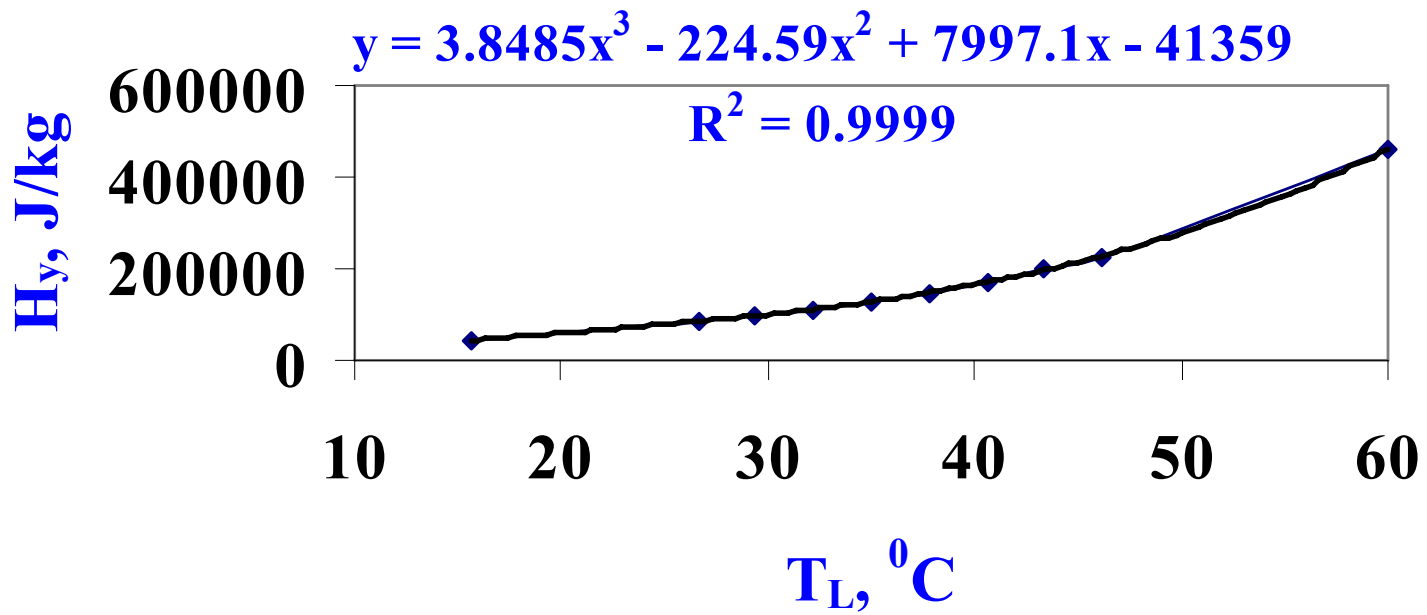$$\frac{(h_L a)}{(k_G a) M_B P} = -41870$$

- Divide the interval between the 2 extreme points of the operating line, that is, (29.4 ^{0}C, 73010 J/kg) and (43.3 ^{0}C, 131210 J/kg), into (say) 20 intervals.

- Then, H_{yi} values can be found <u>graphically</u>.

- Alternately, H_{yi} values are found <u>numerically</u> by solving the equation of line [slope = $-h_L a / k_G a M_B P$] and the <u>fitted</u> equilibrium curve.

- Then, make a Table as shown on the next slide.

H_y	H_{yi}	$H_{yi} - H_y$	$1/(H_{yi} - H_y)$
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- Values of $1/(H_{yi} - H_y)$ are plotted versus H_y and the area under the curve is found **graphically** or **numerically** (trapezoid rule).

- The packed height of the tower is then obtained as:

$$\Rightarrow \quad Z = \left(\frac{G}{M_B \, k_G \, \underline{a} \, P} \right) \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{\left(H_{yi} - H_y \right)}$$

Equilibrium curve

$$y = 3.8485x^3 - 224.59x^2 + 7997.1x - 41359$$

$$R^2 = 0.9999$$

H_y, J/kg

T_L, ^0C

- **The _fitted_ equation of the equilibrium curve using a cubic polynomial (Y-intercept ≠ 0) is,**

$$H_{yi} = 3.8485\left(T_i^3\right) - 224.59\left(T_i^2\right) + 7997.1\left(T_i\right) - 41359$$

- **The equation of the operating line is,**

$$H_y = 4187.1\left(T_L\right) - 50089$$

and,
$$\frac{\left(H_{yi} - H_y\right)}{\left(T_i - T_L\right)} = -\left(\frac{h_L\,\underline{a}}{M_B\,k_G\,\underline{a}\,P}\right)$$

$$\Rightarrow \frac{\begin{bmatrix} 3.8485\left(T_i^3\right) - 224.59\left(T_i^2\right) \\ +7997.1\left(T_i\right) - 41359 - H_y \end{bmatrix}}{\left(T_i - T_L\right)} = -41870$$

Find T_i by trial-and-error, and then get H_{yi}.

Repeat the procedure for all points $\left(T_L, H_y\right)$.

For 1 to 100 ^{0}C, Antoine constants for water are,

$$A = 8.07131; \ B = 1730.63; \ C = 233.426$$

$$\log_{10}\left(VP_{mmHg}\right) = A - \frac{B}{C + T^0C}$$

$$H = \left(\frac{18.02}{28.97}\right)\frac{p_A}{P - p_A} \ \frac{kg \ H_2O}{kg \ DRY \ air}$$

$$H_S = \left(\frac{18.02}{28.97}\right)\frac{p_{AS}}{P - p_{AS}} \ \frac{kg \ H_2O}{kg \ DRY \ air}$$

$$760 \ mmHg = 1 \ atm = 101325 \ Pa$$

$$\Rightarrow (x) \ mmHg = \frac{(x)}{760} \ atm = \frac{101325(x)}{760} \ Pa$$