Chapter No. 01

Humidification

Lecture 1 – Introduction and Fundamentals of Humid Air

1) Introduction to Humidification Processes :

Humidification is a process in which dry or partially dry **air is brought into contact with liquid water**, causing some of the water to evaporate into the air. As a result, the air becomes more humid, meaning its **moisture content increases**.

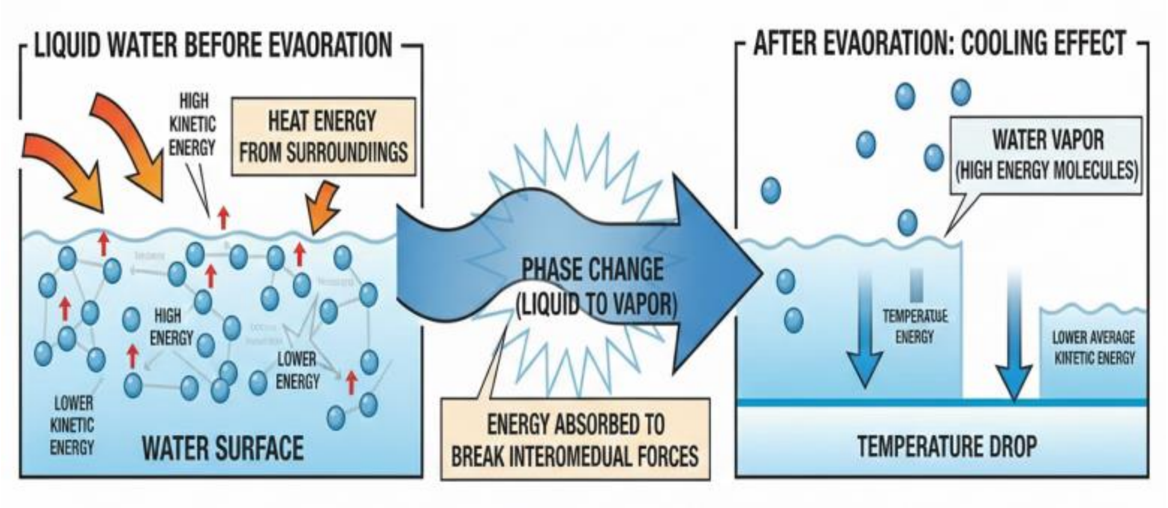


Figure 1 – Coupled *heat*- and *mass*- transfer process.

During evaporation, water requires energy (latent heat) to change from liquid to vapor. This energy is taken from the air and the water itself near to the interface, which often leads to a local decrease in air and water temperature. Because evaporation (mass transfer) and heat exchange occur at the same time and influence each other, humidification is considered a combined *heat*- and *mass*-transfer process. The opposite process, where moisture is removed from air, is called **dehumidification**.

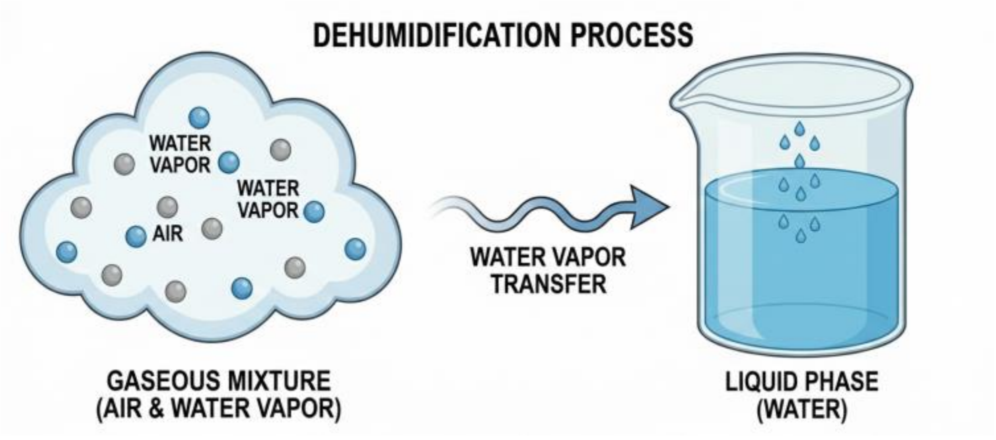


Figure 2 – Dehumidification process.

Industrial Importance –

Humidification processes are widely used in chemical and thermal engineering, especially in:

→ **Cooling towers** (cooling of hot water by evaporation)

Hot water enters the cooling tower through the **hot water inlet** and is distributed over the **fill material** by sprinklers, forming thin films or droplets. Dry air, drawn upward by the fan, creates convection that removes heat from the water, while conduction transfers heat within the water to its exposed surfaces. **Evaporation occurs mainly on the surface of the thin water films or droplets on the fill**, removing **latent heat** and cooling the remaining water, while the air carries away the heat and water vapor. The **cooled water** collects at the bottom and exits through the **cold water outlet** to be returned to the system, completing the circulation.

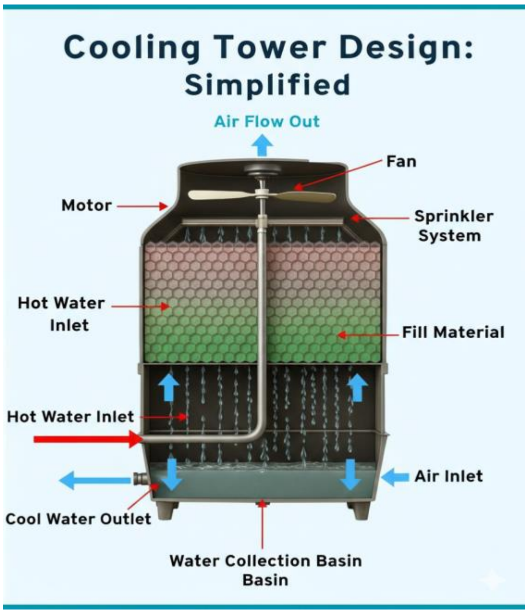


Figure 3 – Cooling tower design.

→ **Air conditioning systems** (control of air temperature and humidity)

Air-conditioning systems are used to control both the temperature and the humidity of indoor air. They operate by continuously **removing heat from the air inside a room** and **rejecting it to the outside** using a **refrigeration cycle**.

In this cycle, a special fluid called a **refrigerant** circulates through four main components. First, the **compressor** increases the pressure and temperature of the refrigerant vapor. The hot refrigerant then flows to the **condenser**, where it releases heat to the outdoor air and changes into a liquid. This liquid passes through an **expansion valve**, which reduces its pressure and temperature. The cold refrigerant enters the **evaporator**, where it absorbs heat from the indoor air and evaporates.

As indoor air passes over the cold **evaporator coil**, it is cooled. At the same time, excess water vapor in the air can condense on the coil, which reduces the air humidity. The cooled and dehumidified air is then circulated back into the room by a **fan**. The refrigerant vapor returns to the compressor, and the cycle repeats until the desired indoor conditions are reached.

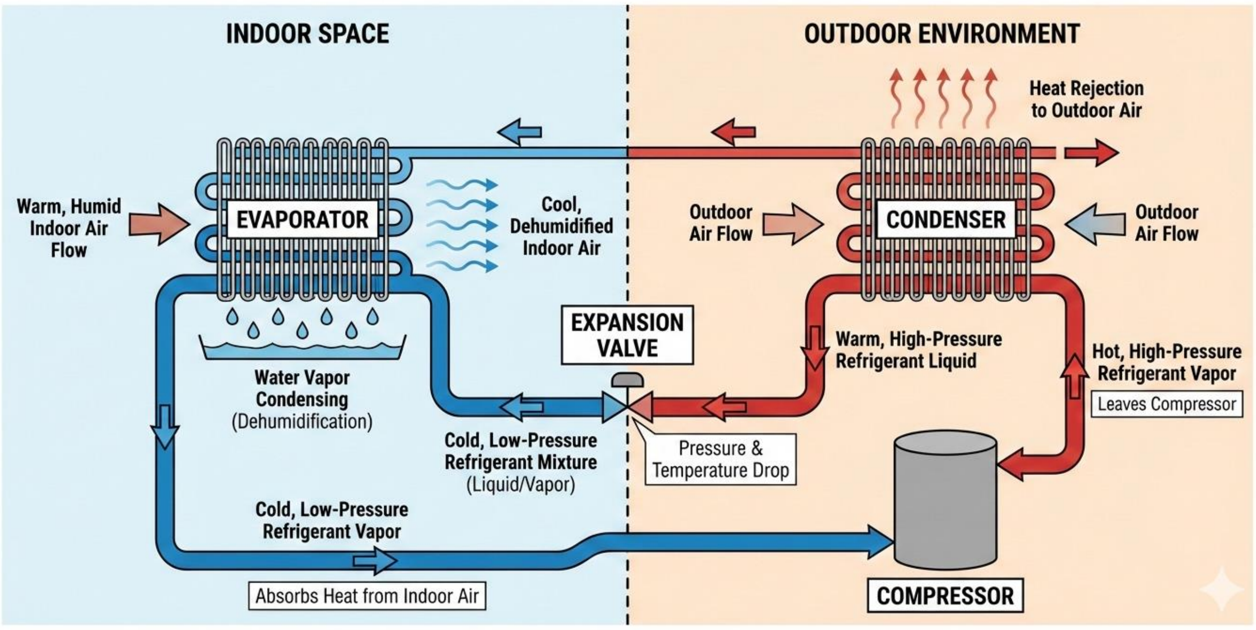


Figure 4 – Air-conditioning system: temperature & humidity control.

2) Humid Air:

2.1 Definition:

Humid air is defined as a **binary gaseous mixture** composed of **dry air** and **water vapor**. This representation allows humid air to be analyzed using simple mass and energy balances in humidification processes.

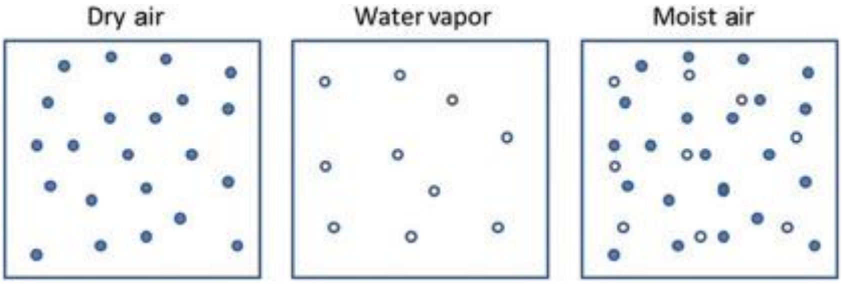


Figure 5 – Schematic diagram of dry and moist air.

Dry air is itself a mixture of gases, mainly:

- Nitrogen (N_2): 78%
- Oxygen (O_2): 21%
- Other gases (argon, CO_2, etc.): ≈ 0.9%

The proportions of nitrogen, oxygen, and argon **remain** essentially **constant** under normal operating conditions. For this reason, dry air is treated as a single, inert component in engineering calculations.

In contrast, **water vapor** is the **variable component** of humid air. Its amount depends mainly on the **temperature (T)** and **pressure (P)** of the system, as well as on contact with liquid water.

According to **Dalton's law**, the total pressure of humid air is the sum of the partial pressures of dry air and water vapor:

$$\boldsymbol{P = P_{da} + P_v}$$

Where

$\boldsymbol{P}$: total pressure of humid air

$\boldsymbol{P_{da}}$: partial pressure of dry air

$\boldsymbol{P_v}$: partial pressure of water vapor

Humid air is a mixture of **dry air** (**carrier gas**, **constant composition**) and **water vapor** (**transferred spice**, **variable amount**), where only the water vapor participates in mass transfer.

3) Fundamental Psychrometric Properties:

Now that humid air has been defined as a mixture of dry air and water vapor, the next step is **to quantify** how much water vapor is present in the air and how it affects air behavior. For this purpose, several **psychrometric properties** are introduced. These properties provide practical measures of air moisture content and are essential for analyzing humidification, dehumidification, and air-conditioning processes.

3.1 Humidity (H)

The **humidity** H of an air–water vapor mixture is defined as the **kg of water vapor** contained in **1 kg of dry air**. The humidity so defined depends only on the **partial pressure P_A of water vapor in the air** and on the **total pressure P** (assumed to be **101.325 kPa**, **1.0 atm abs**, or **760 mmHg**). Using the molecular weight of water (A) as **18.02** and of air as **28.97**, the humidity H in kg H_2O/kg dry air

$$H = \frac{m_{H_2O}}{m_{dry\ air}} \qquad (kg \text{ water vapor / } kg \text{ dry air})$$

We write each mass as : m = n.M, then,

$$H = \frac{n_{H_2O} \times M_{H_2O}}{n_{dry\ air} \times M_{dry\ air}}$$

Where

$M_{H_2O} = 18.02\ kg/kmol$

$M_{air} = 28.97\ kg/kmol$

Thus:

$$H = \frac{18.02}{28.97} \frac{n_{H_2O}}{n_{dry\ air}}$$

For an ideal gas mixture: $n_i = \frac{P_i V}{RT}$, hence: $\frac{n_{H_2O}}{n_{dry\ air}} = \frac{P_{H_2O}}{P_{dry\ air}}$

Now apply Dalton's law: $P_{dry\ air} = P - P_{H_2O}$

So: $\frac{n_{H_2O}}{n_{dry\ air}} = \frac{P_{H_2O}}{P - P_{H_2O}}$

Substituting into the definition of H:

$$\boldsymbol{H = 0.622 \frac{P_{H_2O}}{P - P_{H_2O}}}$$

Saturated air is air in which the **water vapor is in equilibrium with liquid water** at the given conditions of pressure and temperature **($\boldsymbol{P_{H_2O} = P_{AS}}$)**. In this mixture, the partial pressure of the water vapor in the air–water mixture is equal to the **vapor pressure P_{AS}** of pure water at the given temperature. Hence, the **saturation humidity H_S** is

$$\boldsymbol{H_S = 0.622 \frac{P_{AS}}{P - P_{AS}}}$$

Humidity can be given in **grams per cubic meter** (**g/m^3**).

3.2. Percentage Humidity (H_P)

The **percentage humidity H_P** is defined as 100 times the actual humidity H of the air divided by the humidity H_S if the air was saturated at the same temperature and pressure:

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

3.3. Percentage Relative Humidity (or hygrometric degree)

Percentage relative humidity (**H_R** in %) is defined as:

$$\boldsymbol{H_R = \frac{P_A}{P_{AS}} \times 100}$$

Where

P_A: partial pressure of water vapor;

P_{AS}: saturation vapor pressure of water at the same temperature.

Interpretation:

- H_R = 100% → saturated air
- H_R = 0% → perfectly dry air

3.4. Temperatures of Humid Air

a) Dry-Bulb Temperature (DBT):

The dry temperature corresponds to the standard temperature given by a thermometer, but protected from humidity and radiation.

b) Wet-Bulb Temperature (DBT):

This is the temperature indicated by a thermometer whose bulb is wrapped in wet gauze, swept by moving air, and protected from solar radiation.

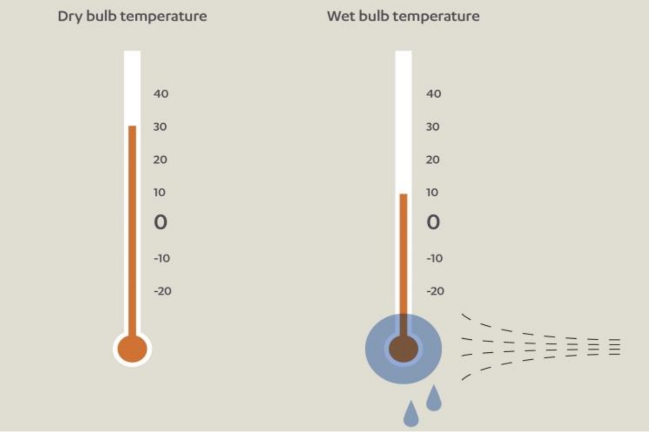


Figure 6 – Dry-bulb temperature vs wet-bulb temperature.

c) Dew point of an air – water vapor mixture:

The temperature at which a given mixture of air and water vapor would be saturated is called the **dew point temperature** or simply the **dew point**. For example, **at 26.7 °C**, the saturation vapor pressure of water is **P_{AS} = 3.50 kPa**. Hence, the dew point of a mixture containing water vapor having a partial pressure of **3.50 kPa** is **26.7 °C**.

If an air – water vapor mixture is at **37.8 °C** (often called the dry bulb temperature) and it contains water vapor of **P_A = 3.50 kPa**, the mixture **would not be saturated**. On cooling to **26.7 °C**, the air would be **saturated**, that is, at the dew point. On further cooling, **some water vapor would condense**, since the partial pressure cannot be greater than the saturation vapor pressure.

Lecture 2 – Humidification

1. INTRODUCTION

Humidification is involved in many natural and industrial processes such as cooling towers, air conditioning, drying, and atmospheric phenomena. It concerns the behavior of **humid air**, which is **a binary mixture** of **dry air** and **water vapor**, where heat and mass transfer occur simultaneously.

In a gas mixture, each component exerts a **partial pressure (P_i)**. For humid air, the **total pressure (P_T)** is expressed as:

$$P_T = P_{dry\,air} + P_v$$

Where

P_v **:** the partial pressure of water present in the air.

When liquid water is **in contact** with air, **evaporation** and **condensation** occur simultaneously. At liquid–vapor equilibrium, the **rate of evaporation** equals the **rate of condensation**, and **no net mass transfer** takes place. For a given temperature, this equilibrium is possible only when the vapor pressure reaches a specific value known as the **saturation vapor pressure**:

$$P_v = P^{sat}(T)$$

which depends solely on temperature and increases rapidly with it.

The variation of the saturation vapor pressure with temperature can be obtained from **tables, charts (psychrometric charts), or specialized software**. It can also be calculated using **empirical correlations**, the most commonly used being the **Antoine equation:**

$$\log_{10}(P^{sat}) = A - \frac{B}{T + C}$$

Where

P^{sat}: is the saturation vapor pressure;

T: is the temperature;

$A, B\ et\ C$: are substance-specific empirical constants.

Humidification processes consist in bringing air into contact with liquid water, causing water to evaporate or condense depending on operating conditions. The **driving force for mass transfer** (ΔP) is the difference between the actual vapor pressure in air and the saturation vapor pressure at the interface temperature:

$$\Delta P = P^{sat}(T) - P_v$$

To quantify how close air is to equilibrium, the **relative humidity** is defined as:

$$\varnothing = \frac{\boldsymbol{P_v}}{\boldsymbol{P^{sat}(T)}}$$

A value of $\varnothing = \mathbf{1}$ corresponds to **saturated air**,

While $\varnothing < \mathbf{1}$ indicates **unsaturated air** capable of absorbing additional water vapor.

2. SATURATION CURVE

The **saturation curve** represents the set of points where **air is fully saturated with water vapor** at a given temperature and pressure.

Mathematically, it corresponds to conditions where:

$$\boldsymbol{(Partial\ pressure\ of\ water\ vapor) = (Saturation\ vapor\ pressure)} \quad \rightarrow \quad \boldsymbol{P_v = P^{sat}(T)}$$

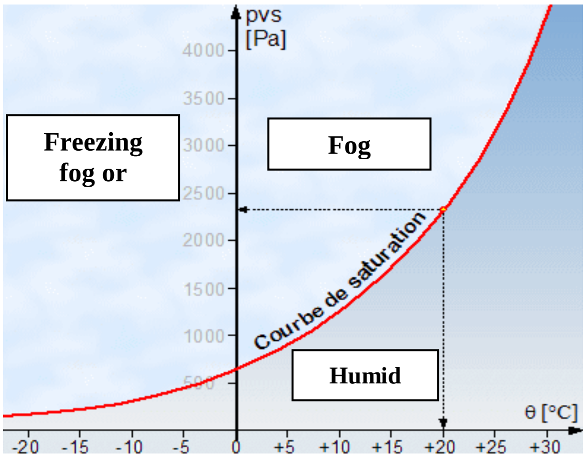


Figure 1 – Saturation curve of humid air.

Physical interpretation:

→ Below the curve: $\boldsymbol{P_v < P^{sat}(T)}$ → air is unsaturated; water can evaporate into the air.

→ On the curve: $\boldsymbol{P_v = P^{sat}(T)}$ → air is saturated; equilibrium exists between evaporation and condensation.

→ Above the curve: $\boldsymbol{P_v > P^{sat}(T)}$ → condensation occurs; air cannot hold more vapor at this temperature.

Practical Exercise:

The relative humidity in the ambient air (**1 atm**, **25 °C**) is measured at **65%**. The saturation pressure of water, depending on temperature, is given by:

$$\boldsymbol{\log_{10} P^{sat} = 23.1964 - \frac{3816.44}{T - 46.13}}$$

(With T in K and P^{sat} in Pa)

– Calculate the absolute humidity and the mole fraction of water vapor in this air.

– Calculate the dew point temperature.

3. Fundamental Psychrometric Properties (Continue):

3.5. Humid Heat (C_H)

Humid heat (c_H) is defined as the sum of the specific heat of dry air (c_{da}) and the specific heat of vapor (c_v) in the gas multiplied by the absolute humidity (H).

For an air-water system, at normal temperature and pressure:

$$\boldsymbol{c_H = c_{da} + H.c_v} \qquad (\frac{kJ}{kg\ dry\ air.K})$$

With

$\boldsymbol{c_{dg}}$: is the specific heat of dry air ($\boldsymbol{c_{dg} = 1.005\frac{kJ}{kg.K}}$)

$\boldsymbol{c_v}$: is the specific heat of water vapor ($\boldsymbol{c_v = 1.88\frac{kJ}{kg.K}}$)

The humid heat of humid air can be expressed as:

$$\boldsymbol{c_H = 1.005 + 1.88 \times \mathrm{H}}$$

Humid heat (c_H) is used in **sensible heat calculations** involving humid air:

$$\boldsymbol{Q_{sensible} = \dot{m}_{da}.c_H.\Delta \mathrm{T}}$$

Where:

$\boldsymbol{\dot{m}_{da}}$: is the mass flow rate of dry air,

ΔT: is the temperature change.

3.6. Humid Enthalpy (h_H)

The enthalpy of a steam-gas mixture is the sum of the enthalpies of the dry air and the vapor in the air. For an air-water system, the enthalpy of the moist air per unit of dry air mass is given by:

$$\boldsymbol{H_E = c_H.(T_{air} - T_0) + H.\lambda_0} \qquad (\frac{kJ}{kg\ dry\ air.K})$$

With: $c_H = c_{da} + H.c_v$

Where $\boldsymbol{\lambda_0}$ is the latent heat of vaporization of water at $\boldsymbol{T_0 = 0\ °C, \lambda_0 = 2500\ kJ/kg}$.

3.7. Humid volume (v_H)

The **humid volume** is defined as the **specific volume of humid air per unit mass of dry air**. It represents the total volume occupied by **dry air and the associated water vapor** at given temperature and pressure.

Given by:

$$\boldsymbol{v_H = \frac{R_a T}{P}(1 + 1.607H)}$$

Where:

$\boldsymbol{v_H}$: humid volume (**$\mathbf{m^3}$ / $\mathbf{kg_{dry\ air}}$**),

$\boldsymbol{R_a}$: gas constant of dry air (**287 $\mathbf{J.kg^{-1}.K^{-1}}$**),

$\boldsymbol{T}$: absolute temperature (**K**),

$\boldsymbol{P}$: total pressure (**Pa**),

$\boldsymbol{H}$: humidity ratio (**$\mathbf{kg_{vapor}}$ / $\mathbf{kg_{dry\ air}}$**),

$\boldsymbol{1.607 = \frac{R_v}{R_a}}$ (ratio of gas constants).

Lecture 3 – Psychrometric Chart

1. Introduction :

1.1. Definition

A **psychrometric chart** is a graphical representation of the thermodynamic properties of moist air at a fixed total pressure (usually 1 atm). It allows rapid determination of:

- Moisture content,
- Enthalpy,
- Relative humidity,
- Wet-bulb temperature,
- Dew point temperature,
- Specific volume.

It is an essential engineering tool in:

- HVAC system design,
- Drying processes,
- Cooling towers,
- Air-conditioning systems,
- Combustion air analysis.

2. Structure of the Psychrometric Chart:

Standard chart at: 1 atm.

2.1. Main Axes:

- X-axis → Dry bulb temperature (°C)
- Y-axis → Humidity ratio (kg/kg dry air)

2.2. Lines on the Chart:

- **Saturation Curve (100% RH):**

Upper boundary of chart.

Represents saturated air (condensation limit).

- **Relative Humidity Lines:**

Curved lines (10%, 20% … 100%).

- **Wet-Bulb Temperature Lines:**

Almost straight diagonal lines.

Represent adiabatic saturation processes.

- **Enthalpy Lines:**

Nearly parallel to wet-bulb lines.

- **Specific Volume Lines:**

Inclined lines (m^3/kg dry air).

- **Dew Point Temperature:**

Horizontal projection to saturation curve.

3. Using the Psychrometric Chart:

Example 1: Property Determination

Given:

$T_{db} = 30°C$

RH = 50%

P = 1 atm

From chart:

H ≈ 0.013 kg/kg dry air

h ≈ 60 kJ/kg dry air

$T_{wb} \approx 22°C$

$T_{dp} \approx 18°C$

v ≈ 0.88 m^3/kg dry air

Example 2: Heating Process (Sensible Heating)

Air heated from 20°C to 40°C

No moisture added.

- Horizontal movement to the right,
- H = constant,
- Enthalpy increases.

Energy balance:

$$Q = \dot{m}_a(h_2 - h_1)$$

Example 3: Cooling and Dehumidification

Air cooled below dew point.

Process:

Sensible cooling (horizontal left)

Condensation (down along saturation line)

Moisture removed:

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2)$$

Example 4: Adiabatic Humidification

Water sprayed into air.

- Moves along constant enthalpy line,
- Temperature decreases,
- Humidity ratio increases.

This is the principle used in:

- Evaporative coolers,
- Cooling towers.

Exercises for application:

1. Air at 35°C and 40% RH is cooled to 15°C.
    - Determine final humidity ratio
    - Calculate condensed water
    - Evaluate cooling load

2. Air at 25°C, 60% RH is heated to 45°C.
    - Determine final RH
    - Calculate energy added

3. In a drying chamber, air enters at 60°C and leaves at 35°C saturated.
    - Determine moisture removed per kg dry air.

Lecture 4 – Cooling Towers

1. Introduction: Why Cooling Towers?

In chemical plants, heat must be removed from: condensers, reactors, compressors and heat exchangers.

Cooling towers reject heat to the atmosphere using **evaporation**.

When a small amount of water evaporates, it absorbs a large amount of heat (latent heat of vaporization).

This cools the remaining water. Cooling is limited by the wet-bulb temperature (WBT) of ambient air

2. Types of Cooling Towers:

2.1. Natural Draft:

Hot water from the system is cooled through direct contact with fresh air. This increases the temperature and humidity of the air in the tower. Warm and moist air is less dense, which causes it to moves out of the tower into the atmosphere and draw in denser fresh air.

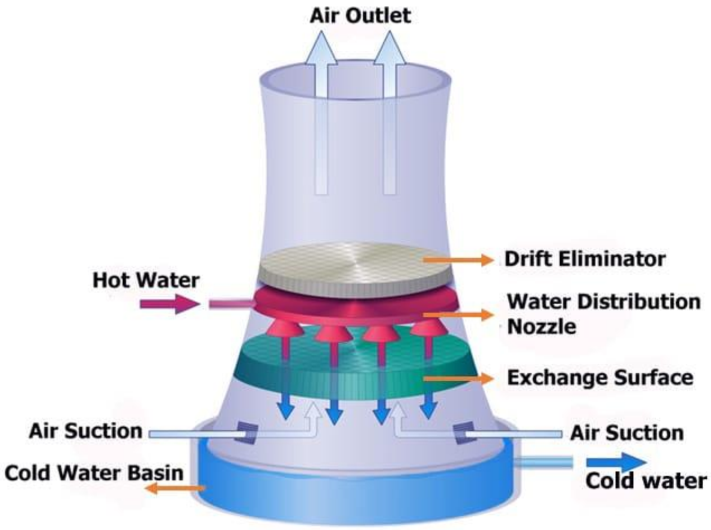


Figure 1 – Natural draft.

2.2. Mechanical Draft (Industrial Plants):

Air is moved by fans. And there are two main configurations:

a) Counter-Flow induced draft:

In counter-flow cooling towers, air moves vertically upward against the downward flow of water through the fill. Instead, water is distributed at the top of the fill through a pressurized piping and spray nozzle system, spaced to avoid restricting airflow. Fans are installed at the top of the tower to draw air upward through the fill media.

b) Counter-Flow forced draft:

This type of tower is similar to counter flow induced draft cooling tower, only difference is that air is pushed by blowers located at the base of the air inlet face.

c) Cross-Flow:

In crossflow cooling towers, water descends vertically through the fill while air moves horizontally across the falling water. Since the air does not pass through the water distribution system, gravity-fed hot water basins can be installed above the fill. These open distribution basins are a standard feature in crossflow tower designs.

In most chemical industries, induced draft counter-flow towers are common.

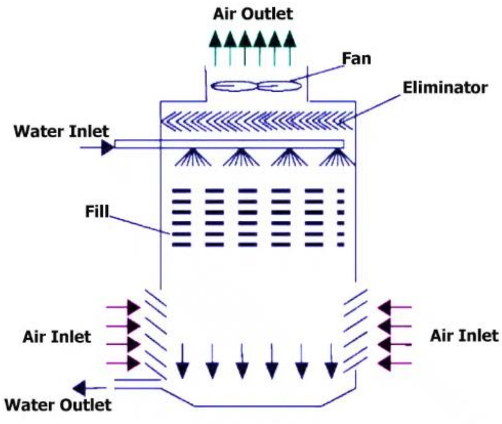


Figure 2 – Counter-flow induced draft.

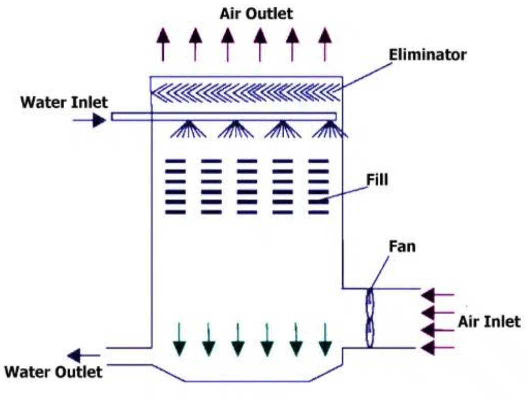


Figure 3 – Counter-flow forced draft.

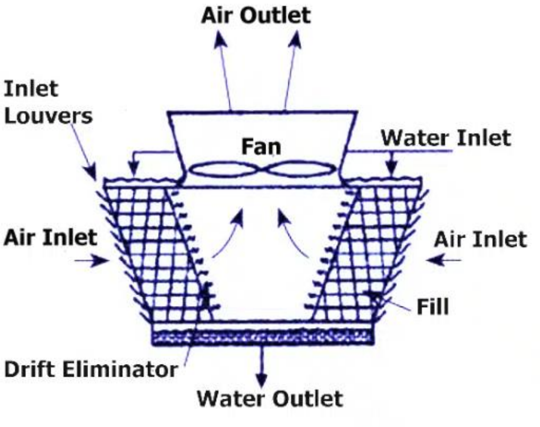


Figure 4 – Cross-flow induced draft.

3. Cooling Tower Components and Performance Parameters:

3.1. Main Components:

- **Fill:** used to facilitate heat transfer by maximizing water and air contact.
- **Fan:** to deliver the desired air flow.
- **Drift eliminator:** used to capture water droplets entrapped in the air stream that otherwise would be lost to the atmosphere.
- **Water distribution nozzles:** to uniform distribute water at the top of the fill and achieve proper wetting of the entire fill surface.
- **Cold water basin:** receives the cooled water that flows through the tower and fill.

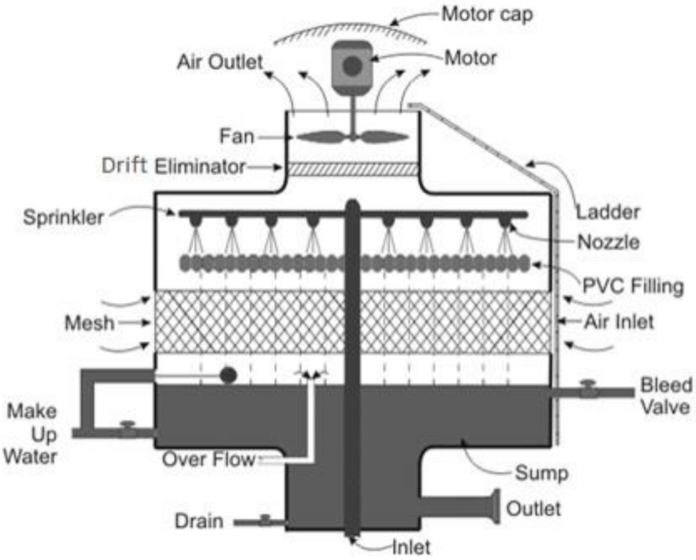


Figure 5 – Cooling tower main components.

3.2. Cooling Tower Performance Parameters :

The significant factors of cooling tower are:

a) Range:

Temperature drop of the circulating water across the tower.

$$\mathbf{Range} = \mathbf{T}_{hot} - \mathbf{T}_{cold}$$

Example:

T_{hot} = 95°C → T_{cold} = 85°C: Range = 10°C

b) Approach:

Indicates how close the tower operates to its thermodynamic limit.

$$\mathbf{Approach} = \mathbf{T}_{cold} - \mathbf{T}_{wet\text{-}bulb}$$

If: Cold water = 32°C and Wet bulb = 27°C, so: Approach = 5°C

Smaller approach → bigger and more expensive tower.

c) Effectiveness:

Measure of tower performance relative to the maximum possible cooling.

$$Effectiveness = \frac{Range}{Range + Approach} \times 100$$

Higher effectiveness means better performance.

d) Energy Balance (Cooling Capacity):

Rate of heat removed from circulating water.

Heat removed from water equals heat gained by air.

$$Q = \dot{m}_w c_p (T_{hot} - T_{cold})$$

Where:

$\dot{m}_w$: Water mass flow rate. (Mass of water circulated per unit time through the tower.)

c_p: ≈ 4.18 kJ/kg·K

Example 1:

Water flow = 100 m³/h

Hot water = 40°C

Cold water = 30°C

Range = 10°C

Water mass flow: 100 × 1000 = 100 000 kg/h

Heat removed: 100 000 kg/h × 4.18 kJ/kg·K × 10°C = 4 180 000 kJ/h = 1 161 kW

This is the cooling capacity.

e) Water Losses and Water Balance:

Cooling towers consume water due to evaporation.

- **Evaporation Loss:**

Amount of water lost as vapor due to evaporation during cooling.

Approximate formula:

$$\boldsymbol{evaporation\left(\frac{m^3}{h}\right) \approx 0.001 \times Flow \times Range}$$

Example: Flow = 100 m³/h and Range = 10°C, so: Evaporation ≈ 1 m³/h

- **Cycles of Concentration (COC) :**

Indicates how many times dissolved solids are concentrated in the system.

$$COC = \frac{dissolved\ solids\ in\ circulating\ water}{dissolved\ solid\ in\ makeup\ water}$$

$$COC = \frac{\text{TDS in circulating water}}{\text{TDS in make-up water}}$$

Higher COC → less blowdown → less water consumption.

- **Blowdown :**

Intentional discharge of a portion of circulating water to control salt concentration.

$$\text{Blowdown} = \frac{\text{Evaporation}}{COC - 1}$$

If COC = 4: = 1/3 = 0.33 m³/h

- **Make-Up Water :**

$$\text{Make-up} = \text{Evaporation} + \text{Blowdown}$$

= 1 + 0.33 = 1.33 m³/h

f) Liquid-to-Gas Ratio (L/G):

$L/G = \frac{\dot{m}_w}{\dot{m}_a}$ This ratio influences tower size.

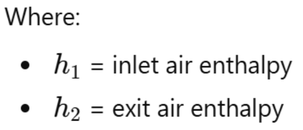
Ratio of water flow to air flow.

Controls heat and mass transfer performance.

$\dot{m}_a$ Mass of air flowing through the tower per unit time.

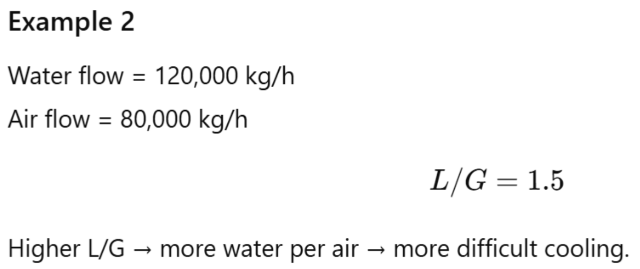
Energy balance form:

$$\dot{m}_w C_p (T_{hot} - T_{cold}) = \dot{m}_a (h_2 - h_1)$$



Where:

- h_1 = inlet air enthalpy
- h_2 = exit air enthalpy



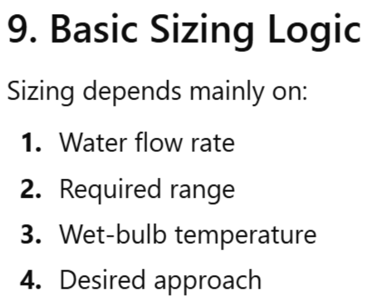
Example 2

Water flow = 120,000 kg/h

Air flow = 80,000 kg/h

$$L/G = 1.5$$

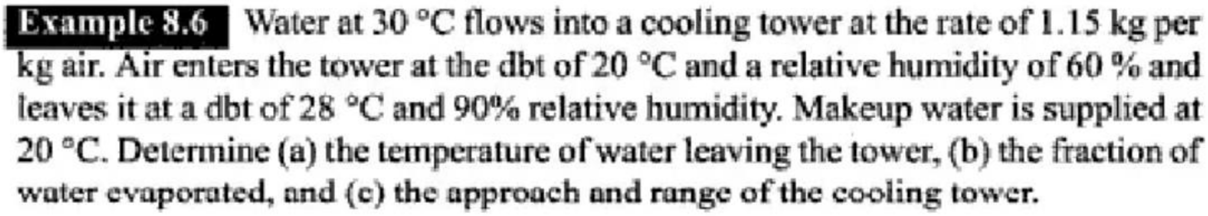
Higher L/G → more water per air → more difficult cooling.



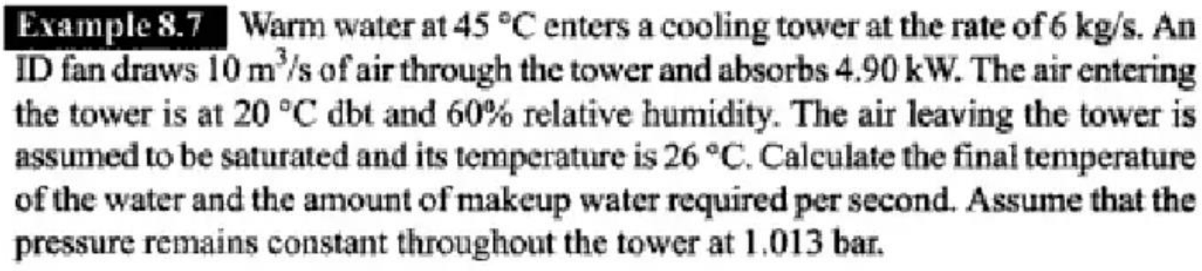
9. Basic Sizing Logic

Sizing depends mainly on:

1. Water flow rate
2. Required range
3. Wet-bulb temperature
4. Desired approach



Example 8.6 Water at 30 °C flows into a cooling tower at the rate of 1.15 kg per kg air. Air enters the tower at the dbt of 20 °C and a relative humidity of 60 % and leaves it at a dbt of 28 °C and 90% relative humidity. Makeup water is supplied at 20 °C. Determine (a) the temperature of water leaving the tower, (b) the fraction of water evaporated, and (c) the approach and range of the cooling tower.



Example 8.7 Warm water at 45 °C enters a cooling tower at the rate of 6 kg/s. An ID fan draws 10 m^3/s of air through the tower and absorbs 4.90 kW. The air entering the tower is at 20 °C dbt and 60% relative humidity. The air leaving the tower is assumed to be saturated and its temperature is 26 °C. Calculate the final temperature of the water and the amount of makeup water required per second. Assume that the pressure remains constant throughout the tower at 1.013 bar.

8.7 Water from a cooling system is itself to be cooled in a cooling tower at a rate of 2.78 kg/s. The water enters the tower at 65 °C and leaves a collecting tank at the base at 30 °C. Air flows through the tower, entering the base at 15 °C, 0.1 MPa, 55% RH and leaving the top at 35 °C, 0.1 MPa, saturated. Makeup water enters the collecting tank at 14 °C. Determine the air flow rate into the tower in m^3/s and the makeup water flow rate in kg/s.

[*Ans*. 3.438 m^3/s, 0.129 kg/s]

8.8 Cooling water enters a cooling tower at a rate of 1000 kg/h and 70 °C. Water is pumped from the base of the tower at 24 °C and some makeup water is added afterwards. Air enters the tower at 15 °C, 50% RH, 1.013 bar, and is drawn from the tower saturated at 34 °C, 1 bar. Calculate the flow rate of the dry air in kg/h and the makeup water required per hour.

[*Ans*. 2088 kg/h, 62.9 kg/h]

Parameter	Symbol	Definition	Unit	Engineering Significance
Hot Water Temperature	T_{hot}	Temperature of water entering the tower	°C	Fixed by process heat source
Cold Water Temperature	T_{cold}	Temperature of water leaving the tower	°C	Determines cooling effectiveness
Wet-Bulb Temperature	T_{WBT}	Minimum theoretical cooling temperature by evaporation	°C	Thermodynamic limit of cooling
Range	$T_{hot} - T_{cold}$	Water temperature drop across tower	°C	Proportional to heat removed
Approach	$T_{cold} - T_{WBT}$	Distance from cooling limit	°C	Smaller value → larger tower
Effectiveness	$\frac{\text{Range}}{\text{Range} + \text{Approach}}$	Performance indicator	–	Closer to 1 → better performance
Heat Load	$Q = \dot{m}_w C_p \Delta T$	Rate of heat removed from water	kW	Determines required tower size
Water Mass Flow	$\dot{m}_w$	Circulating water flow rate	kg/s	Affects cooling capacity
Air Mass Flow	$\dot{m}_a$	Air flowing through tower	kg/s	Controls heat & mass transfer
Liquid/Gas Ratio	$L/G = \dot{m}_w/\dot{m}_a$	Water-to-air flow ratio	–	Governs tower performance
Evaporation Loss	-	Water lost as vapor	m³/h	Main water consumption
Blowdown	-	Water discharged to control solids	m³/h	Maintains water quality
Cycles of Concentration	COC	Ratio of dissolved solids concentration	–	Higher COC → lower water usage
Make-Up Water	-	Fresh water added to system	m³/h	Compensates losses
Enthalpy of Air	h	Total heat content of moist air	kJ/kg dry air	Driving force for cooling
Fill	-	Internal packing material	–	Increases heat transfer area