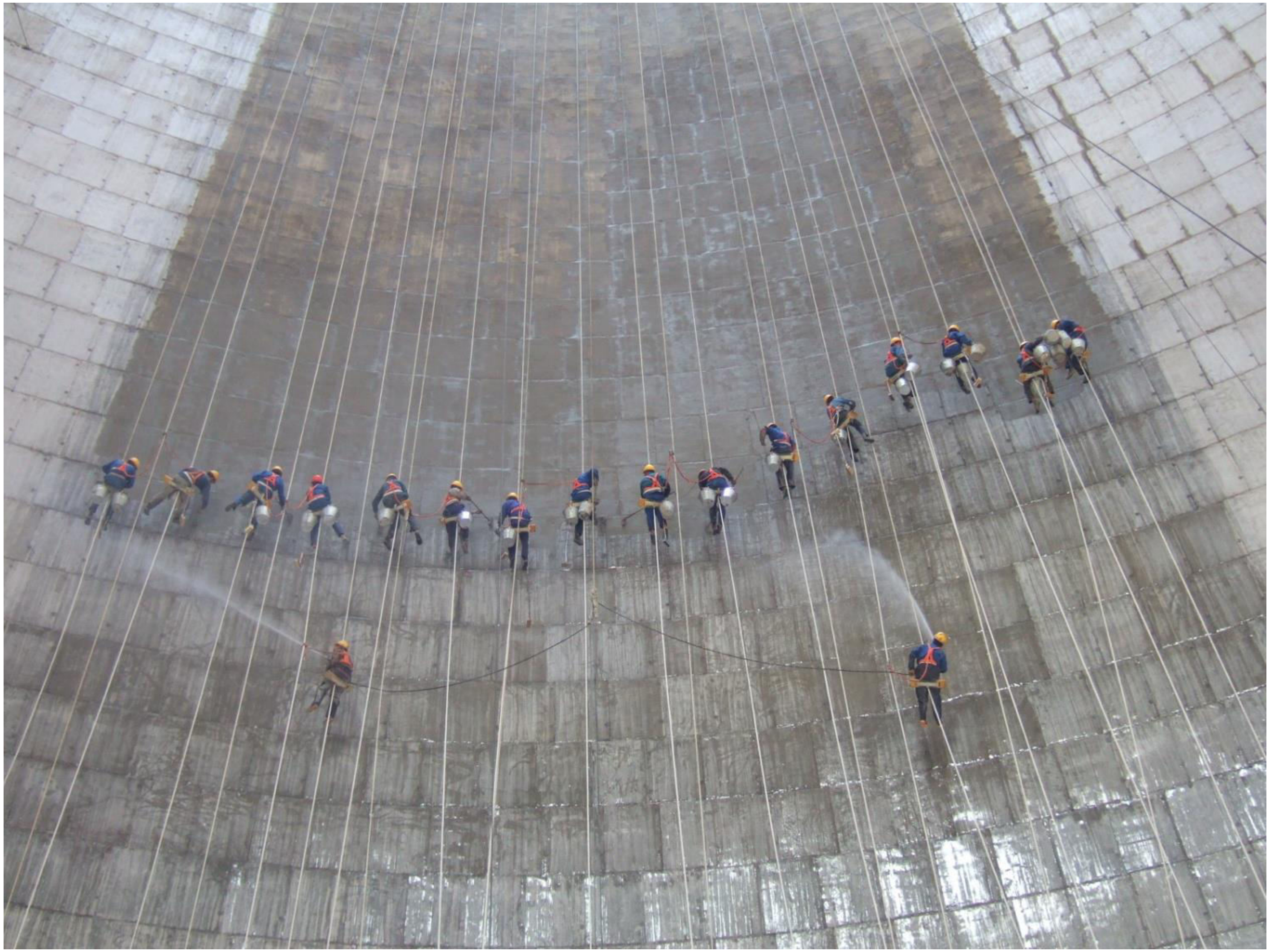
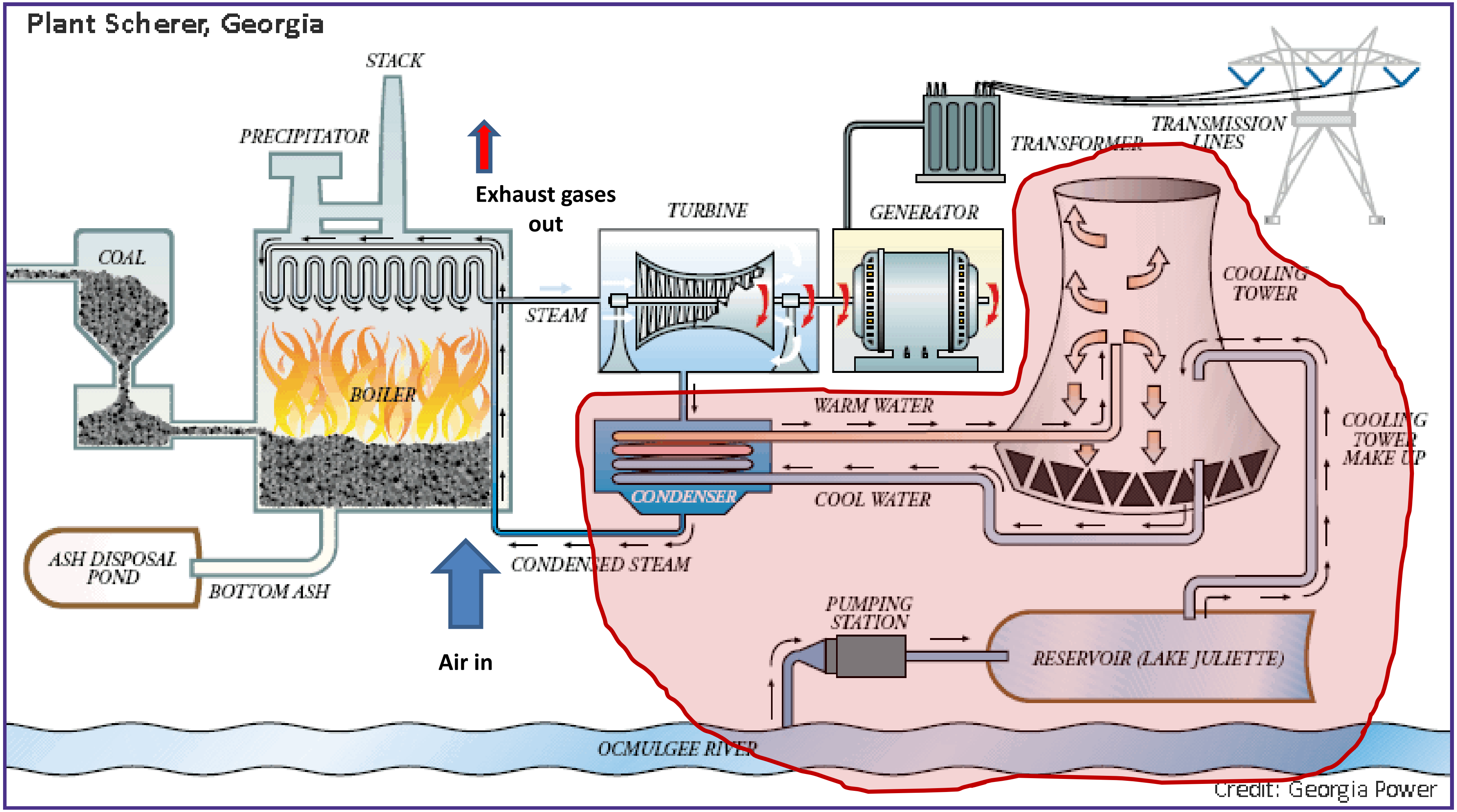
Module 5: Power plant heat rejection systems



Applied Thermo Fluids-II (Autumn 2017):

Dr. M. Ramgopal, Mechanical Engineering, IIT Kharagpur



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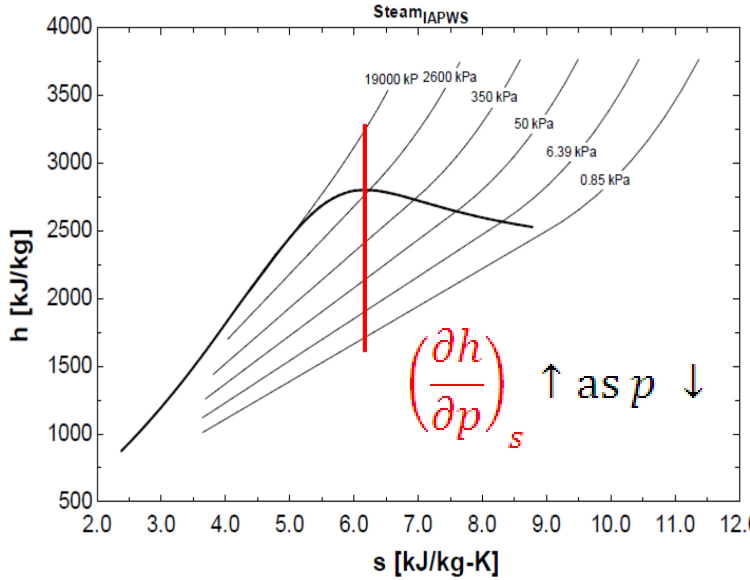
Heat rejection in a thermal power plant

- According to 2^{nd} **law of thermodynamics**, a continuous conversion of heat into work is possible only when **some part of the heat supplied is rejected to a heat sink**
- The amount of **heat rejected** in power plants can be **very large**, e.g. for **1 MW power** generated about **2 MW heat** is **rejected**
- **Heat rejection** in a steam power plant takes place in the **condenser** and through the **chimney**
- Though, **theoretically** a steam power **plant can operate without a condenser** discharging steam from the turbine, directly into the atmosphere, e**fficiency of condensing type power plant** is **higher** than the non-condensing type

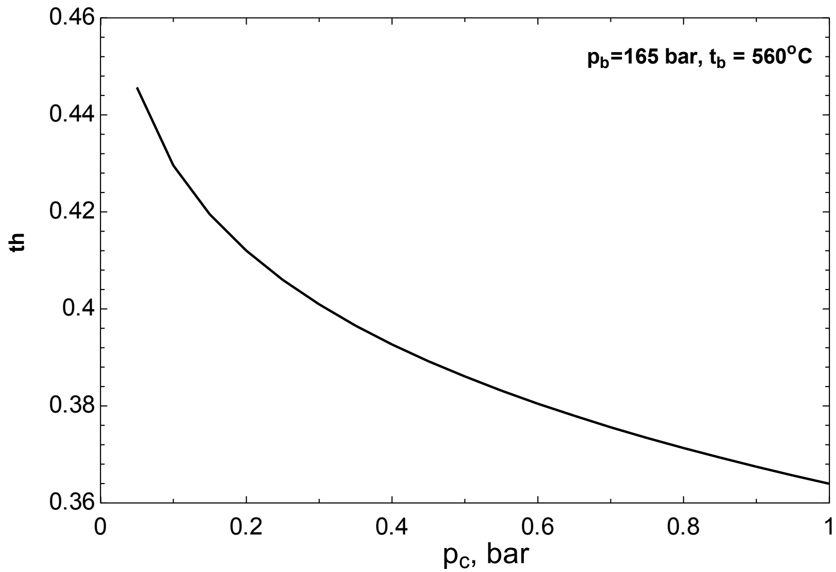
Need for condenser in a thermal power plant

The **rate at which enthalpy drops with pressure** increases **as pressure decreases** leading to higher specific turbine output at lower condensing pressures



Hence **the efficiency** of a steam power plant **improves** as the temperature at which heat is rejected in the condenser **decreases**

Availability of a suitable heat sink puts a constraint the **lowest possible condensing pressure**



For **a given heat sink**, there normally is an optimum condensing pressure where the overall performance of the power plant is best

Condenser classification

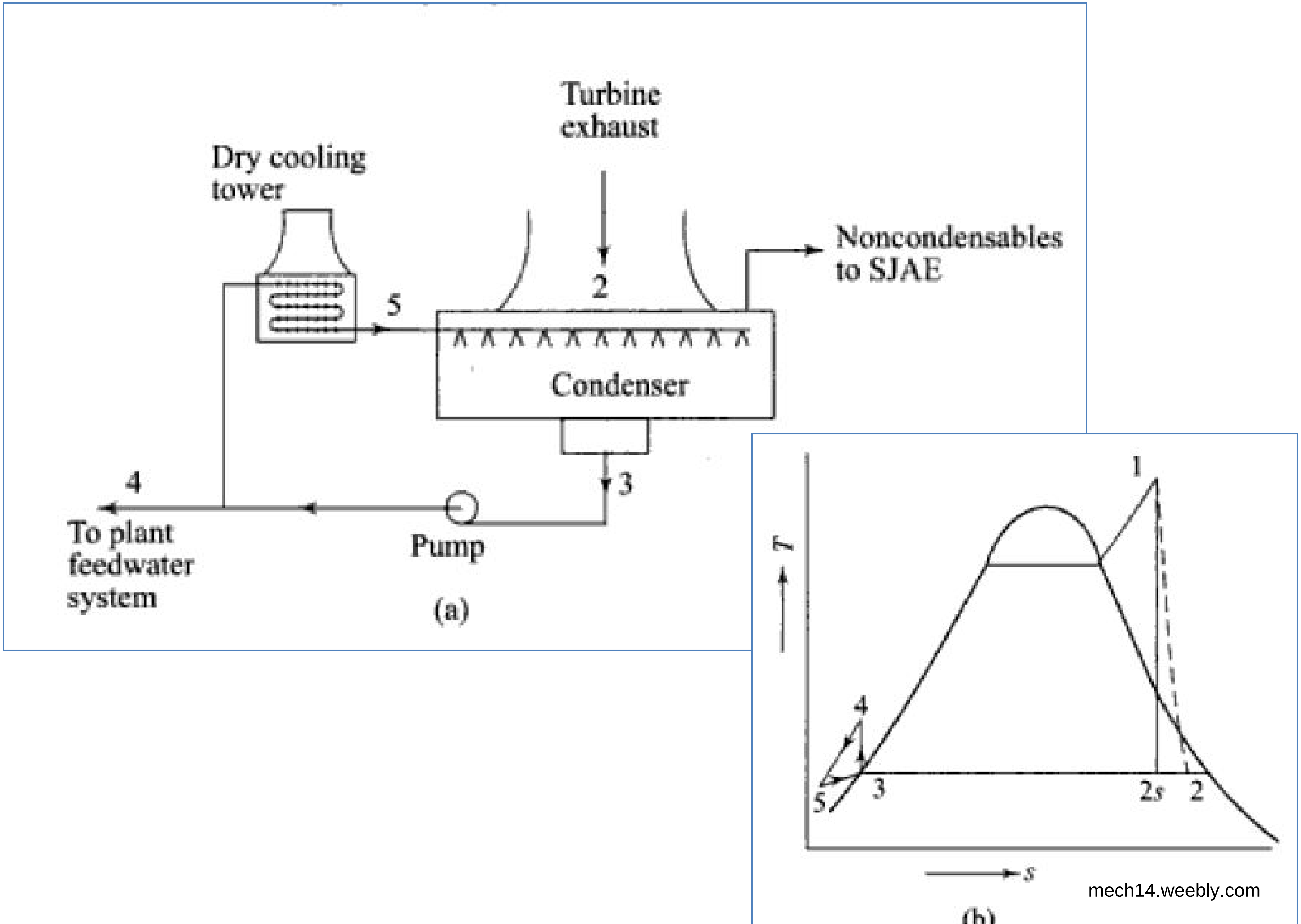
- Depending upon the heat sink, condensers can be classified into:

1. **Water cooled condensers**, or
2. **Air cooled condensers**

- **Water cooled condensers** can be further classified into:

1. **Direct contact type** condensers, and
2. **Indirect contact type** or surface condensers

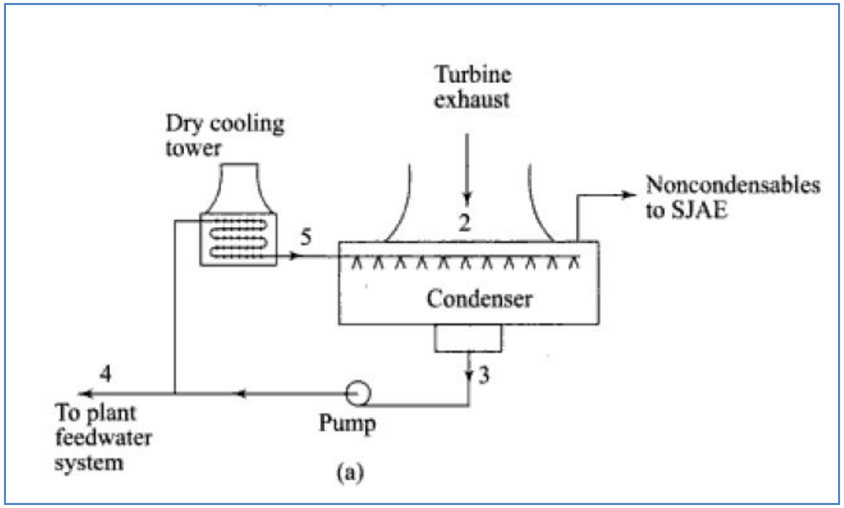
Direct contact type spray condensers



Direct contact type spray condensers

From mass and energy balance for the direct contact spray condenser it can be shown that:

$$\boxed{\frac{\dot{m}_5}{\dot{m}_2} = \frac{(h_2 - h_3)}{(h_3 - h_5)}}$$



This implies that the **amount of water to be circulated by the pump** is much higher than the steam flow rate

The **heat transfer rate** in the dry cooling tower is:

$$Q_{dry\ ct} = \dot{m}_5(h_3 - h_5) \approx \dot{m}_5 c_w (t_3 - t_5)$$

where c_w is the specific heat of the liquid water

Not commonly used in **large power plants** as the **purity** of coolant water **should be very high**

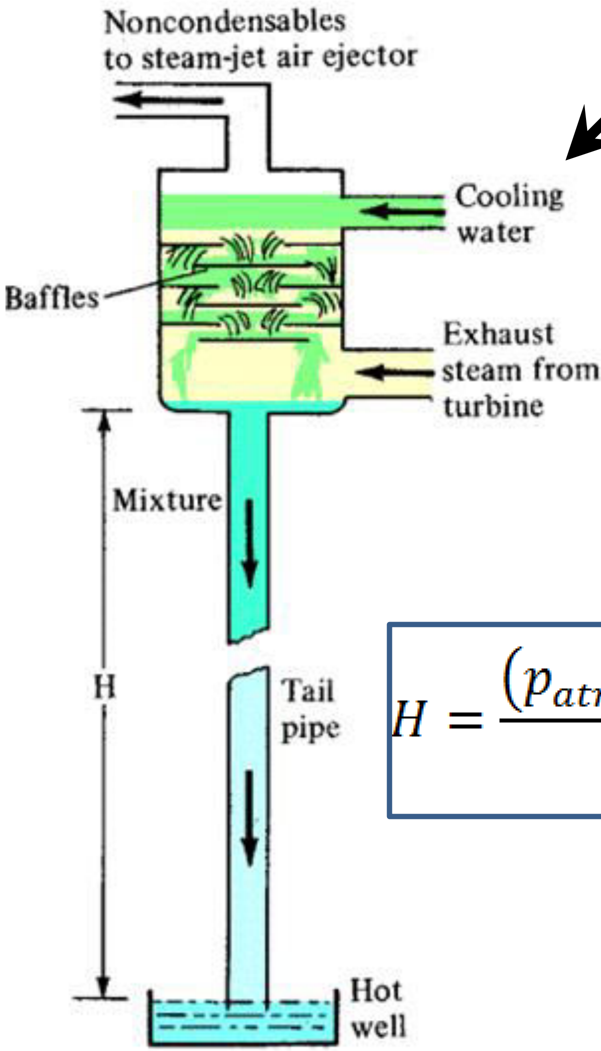
Example 1

- In a direct contact type condenser, 2.4 kg/s of saturated steam at **0.1 bar** (t = 45.8°C) condenses by coming in contact with the water coming from the **dry cooling tower**. Heat rejection in the dry cooling tower takes place between the hot condensed water and air. Neglecting pump work, and taking temperature of air as **38°C** and a minimum required temperature difference of **5 K** for heat transfer in dry condenser, find:
- a) Mass flow rate of condensed water through the condensate pump
- b) Rate at which entropy is generated
- Cp of water = **4.2 kJ/kg.K**. Use the data given below:

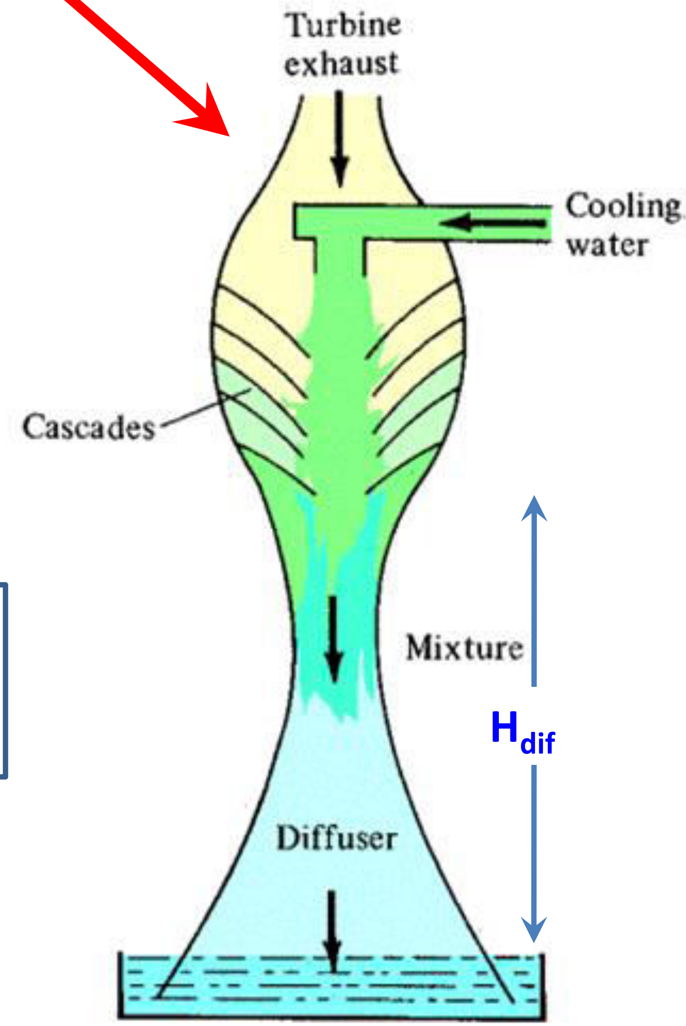
p (bar)	x	h (kJ/kg)	s (kJ/kg.K)
0.1	1	2584	8.148
0.1	0	191.8	0.6493

Ans.: **a) 487.6 kg/s, b) 0.4522 kW/K**

Direct contact, barometric & diffuser type condensers



$$H = \frac{(p_{atm} - p_c + \Delta p_{friction})}{(\rho_w g)}$$



$\boxed{H_{dif} < H}$

Example: p_{atm} = 101 kPa, p_c = 10 kPa, $\Delta p_{friction}$ = 1 kPa

ρ_w = 1000 kg/m^3, g = 9.81 m/s^2 $\Rightarrow$ **H = 9.378 m**

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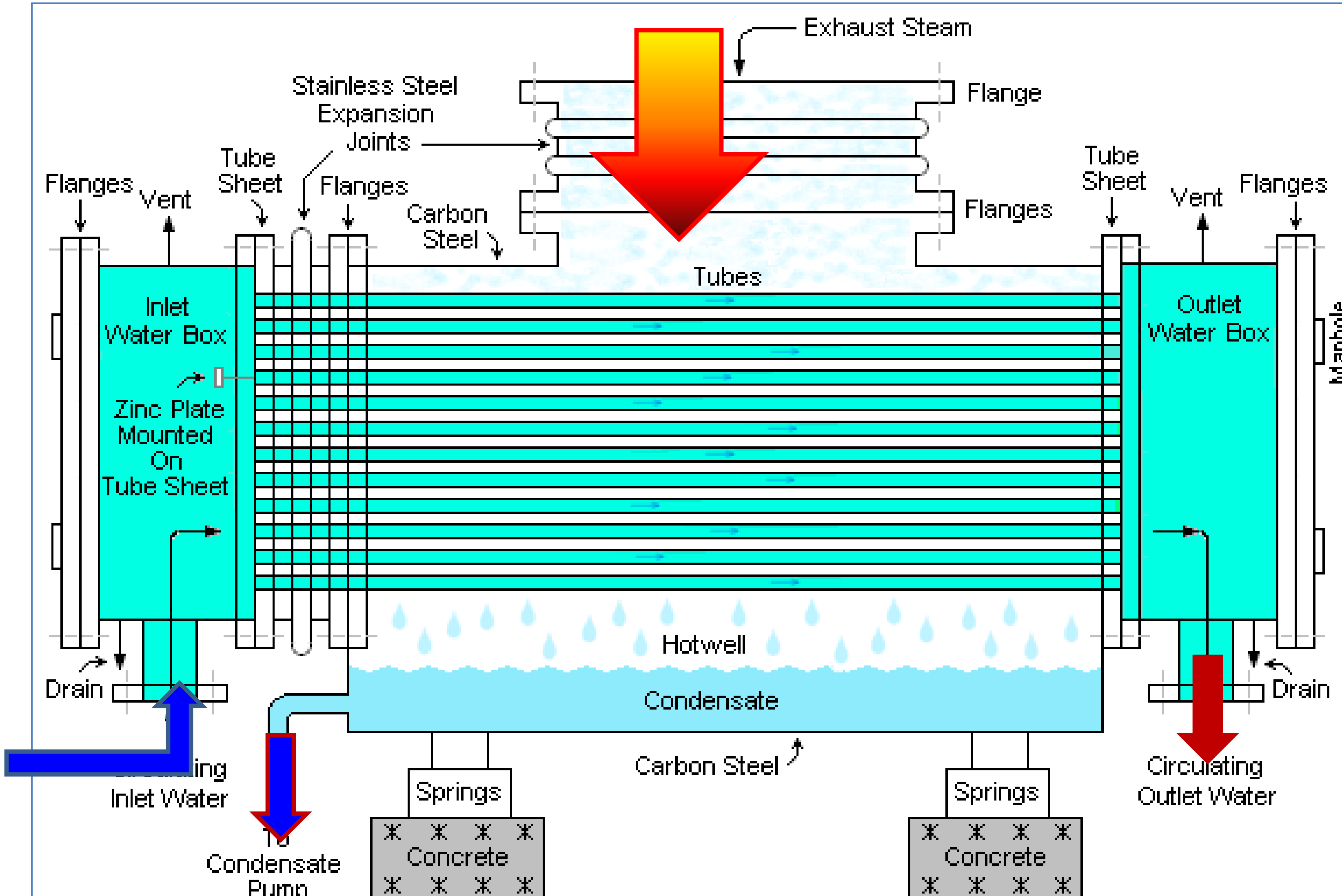
Indirect contact or surface condensers



Note: Tubes are brass, cupro nickel, titanium or stainless steel. The tubes are expanded or rolled and bell mouthed at the ends in the tubesheets.

Typical Power Plant Condenser

Indirect contact or surface condensers

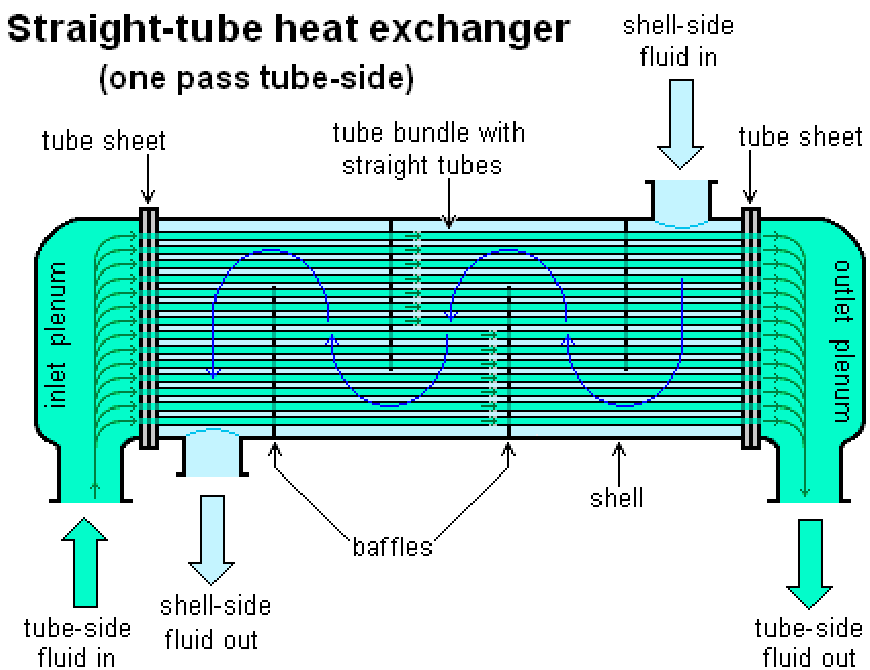
- These condensers, which are similar to **Shell-and-tube type heat exchangers** are **most commonly used** in power plants
- The **low pressure steam** from the turbine condenses on the shell side, while the **cooling water** flows **through the tubes**
- Due to large size, the surface condensers are **made of strong plates** and are **in the form of a box**
- **Zinc** plates which act as **sacrificial anodes** are provided in the water boxes for cathodic protection **against corrosion**

Indirect contact or surface condensers (contd.)

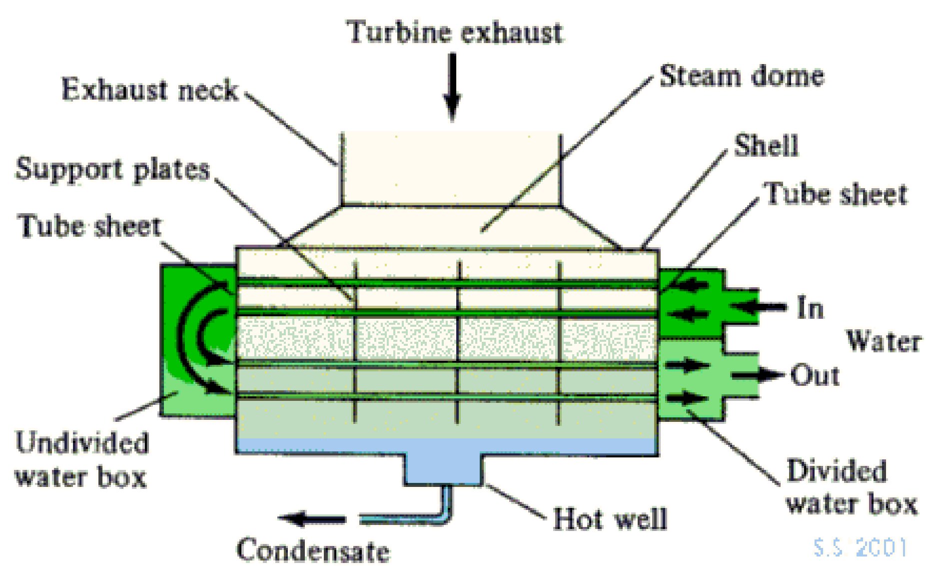
- To **minimize the pressure drop** on the **low pressure condensing steam side**, the **tube spacing at the top** is more and it gradually reduces towards the bottom
- Due to high heat transfer, the number of tubes are also more at the top compared to the bottom $\Rightarrow$ **Funnel shape arrangement**
- The required heat transfer area can be as high as **1,00,000 m^2** with thousands of tubes, each of length as high as **30 m!**

Nippon power plant condensers

- Surface condensers can **Single pass or multi-pass**



1-pass



2-pass

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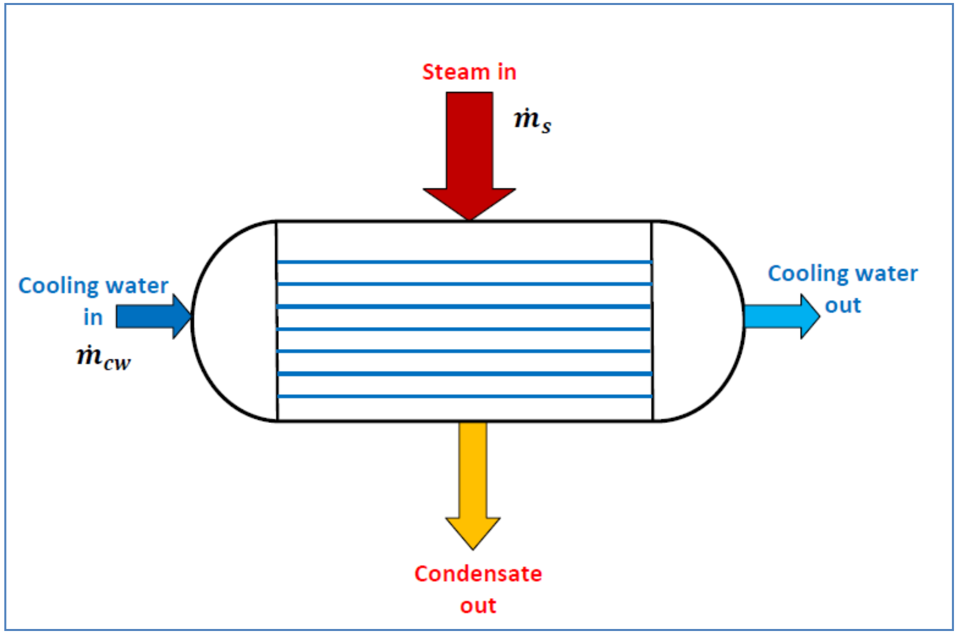
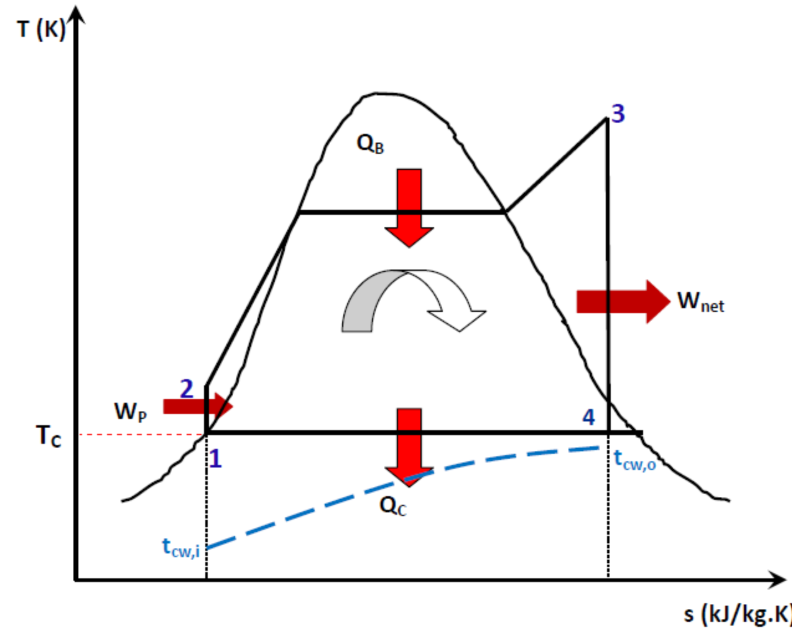
Single-Pass versus multi-pass

- For the **same cooling water velocity** through the tubes, the **required cooling water** mass flow rate **decreases as the no. of passes increase**
- However, the **exit cooling water temperature**, and hence the **condensing temperature increase** with no. of passes
- Thus a **multi-pass condenser** results in **lower water consumption and pumping power**, but **higher condensing pressure**, and hence **lower thermal efficiency** of the plant
- Thus the **final selection** is a **trade-off** between **cooling water cost** and **plant efficiency**

Surface condenser calculations





Heat transfer rate in condenser, **Q_c**:

$$Q_C = \dot{m}_s(h_4 - h_1)$$

$$Q_C = \dot{m}_{cw}c_w\left(t_{cw,o} - t_{cw,i}\right)$$

$$Q_C = UA(LMTD) = UA\left[\frac{\left(t_{cw,o} - t_{cw,i}\right)}{ln\left[\frac{\left(T_C - t_{cw,i}\right)}{\left(T_C - t_{cw,o}\right)}\right]}\right]$$

The **cooling water temperature rise** across the power plant condenser is usually in the range of **6 to 14 K**

The **velocity of cooling water** is usually in the range of **1.5 to 2.5 m/s** for acceptable levels of **water side heat transfer coefficient** and **tube erosion**

Considering all the resistances to heat transfer, the **overall heat transfer coefficient**, **U** is:

$$\boxed{\frac{1}{UA} = \frac{1}{h_w A_w} + \frac{1}{h_s A_s} + R_w + R_{f,w} + R_{f,s}}$$

Where:

h_w and A_w are **heat transfer coefficient** and **area** on **coolant fluid** side,

h_s and A_s are **heat transfer coefficient** and **area** on **steam side**,

R_w is the resistance of the **tube wall**,

$R_{f,w}$ and $R_{f,s}$ are the resistance due to **fouling** on coolant and steam sides, respectively

Overall heat transfer coefficient (U-value) in condensers (Heat Exchanger Institute)

$$U = C_1 C_2 C_3 C_4 \sqrt{V_{cw}}$$

C_1 = Constant that depends on **tube outer diameter**

(2777/2705/2582 for tube ODs of 3/4th, 7/8th and 1” respectively)

C_2 = Correction factor for **inlet temperature of cooling** water

(0.57 for 1.7°C and 1.1 for 37.8°C)

C_3 = Correction factor for **tube material and thickness**

(0.58 for 18 gauge and SS; 0.83 for 18 gauge and Cu-Ni etc..)

C_4 = Correction factor for **tube cleanliness**

(0.85 for clean tubes and less for dirty tubes)

Cleaning of condenser tubes is very important as the cooling water used may contain **many impurities** and may lead to **scale formation** and **clogging of the tubes**

Continuous purging of the condenser is done using **a Steam Jet Air Ejector** in all power plant condensers to **remove the air leaking** into the condenser that is under vacuum

Example 2

- A power plant condenser has to reject **100 MW** of heat. Using the following data and Arthmatic Mean Temperature Difference in place of LMTD, find:

a) **No. of tubes required** and **tube length**

b) **Heat transfer coefficient** on **condensing steam side**

- Condensing steam temperature = **45°C**
- Water inlet and exit temperatures = **35°C** and **41°C**
- Velocity of water = **2.5 m/s**
- ID and OD of tubes = **16.23 mm** & **19.05 mm**
- k-value of tube material = **30.1 W/m.K** (Cu-Ni 70-30)
- U-value based on ID (from $U = C_1 C_2 C_3 C_4 Vw^{0.5}$) = **3407 W/m².K**

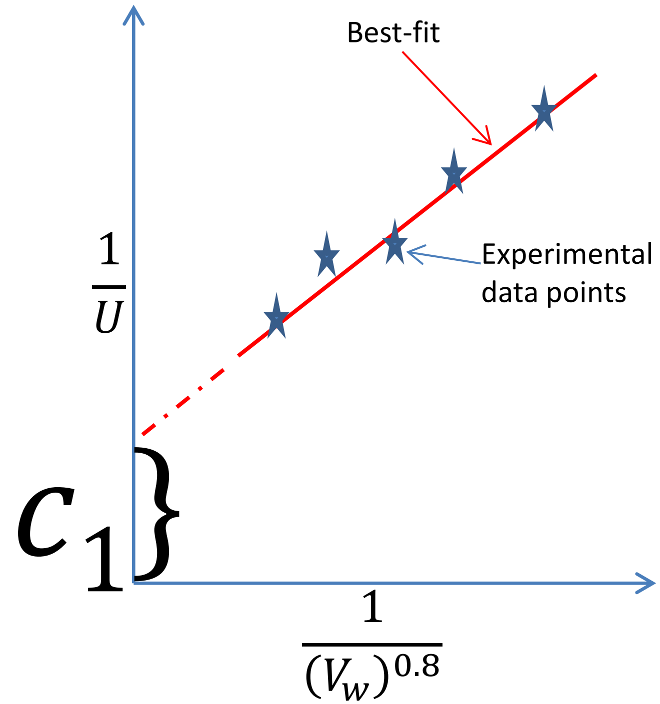
For water: ρ = **1000** kg/m³, μ = **679x10⁻⁶** N-s/m² c_p = **4.2** kJ/kg.K, k = **0.615** W/m.K

Ans.: a) 7675 tubes, 10.72 m long; b) 4583 W/m².K

Wilson's Plot

Wilson's method is an **experimental technique** for estimating heat transfer coefficients under **complex geometry or physical situations**

It is based on the **assumption** that the **heat transfer coefficient** that is being estimated remains constant when the **fluid flow rate on the other side is varied**



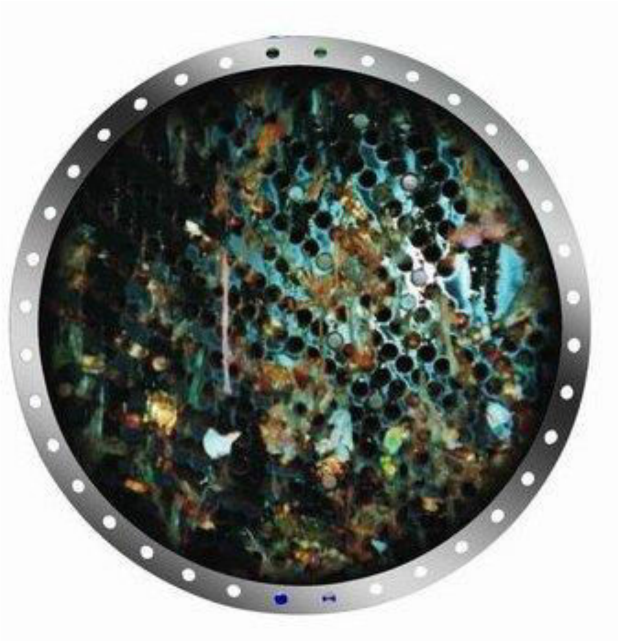
When applied to power plant condenser, **the equation for Wilson's plot is:**

$$\boxed{\frac{1}{U} = \frac{c_o}{(V_w)^{0.8}} + c_1}$$

$$\boxed{where\ c_1 = \frac{1}{h_c} + R_w + R_{f,a} + R_{f,s}}$$

Thus from the intercept and **known values of R_w, $R_{f,a}$ and $R_{f,s}$,** one can estimate the condensation heat transfer coefficient, h_c

Fouling and scale formation in power plant condensers



Macro fouling in steam power plant heat exchanger

Corrosion in condenser tubes

Fouling and scaling are serious problems in condensers

Periodic removal of the scale formed is **required** to ensure high performance

Chemical as well as **mechanical techniques** are used to remove the scale

Scale removal can be done **manually** or **automatically**

Corrosion of tubes is another problem that needs to be taken care of

Fouling and scale formation in power plant condensers

Resistance due to fouling and scale formation **increases with time**

The **problem is more severe** on **cooling water side** as maintaining purity on such a large amount of cooling water is difficult

Periodic de-scaling is required **to maintain the capacity and efficiency** at an acceptable level

However, **too frequent de-scaling** affects **economics** due to **losses** incurred during plant shut-down

Fouling resistance can be estimated from the **U-values** of **brand new condenser** and **used condenser**

$$\boxed{R_f = \frac{1}{U_{old}} - \frac{1}{U_{new}}}$$

In recent times several **technologies** are developed that either prevent scale formation or remove scale automatically **without shutting-down the plant**

Cooling water - Fouling Factors in [m^2K/W]

Conditions	cooling water < 50 ° C cooled fluid < 120 ° C		cooling water > 50 ° C cooled fluid > 120 ° C	
Water velocity	v < 1 m/s	v > 1 m/s	v < 1 m/s	v > 1 m/s
Type of Water				
Sea	0.00009	0.00009	0.00018	0.00018
Brackish	0.00035	0.00018	0.00053	0.00035
Cooling tower with inhibitor	0.00018	0.00018	0.00035	0.00035
Cooling tower without inhibitor	0.00053	0.00053	0.00088	0.00070
City grid	0.00018	0.00018	0.00035	0.00035
River minimum	0.00018	0.00018	0.00035	0.00035
River average	0.00053	0.00035	0.00070	0.00035
Engine jacket	0.00018	0.00018	0.00018	0.00018
Demineralized or distilled	0.00009	0.00009	0.00009	0.00009
Treated Boiler Feedwater	0.00018	0.00009	0.00018	0.00018
Boiler blowdown	0.00035	0.00035	0.00035	0.00035

Example 3

- For the condenser described in **Example 2**, find the **heat transfer rate** and **exit water temperature**, if after usage the **overall heat transfer coefficient** is **reduced** due to **fouling resistance**. **Assume all other parameters to remain same**. The fouling resistance is **0.00018 m^2.K/W**.

Ans.: 69.96 MW (30 % reduction) & 39.2°C

Purging of steam condensers

Due to **operation in vacuum**, power plant condensers are prone to ingress of atmospheric air

Due to **presence of air and other non-condensable gases** inside the condenser, for a given condenser pressure ($p_{condenser}$) the **partial pressure of steam** (p_{steam}) decreases leading to poor condensation

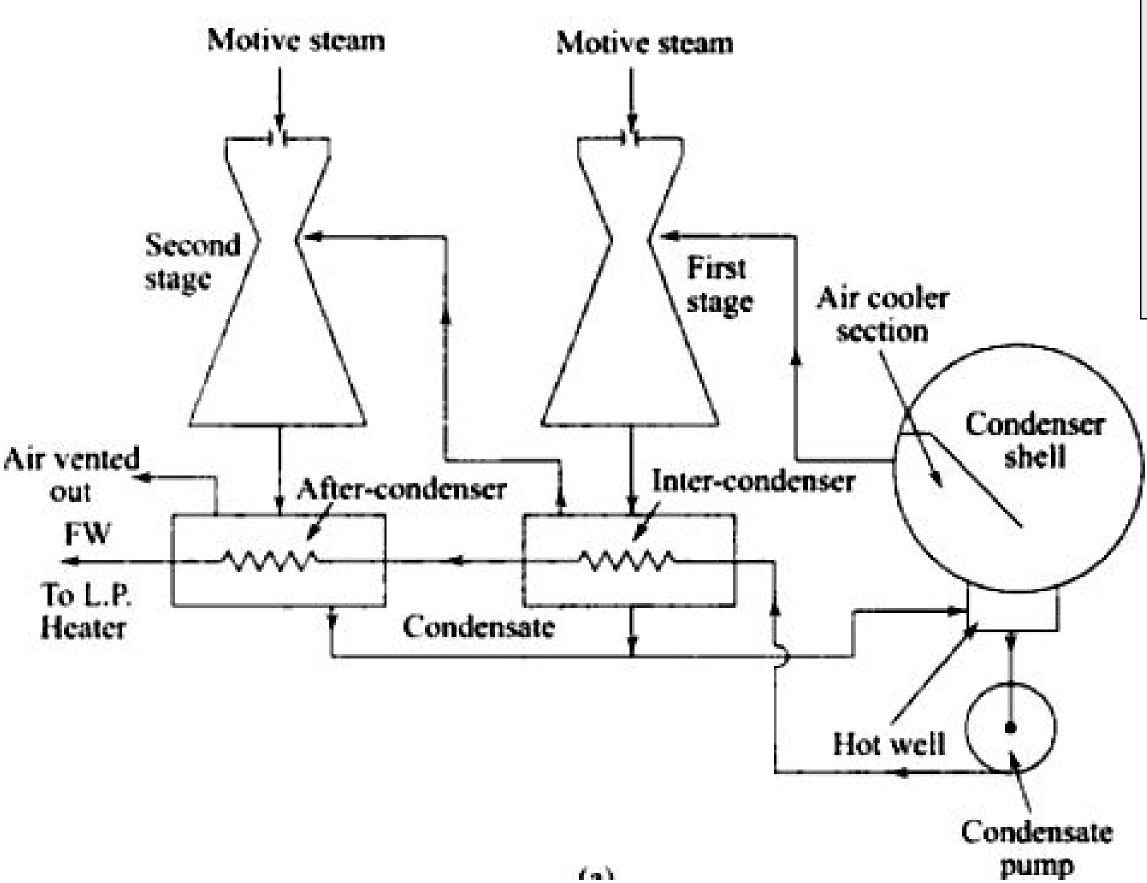
$$\boxed{p_{condenser} = p_{steam} + p_{air}}$$

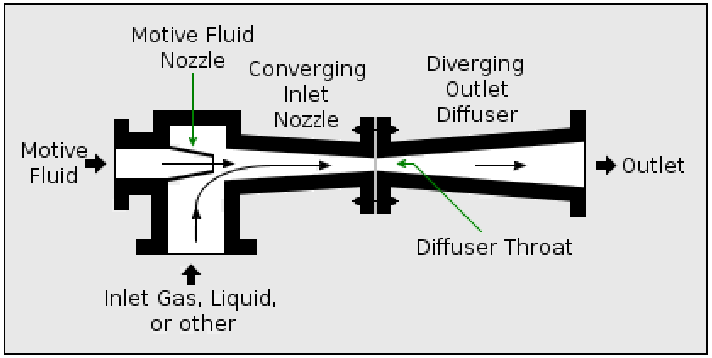
Condensation becomes poor due to **reduced temperature difference** between the **condensing steam** (t_c) and **cooling water** ($t_{w,avg}$)

Thus as **amount of air** inside the condenser (or p_{air}) **increases**, t_c decreases leading to reduced condensation

Purging of air in steam power plant condensers is done using **steam jet air ejectors (SJAE)**

To **minimize the loss of steam** during purging, **air+steam mixture** is extracted **from the air cooler section**, where the partial pressure of water is minimum





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Example 4

- Steam (quality = **0.92**) condenses in a shell-and-tube type, power plant condenser at **40ºC** and leaves the condenser as saturated liquid water. The condenser pressure as indicated by the pressure gage is **0.077 bar** (abs.). The cooling water (**c_p = 4.2 kJ/kg.K**)enters the condenser at 33ºC and leaves at 37ºC. If the flow rate of steam is **50 kg/s**, find
- A) Flow rate of cooling water in m^3/s, and
- B) Rate at which air leaks into the condenser in kg/s
- Assume ideal gas behaviour for air and steam
- **Given at 40ºC**,
- p_{sat} = **7.381 kPa**, h_f = **167.5** & h_g = **2573** kJ/kg, v_f = **0.001008** & v_g = **19.52 m^3/kg**
- Molecular weight of air = **28.97 kg/kmol**
- Density of water at **35ºC = 994 kg/m^3**

Ans.: A) 6.627 m^3/s; B) **3.186 kg/s**

Example 5

If the **U-value** of the condenser based on tube side is **2100 W/m²·K**, find:

a) The number of tubes required if the tube **ID is 25.4 mm** and its **length is 12 m**.

Assume single pass condenser

b) If the heat transfer coefficient on water side follows the equation:

$$Nu_d = 0.023(Re_d)^{0.8}Pr^{0.44}$$

Find the condensing side heat transfer coefficient neglecting tube thickness and scale formation.

Given for water: ρ = **994 kg/m³**, k = **0.6106 W/m.K**, μ = **0.0007196 Pa.s/m** and Pr = **4.855**

Ans.: a) No. of tubes = **11163**,

b) condensation heat transfer coefficient = **3656 W/m²·K**

Air cooled condensers

- In recent years there is a growing interest in air cooled condensers due to the problems associated with water cooled condensers:

1. **Increasing water scarcity** and **levels of water pollution**
2. **Site restrictions** imposed by water cooled condensers
3. **Cooling tower freeze-up** and problem of **tower vapour plume**
4. Problems related to **bio-fouling**, **scaling** etc.

Air cooled condensers

- However, even though air cooled condensers offer solutions to the above problems, the plants that use air cooled condensers suffer as :

1. **Air is bad conductor of heat**, hence, **lower U-value** and **larger surface area** is required
2. **Water** is near **wet bulb temperature**, whereas **air** is at **dry bulb temperature**
3. **Air cooled condensers consume large fan power** and also their **initial cost is high (about 1.5 to 2.5 times)**
4. Higher noise levels and larger land requirements

Air cooled condensers

Air cooled condensers

- Due to very **low heat transfer coefficient** on **airside**, it is necessary to **reduce the heat transfer resistance** on airside by **extending the surface area**
- Hence **externally finned tubes** or other finned surface configurations are used in air cooled condensers
- The **overall heat transfer coefficient** with external airside fins is given by:

$$\boxed{\frac{1}{UA} = \frac{1}{\eta_o h_{air} A_{air}} + \frac{1}{h_s A_s} + R_w + R_{f,s}}$$

- Where η_o is the efficiency of the finned surface
- Compared to **airside resistance**, other resistances **may be** small and **negligible**

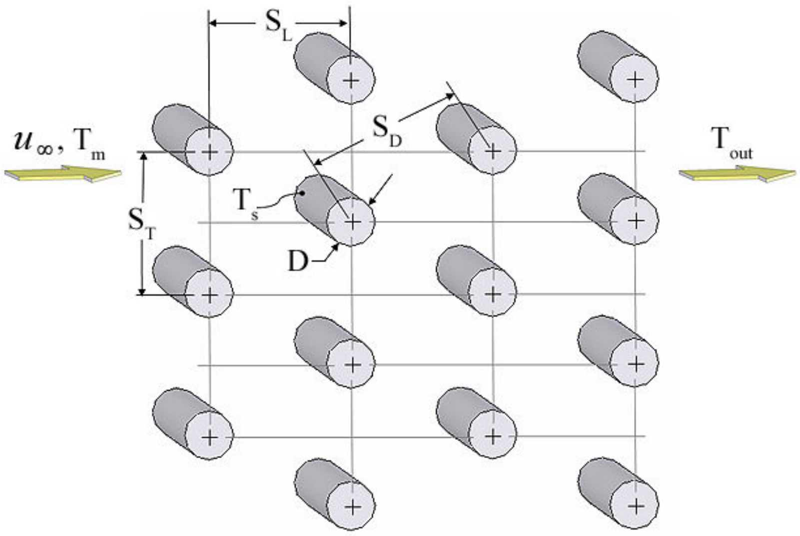
Example-6

- An air cooled condenser is used in a power plant condenser that produces **10 MW** power with an cycle efficiency of **36 %**.. The following is the data:
- Tube inner diameter: **25 mm**
- Length of each tube: **30 m**
- Face velocity of air: **3 m/s**
- Ratio of external-to-internal heat transfer area: **20:1**
- Finned surface efficiency: **90 %**
- Condensation heat transfer coefficient: **4000 $W/m^2.K$**
- Air side heat transfer coefficient: **52 $W/m^2.K$**
- Air side pressure drop: **25 Pa**
- Air density: **1.2 kg/m^3**
- Cp value of air: **1005 J/kg.K**
- Condensing temperature: **45^oC**
- Air inlet temperature: **38^oC**
- Minimum ΔT for heat transfer: **3 K**
- Efficiency of fan: **85 %**

Example-6 (contd.)

- From the given data, find:

1. **Total Number of tubes required**
2. **Height of the condenser**
3. **No. of rows required**
4. **Fan power consumption**



Ans.: 1) 2105

2) 40.95 m

3) 5

4) 108.4 kW

Example-7

- In a power plant condenser, **5000 kg/h** of steam enters the condenser at **38°C** and with a quality of **0.95**. It is estimated that leakage of air into the condenser is **5 kg/h**. If the condensate is at a temperature of **37°C**, find:
- A) Amount of steam carried away along with air due to purging in kg/h
- B) Pumping capacity of the purging system in kg/h
- Given, for steam:
- **At 38°C,** p_{sat} = **6.624 kPa** and v_g = **21.63 m³/kg**
- **At 37°C,** p_{sat} = **6.28 kPa** and v_g = **22.8 m³/kg**
- Gas constant of air = **0.287 kJ/kg.K**
- Assume ideal gas behaviour for water vapour and air.
- **Ans.:**
- A) **57.4 kg of steam**
- B) Pumping capacity of purging system = **1274 m³/h**

Circulating water systems

- The **circulating water system** supplies the necessary **cooling water** to the water cooled condenser of the thermal power plant
- **It also supplies cooling water for**:

1. turbine cooling,
2. water for fire fighting, and
3. cooling of steam generator building, and
4. Reactor building cooling and emergency core cooling in nuclear power plants

- However, **most of the cooling water** (**about 95 %**) is required for **condenser heat extraction**
- The **cooling water** after extracting heat from the power plant condenser has to **discharge** the same to the **environment**

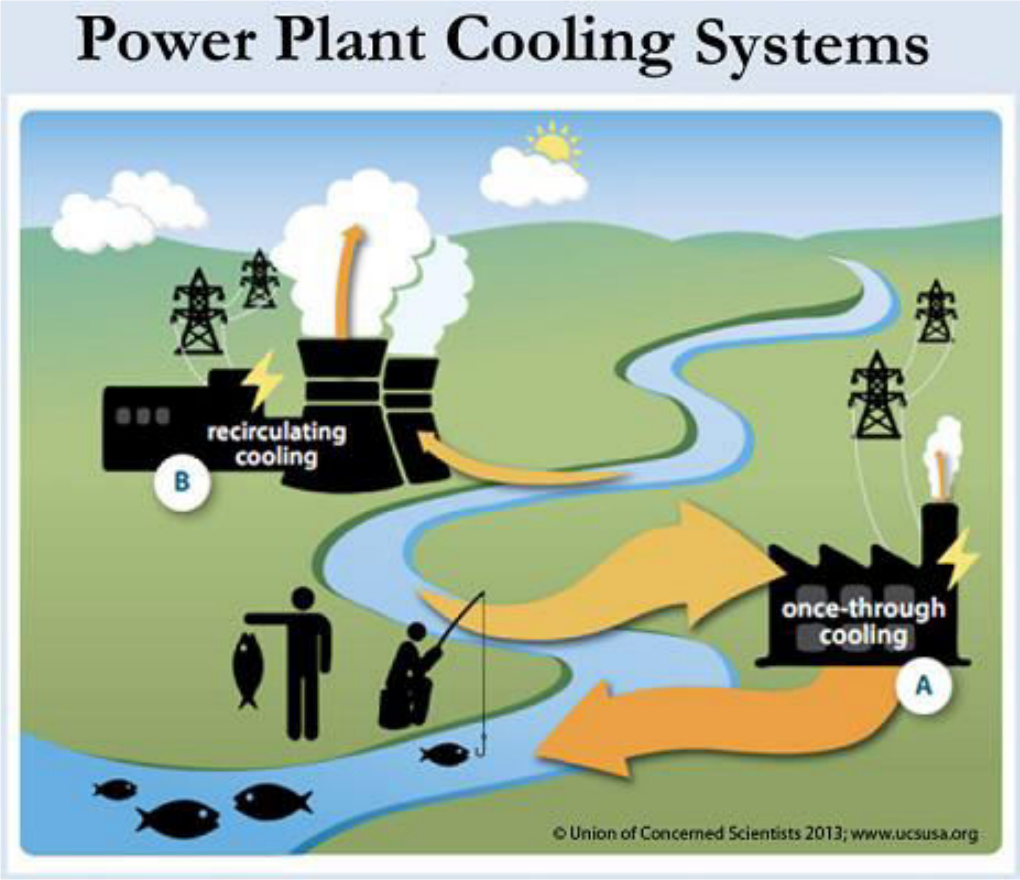
Circulating water systems (contd.)

- The circulating water system can be **classified** as:

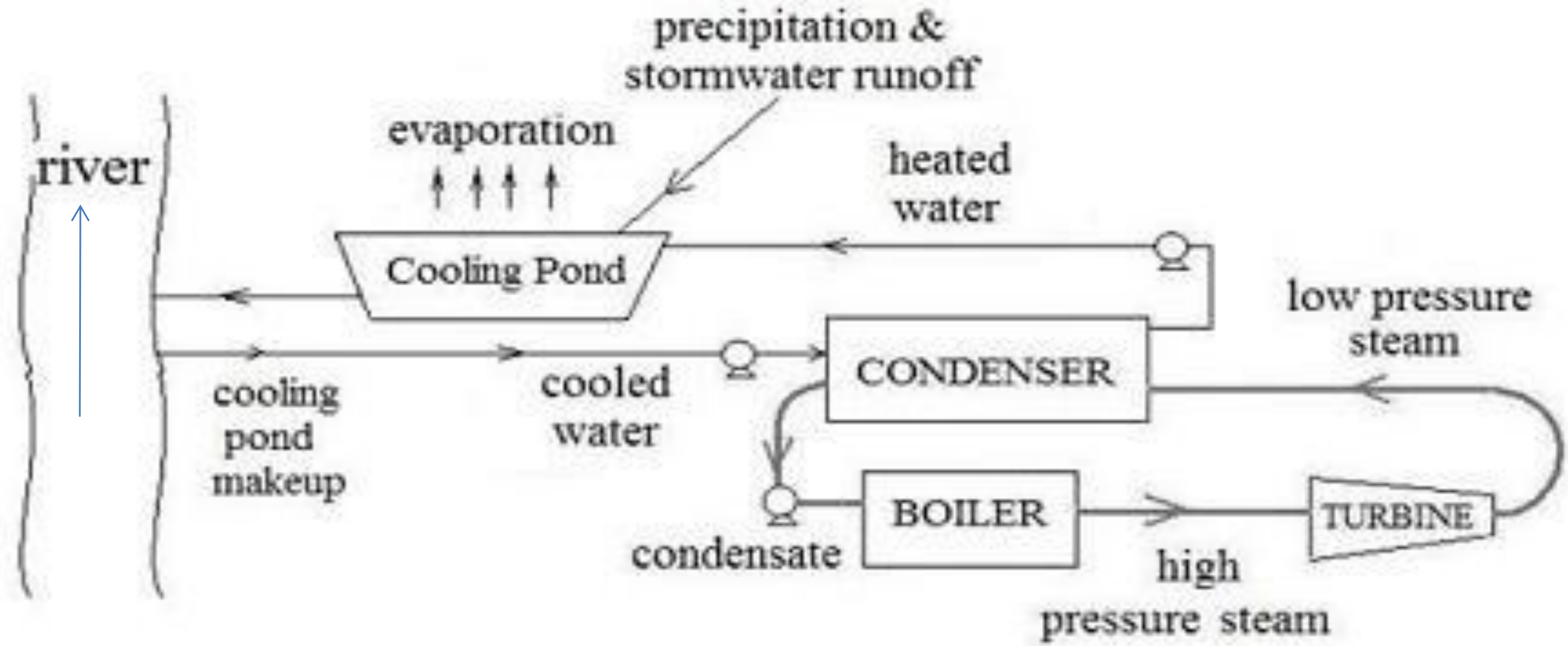
1. **Once through system**
2. **Closed loop system**, and
3. **Combination** of once through and closed loop systems

Once through system

- **Water** is taken from a large water body such as an ocean, river or lake,
- **Pumped** to the **power plant** condenser, and
- The **return water** is **discharged back** into the **water reservoir** in an appropriate manner



Once through system (contd.)



Steam Power Plant Rankine Cycle
with Once Through Cooling Pond

Closed loop system

- In this system the **cooling water from the power plant condenser** is **cooled in a cooling system** and the **cooled water** is **re-circulated**
- The **cooling system** used for cooling the return water **can be**:

1. **A cooling tower**
2. **A cooling pond**
3. **A spray pond**, or
4. **A spray canal**

- Of the above, the cooling tower is most commonly used in large, modern power plants
- A cooling tower can be a wet cooling tower, a dry cooling tower or a combination cooling tower

Spray Pond

Cooling Pond

Cooling Towers

Spray Canal

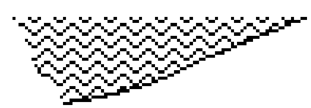
Wet cooling towers – Most commonly used

Wet cooling towers rely on **evaporation of water** for cooling the warm return water from the condenser

Hence there is a **continuous loss of water due to evaporation**

In addition, some amount of water is also lost due to drift and bleed-off (or blow down)

Hence **make-up water** has to be added continuously to account for the losses



Wet Cooling towers

Wet cooling towers can be classified into:

1. **Natural draft cooling towers**
2. **Mechanical draft cooling towers**
3. **Hybrid draft cooling towers**

- **Mechanical draft** cooling towers can be further divided into:

1. **Forced draft** type, or
2. **Induced draft** type

- Depending upon **flow direction**, Cooling towers can be:

1. Counter flow, or
2. Cross flow

Natural Draft cooling towers

Hyperbolic Cooling tower, Westfalen, Germany

Inside a Hyperbolic Cooling tower

Flow of air through the tower is due to buoyancy effect caused by density difference between air inside the tower and ambient air outside the tower

Made of concrete, with diameters as much as 130 m and heights as high as 200 m

High initial cost (60 to 80 % more compared to mechanical draft) but low operating cost

Very sensitive to wind and other ambient conditions

Low water loading capabilities (6.0 to 7.5 $m^3/hr/m^2$ area)

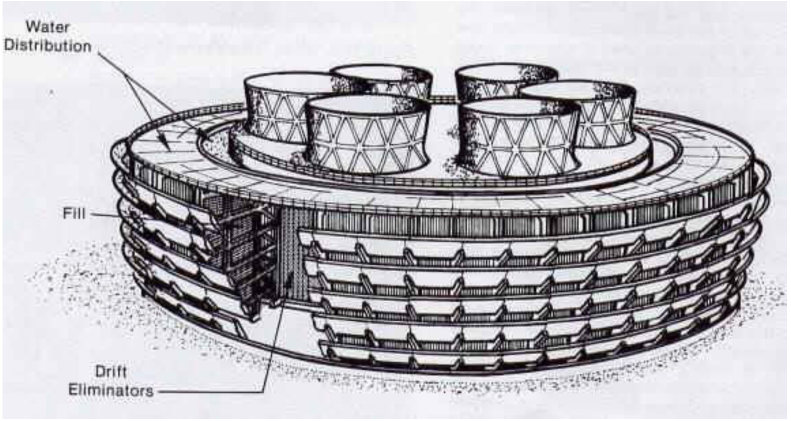
Effective in coastal areas with low dry bulb temperature of air

Mechanical draft cooling towers

Multi-cell, induced draft cooling tower

Multi-cell, concrete cooling tower

- Smaller height requirement
- Compact size due to better heat & mass transfer
- Performance less sensitive to ambient conditions
- Possibility of varying capacity by controlling number of fans and/or fan speed

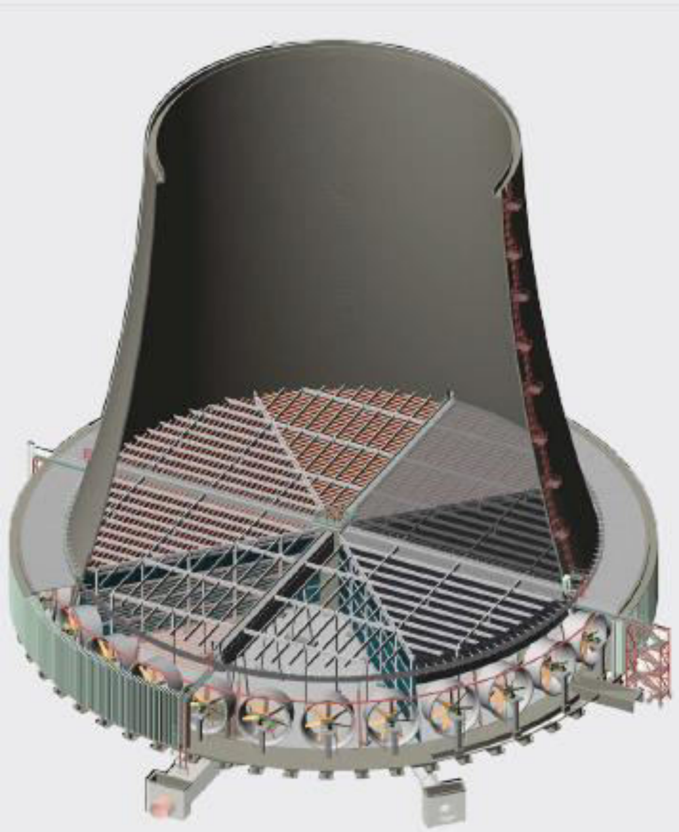


Multi-cell, round, mechanical draft

Higher **running and maintenance costs**, Higher **noise**, Possibility of **recirculation**, Higher **drift losses**

Hybrid draft cooling towers

Courtesy: Marley



Courtesy: Hamon group

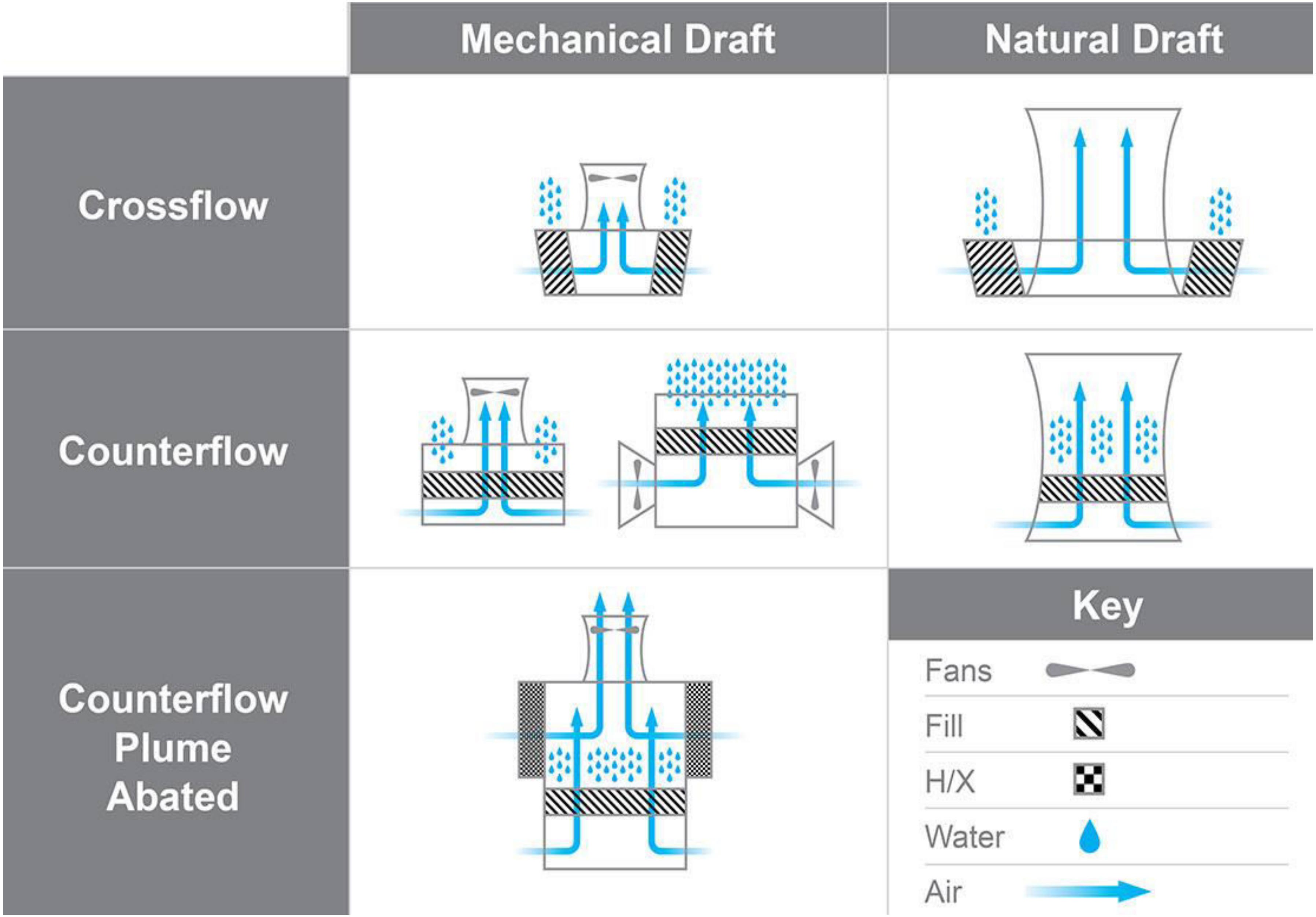
Fan assisted, natural draft cooling towers

Smaller height (compared to natural draft) and reduced power consumption (compared to mechanical draft) due to combined natural and forced draft

Reduced recirculation effect (compared to mechanical draft)

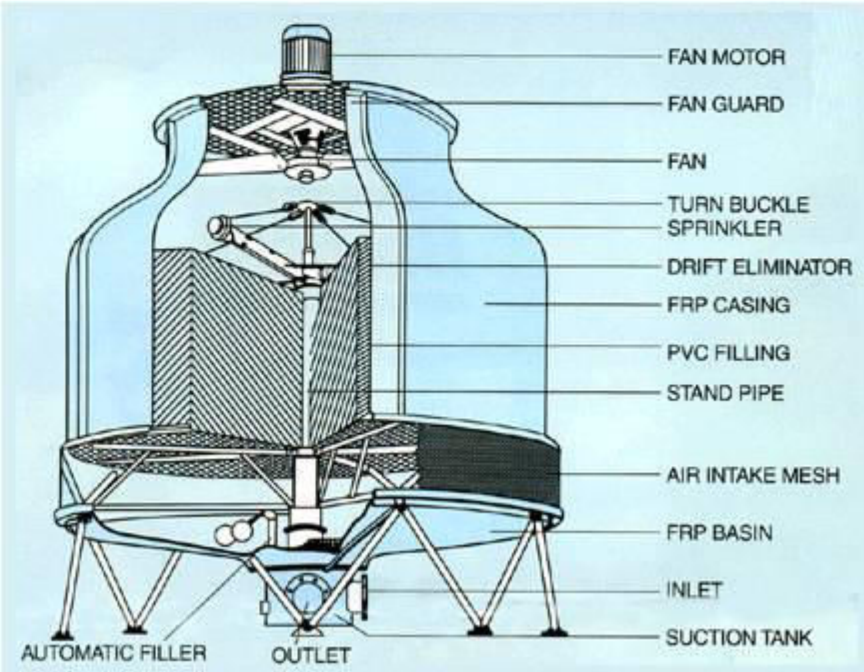
Capability to handle sea water better (compared to mechanical draft) due to dispersion of salt particles through the tall tower plume

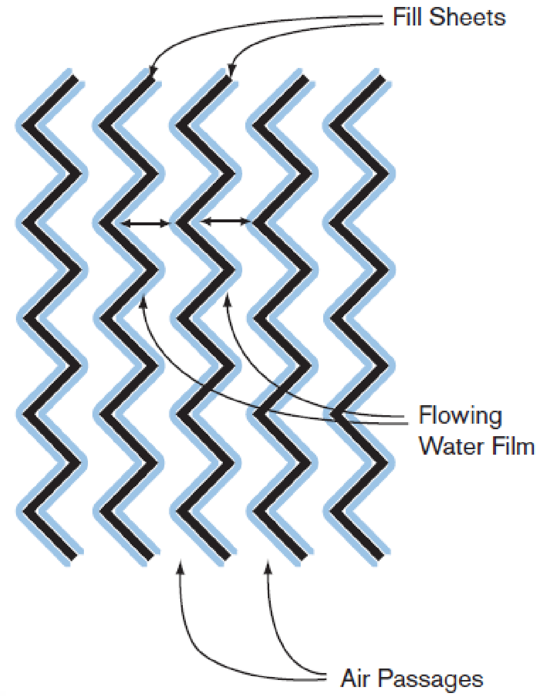
Different arrangements of cooling tower



Source: www.brentwoodindustries.com

High interfacial area is obtained through use of **fills** or **sprays**





Cross Corrugated Fill

- Very efficient
- Can foul
- Max surface area

Vertical Offset Fill

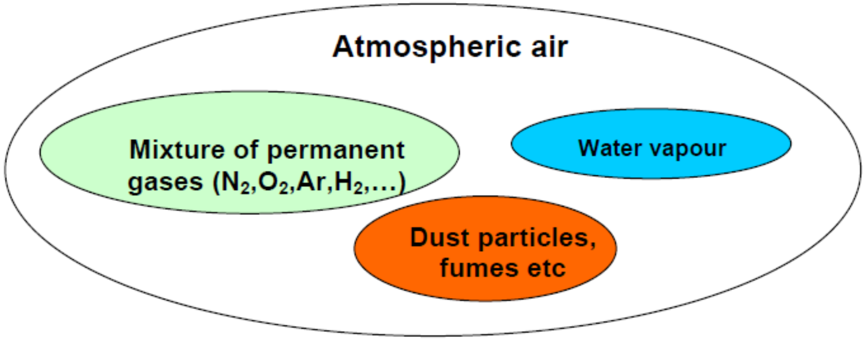
- Efficient
- Less fouling
- Max surface area

Vertical Fill

- Good for dirty water
- Low fouling
- Low pressure drop

Theory of wet cooling tower

- In a **wet cooling tower**, hot water from condenser cools as it comes in direct contact with atmospheric air
- Atmospheric air is a mixture of permanent gases, water vapour and pollutants



- For the purpose of calculations, atmospheric air is treated as a binary mixture of dry air and water vapour
- Dry air: A homogeneous mixture of at least 15 permanent gases – mainly Nitrogen, Oxygen, Argon and Carbon dioxide with a molecular weight of 28.966 kg/kmol
- Water vapour in atmosphere under normal conditions is either in a saturated state or in a superheated state (Molecular weight of water is 18.03 kg/kmol)

- As atmospheric air usually contains some amount of water vapour, it is called as **moist air**
- **Psychrometry:** Study of properties of moist air
- Understanding of cooling tower theory requires basic understanding of psychrometry and wetted surface heat transfer
- **Important properties of moist air:**

1. **Total pressure** (***p_t***) and **partial pressure** of **dry air** (***p_a***) and **water vapour** (***p_v***)
   - Total pressure: Pressure as measured by a barometer
   - From Dalton's law: $p_t = p_a + p_v; (0 \leq p_v \leq p_{sat(t_a)})$
2. **Dry bulb temperature** or DBT (t_a): Temperature of moist air as indicated by a normal thermometer

- The saturation pressure of water, p_{sat} at t_a can be calculated by:

$$\ln p_{sat} = \left(16.54 - \frac{3985}{T_a - 39}\right)$$

- where p_{sat} is in kPa and T_a is in K (i.e., $T_a = t_a + 273.15$)

3. $Relative\ Humidity, \emptyset \approx \left.\frac{p_v}{p_{sat}}\right|_{p_t, t_a}$

4. $Humidity\ Ratio, W\left(\frac{kgw}{kga}\right) = \frac{mass\ of\ water\ vapour}{mass\ of\ dry\ air} \approx 0.622\frac{p_v}{p_t - p_v}$

5. $Dew\ point\ temperature, t_d = t_{sat\ at\ p_v}$

$$t_d \approx \frac{4030(t_a + 235)}{4030 - (t_a + 235)\ln\emptyset} - 235; \qquad (t_d \text{ and } t_a \text{ in °C})$$

6. $Specific\ volume, v_a = \frac{R_a T_a}{(p_t - p_v)}$; $\quad R_a \cong 287\frac{kJ}{kga.K}; T_a\ in\ K, p_t\ \&\ p_v\ in\ kPa$

7. $Enthalpy\ \left(\frac{kJ}{kga}\right) = h_a + Wh_v \approx 1.005t_a + W(2501 + 1.88t_a);\ t_a\ in\ ℃$

8. Thermodynamic wet bulb temperature, t^*: Temperature of water at which the water can bring air to saturation adiabatically at the same temperature and total pressure

9. Wet bulb temperature, t_w: Temperature indicated by a thermometer whose bulb is covered with a wet wick.

For air-water mixtures, in the absence of unusual radiation,

$$t^* \approx t_w$$

From fundamental relations, it can be shown that:

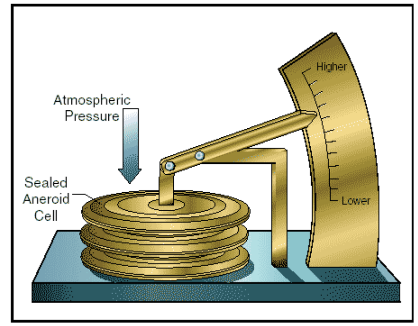
$$\boxed{W = \frac{(2501 - 2.326t^*)W^* - 1.006(t_a - t^*)}{2501 + 1.86t_a - 4.186t^*}}$$

Where W^* is the humidity of saturated air at t^*

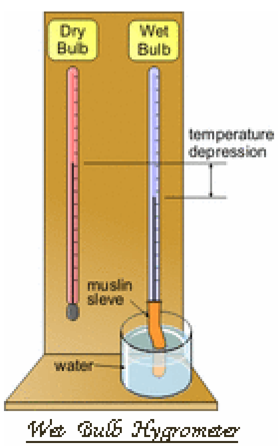
Using the psychrometric properties can be calculated from measured values of total pressure, dry and wet bulb temperatures

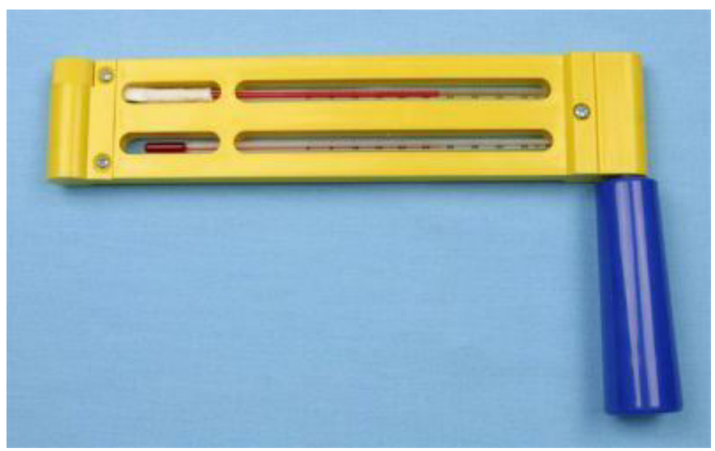
In stead of using equations a psychrometric chart can also be used

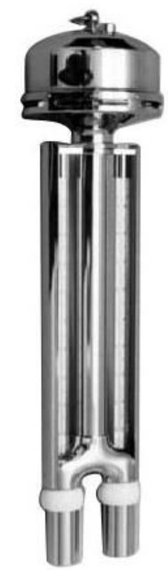
Commonly used instruments for measuring psychrometric properties



Aneroid barometer for measuring total pressure, p_t







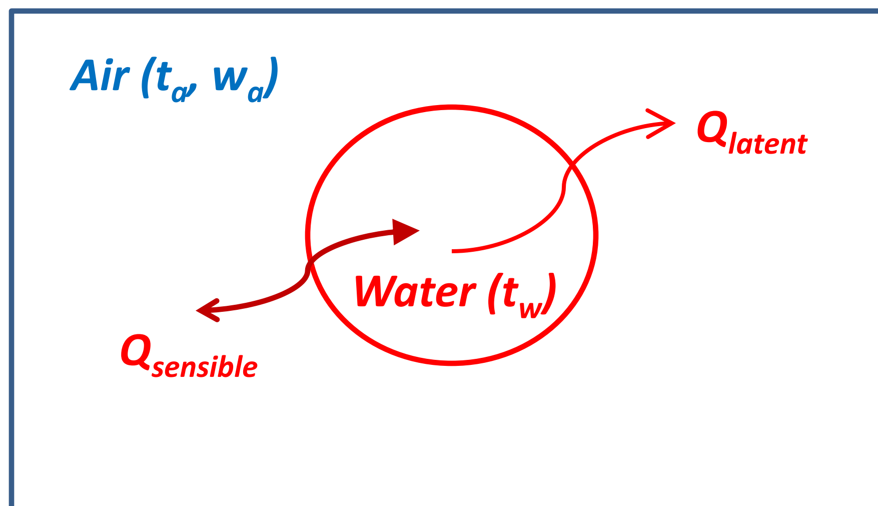
Sling and aspiration psychrometers for measuring DBT and WBT mech14.weebly.com

Theory of wet cooling tower

- In a wet cooling tower, there is an **exchange** of **sensible and latent heat** between **warm water** and **air** with which it comes in contact inside the tower
- **Sensible heat transfer** takes place due to **temperature difference** between water and air
- **Latent heat transfer** takes place due to **vapour pressure difference** between **saturated air film in contact with water** and the **unsaturated surrounding air**

The net heat transfer, Q_{net} is:

$$Q_{net} = Q_{latent} \pm Q_{sensible} = m_w c_w (t_{w,i} - t_{w,o})$$



- For a cooling tower, the net heat transfer, Q_{net}

$$Q_{net} = Q_{latent} \pm Q_{sensible} = m_w c_{pw}(t_{w,i} - t_{w,o}) \Rightarrow \text{should be } \mathbf{+ve}$$

- The latent heat transfer rate is given by:

$$Q_{latent} = h_m A(p_{vs} - p_{va}) h_{fg} \Rightarrow \text{has to be } \mathbf{+ve} \text{ in a cooling tower}$$

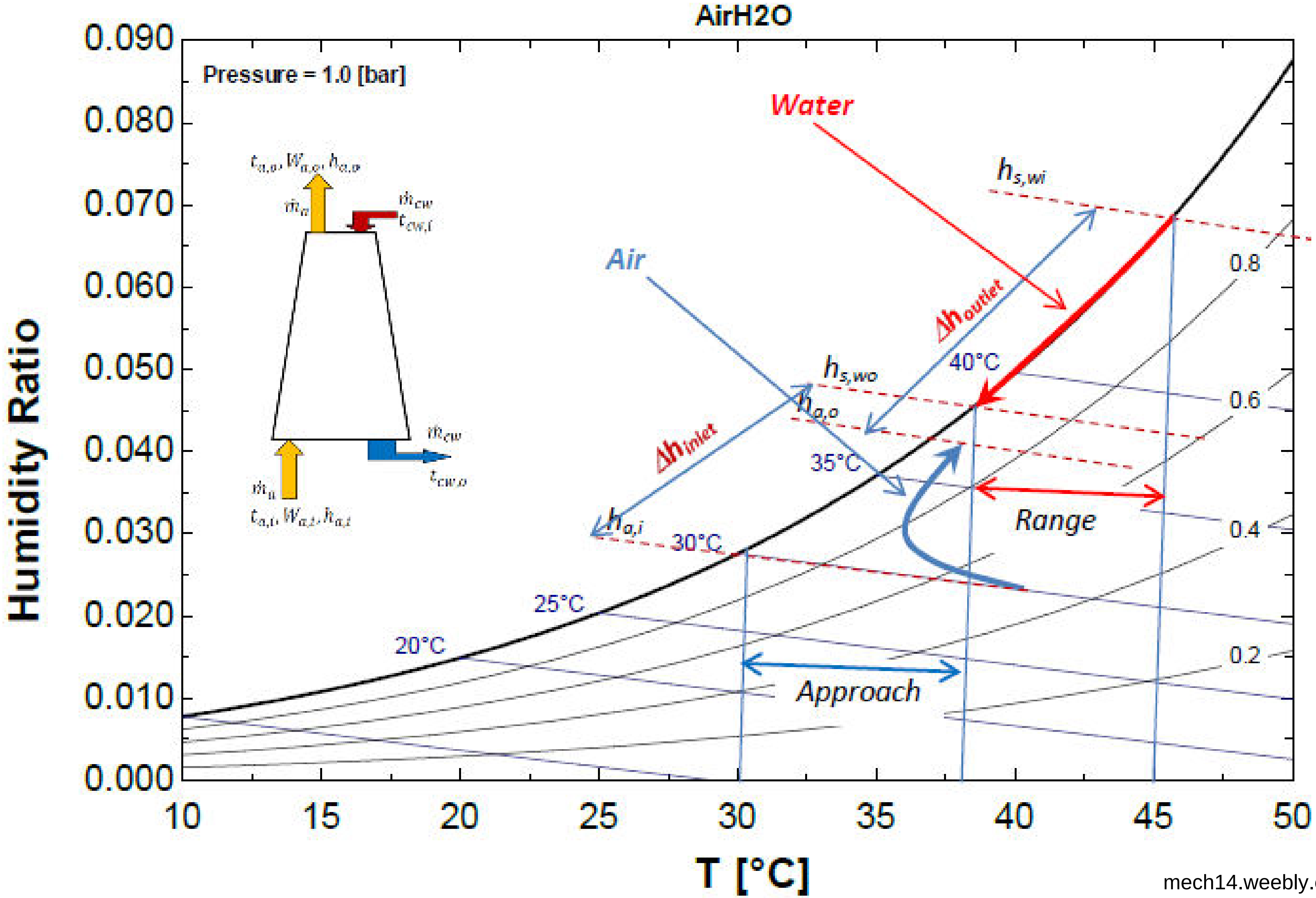
Where:

h_m is the convective **mass transfer coefficient** between water and air,

p_{vs} and p_{va} are the **saturated vapour pressure** at water temperature and **water vapour pressure in air**

h_{fg} is the **latent heat of vapourization** of water

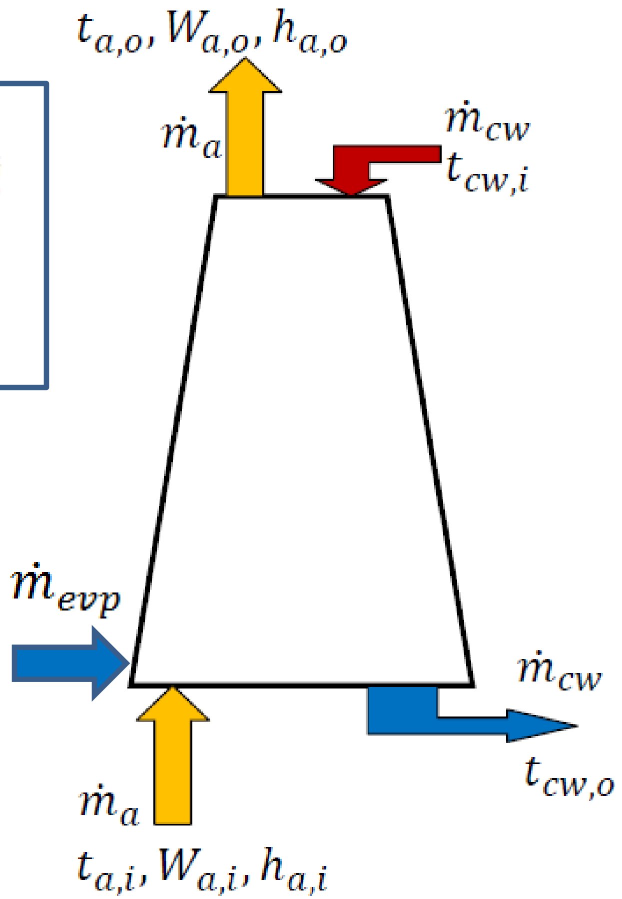
Process undergone by air on psychrometric chart



mech14.weebly.com

From **overall energy balance** considering make-up water required to take care of evaporation:

$$Q_{net} = \dot{m}_a(h_{a,o} - h_{a,i}) - \dot{m}_{evp}h_w = \dot{m}_w c_{pw}(t_{w,i} - t_{w,o})$$



From **overall water balance** across the cooling tower, the **make-up water required for evaporation** is given by:

$$\dot{m}_{evp} = \dot{m}_a(W_{a,o} - W_{a,i})$$

However, the **actual make-up water requirement** is **more than** that required for **evaporation**

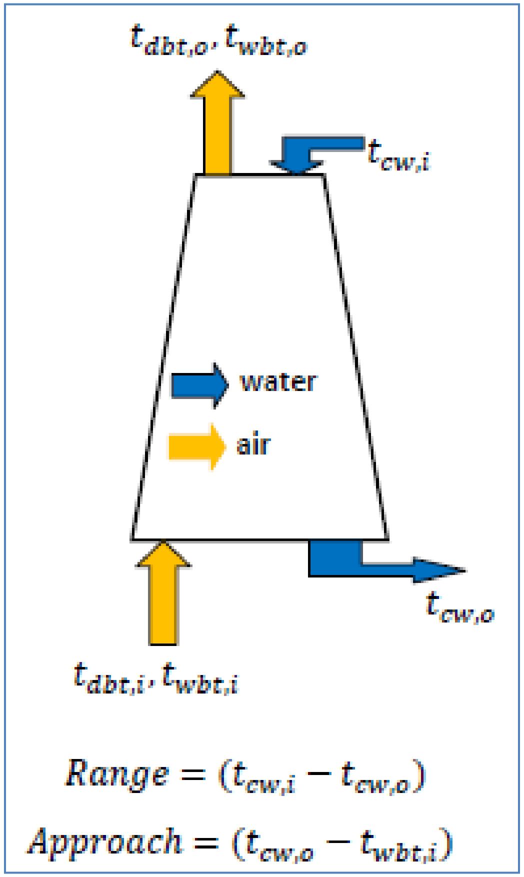
- The **performance of a cooling tower** is indicated in terms of:

1. ***Range:*** Range is the difference between the cooling water temperature at the inlet and the outlet, i.e., the temperature drop undergone by the cooling water as it flows through the cooling tower

$$\text{Range} = (t_{cw,i} - t_{cw,o})$$

2. ***Approach:*** Approach is the difference in between the cooling water outlet temperature and incoming air wet bulb temperature $t_{wbt,i}$, i.e.,

$$\text{Approach} = (t_{cw,o} - t_{wbt,i})$$

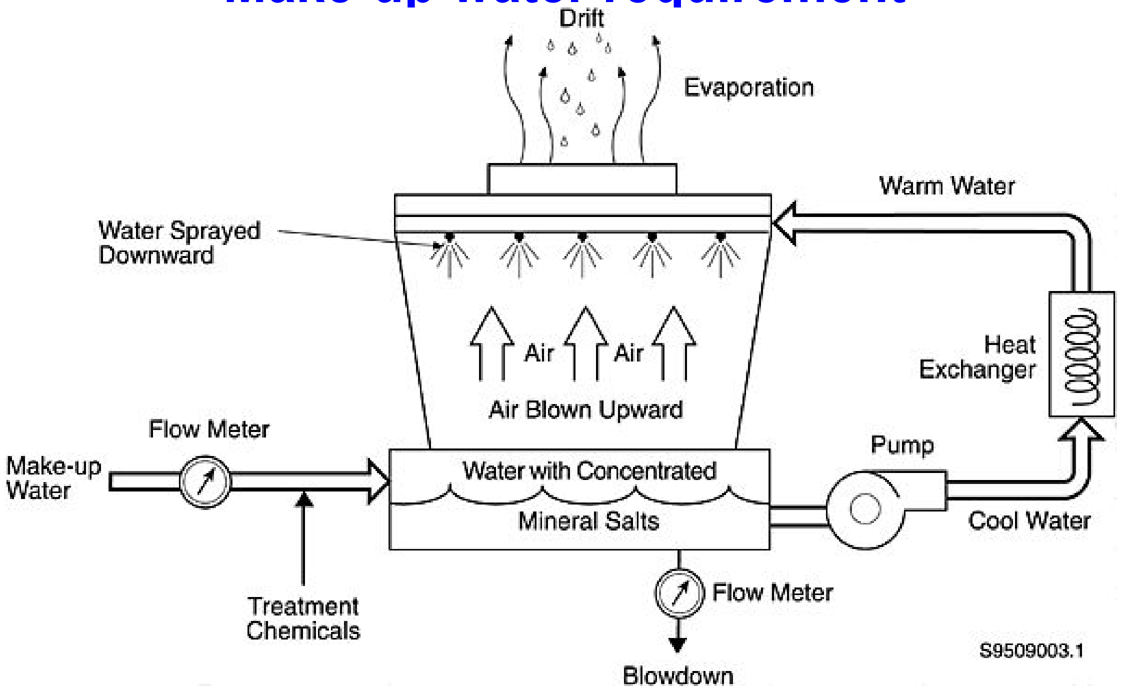


3. Number of Transfer Units (NTU):

$$NTU = \sum \frac{\Delta t_w}{(h_{s,w} - h_a)_i} = \left(\frac{h_c A}{c_{pm}}\right) \frac{1}{\dot{m}_w c_{pw}}$$

Larger the value of NTU, smaller will be the approach and larger will be the size

Make-up water requirement



Make-up water is required to take care of:

1. **Evaporation** – depends upon design and operating conditions
2. **Blowdown** – required to main the concentration level – depends upon evaporation rate and make-up water
3. **Drift losses –** Depends upon design of drift eliminators – in modern cooling towers this is as low as **0.01 to 0.05 %** of circulation rate

http://spxcooling.com/green/leed/water-usage-calculator/

Normal water quality requirements

- Cooling towers act as very effective air washers, i.e., the impurities in incoming air are **absorbed by the water**!
- While this makes the exhaust air purer, the recirculating water becomes impure – level depends on purity of incoming air!
- **Purity level of water affects condenser & tower performance**
- **Normal requirements** of recirculating water in power plants are:

1. pH value between 6 to 8
2. Chlorine content (in the form of NaCl) < 750 ppm
3. SO_4 content < 1200 ppm
4. $NaHCO_3$ content < 200 ppm
5. Maximum water temperature $\approx 50^oC$, and
6. No unusual contaminants

Estimation of Blowdown requirement

The **blowdown required**, **B** to **maintain the concentration of a particular impurity** at an **acceptable level** in the **recirculating water** is given by the equation:

$$\boxed{B = \frac{E - [(C-1) \times D]}{(C-1)}}$$

In the above equation;

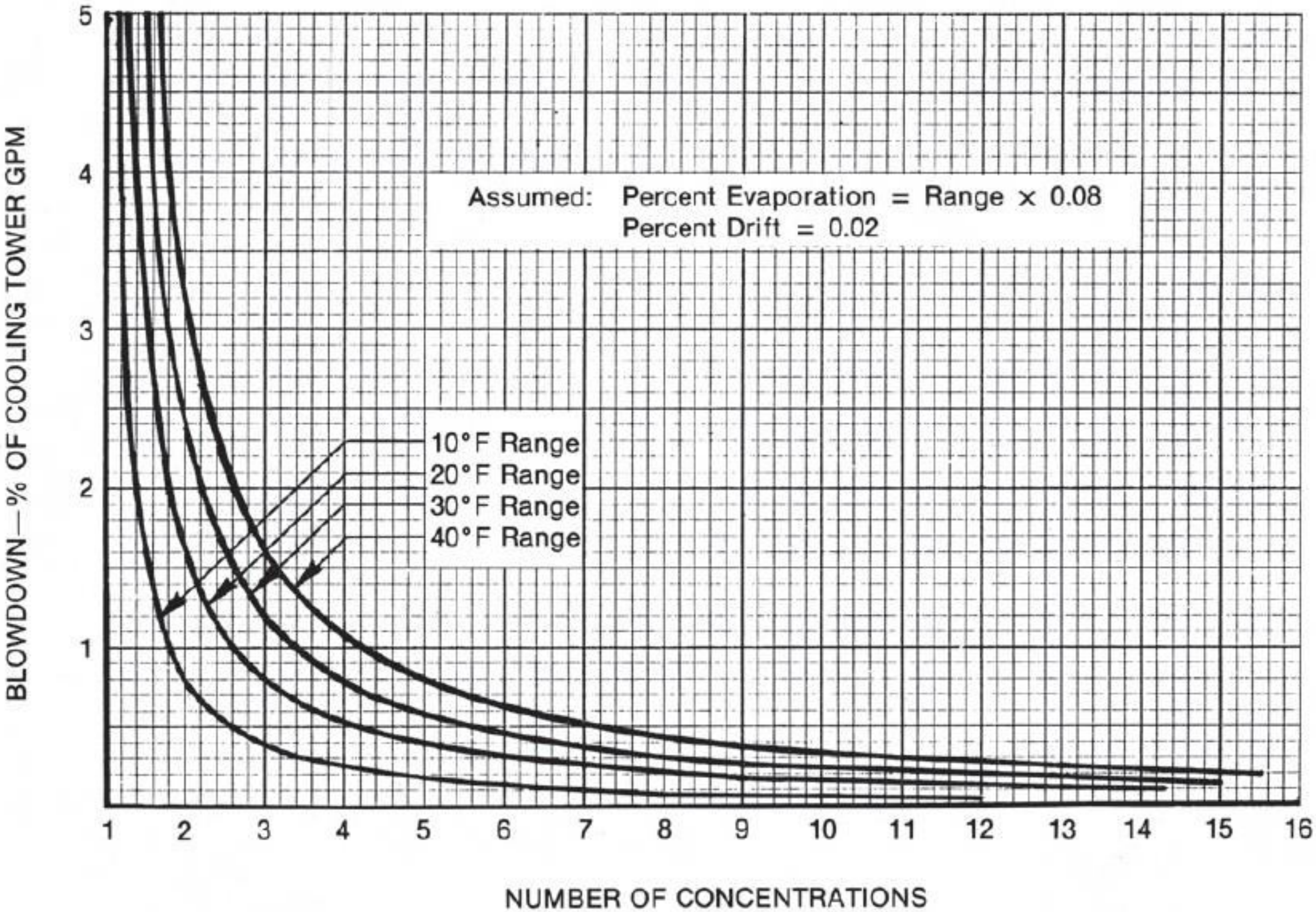
B = Blowdown required (lpm or gpm)

D = Drift loss (lpm or gpm) ≈ **0.02 %** of recirculated water flow rate

E = Rate of evaporation (lpm or gpm) ≈ **1.5 %** of recirculated water flow rate, and

C = Acceptable contaminant concentration in the recirculated water

Blowdown requirement



Cooling Tower Fundamentals, SPX Cooling Technologies, Inc, USA, 2nd Edn., 2009

Example-8

- Estimate the make-up water requirement of a power plant **(in m^3/day)** using the data given below:
- Power plant capacity : **500 MW**
- Condenser heat rejection rate: **0.6 MW/MW**
- Cooling tower range: **6 K**
- Concentration of Cl in make-up water: **250 ppm**
- Allowable Cl concentration in recirculating water: **750 ppm**
- Evaporation loss: **1.5 %** of recirculating water flow rate
- Drift loss: **0.02 %** of recirculating water flow rate
- Specific heat of water = **4.2 kJ/kg.K**

Ans.: **23143 m^3/day** $\approx$ daily water consumption **of 1.5 lakh** people

Example-9

- **3 kg/s** of water from condenser enters a cooling tower at **65°C** and leaves at **30°C**. The make-up water enters the cooling tower at **28°C**. Atmospheric air at **40°C** and **40 %** relative humidity enters the cooling tower and exits as **saturated air** at **35°C**. The air pressure drops by **300 Pa** as it flows through the cooling tower. **Cp** of water = 4.2 kg/kJ.K
- Assuming ideal gas behaviour for atmospheric air find:
- a) Heat transfer capacity of the cooling tower
- b) Make-up water requirement per day
- c) Fan power requirement assuming a fan efficiency of **80 %**

- **Ans.: a) 441 kW, b) 17539.2 kg/day, c) 3.885 kW**

Example-11

- In a small cooling tower **5.5 kg/s** of water is cooled from an inlet temperature of **44^{o}C** by bringing it in contact with **9 m^3/s** of air. The air enters the tower at 18^{o}C and **60 % RH**. The induced fan which maintains the required air flow consumes **4.75 kW** of power. a) Find the exit temperature of water, if the air leaves the cooling tower at **26^{o}C** and **100 % RH**. b) Also find the make up water requirement, assuming that water is added outside the cooling tower.

- **Ans.: a) 23.98^{o}C, b) 0.1478 kg/s**

Cooling water treatment

- **Contaminant**s in the cooling water cause the following problems:

1. **Scale formation** in condenser tubes
2. **Fouling** of condenser tubes
3. **Tube erosion** by suspended particles
4. **Corrosion** of metallic parts
5. **Health and environmental problems**

- For effective operation of the power plant, the **water used** in a cooling tower has to be **cleaned** of the following **contaminants**:

1. **Bi-carbonates** and **sulphates** of Ca, Na and Fe
2. **Suspended solids, silt, sand etc**
3. **Biological contaminants**, e.g. **algae, bacteria**

- A wide variety of **physical (filtration)**, **chemical** and **non-chemical techniques** are employed to treat the cooling water
- Since some amount of **cooling water is discharged back into the environment** in the form of **evaporation**, **purge** (or blow-down), **leakage** etc., the **water treatment procedure** has **to meet the environmental safety guidelines**

Important issues related to wet cooling towers

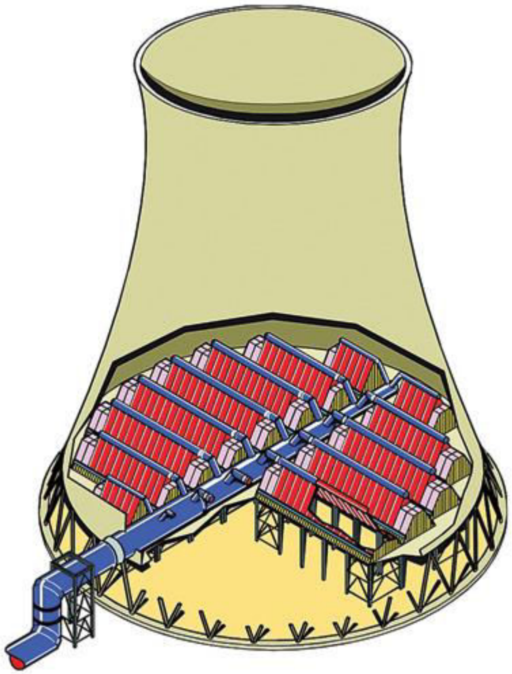
- Large **requirement** of **treated make-up water**
- **Discharge of pollutants** containing **chlorine**, **chromium**, **zinc** etc. into the environment through **purging, leakages, drift and evaporation**
- **Atmospheric plume formation** affecting visibility and aesthetics
- **Fan noise**
- Possibility of **tower freezing** leading to partial or complete tower collapse
- **Legionnaire's disease**

Dry cooling towers

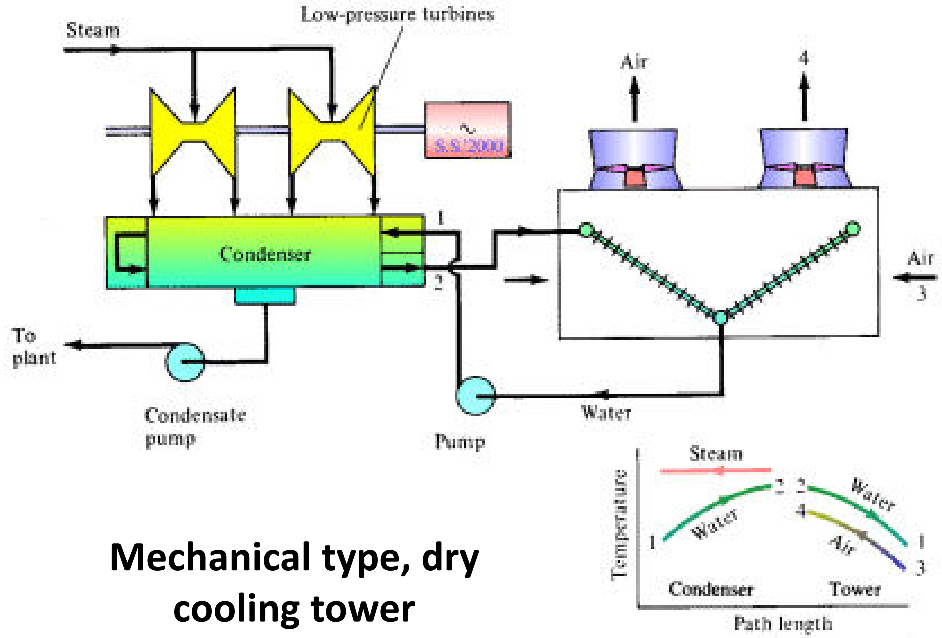
In dry cooling tower the return water from the condenser is **cooled sensibly** using atmospheric air

A **dry cooling tower** can be;

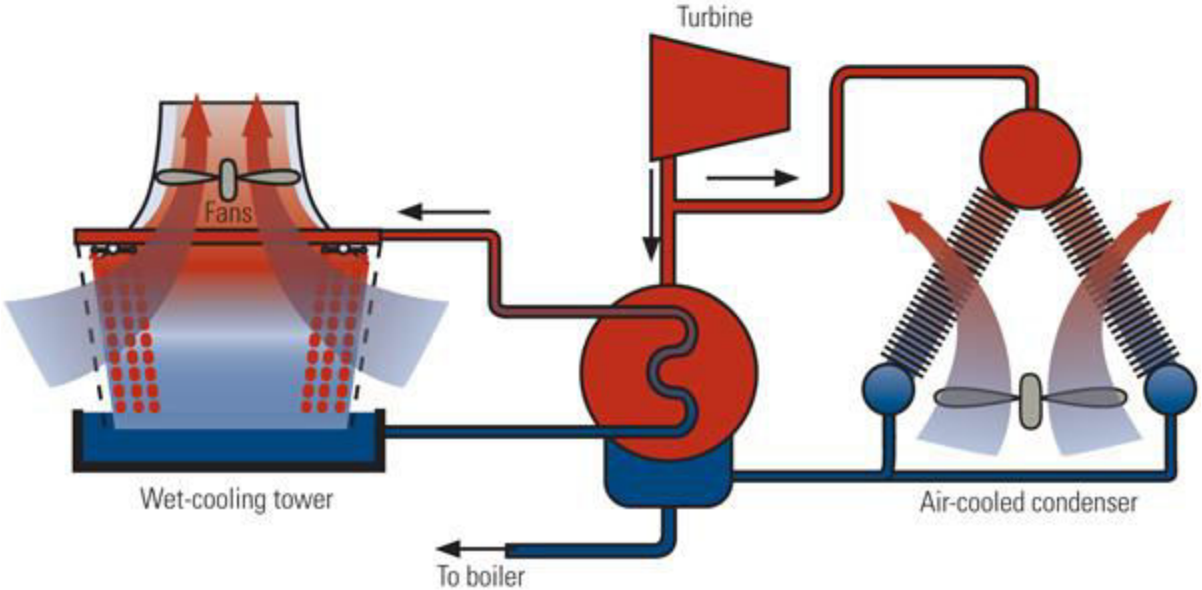
1. **Natural draft type**, or
2. **Mechanical draft type**, or
3. **Hybrid**



Natural draft type, dry cooling tower



Mechanical type, dry cooling tower



Hybrid Cooling Tower

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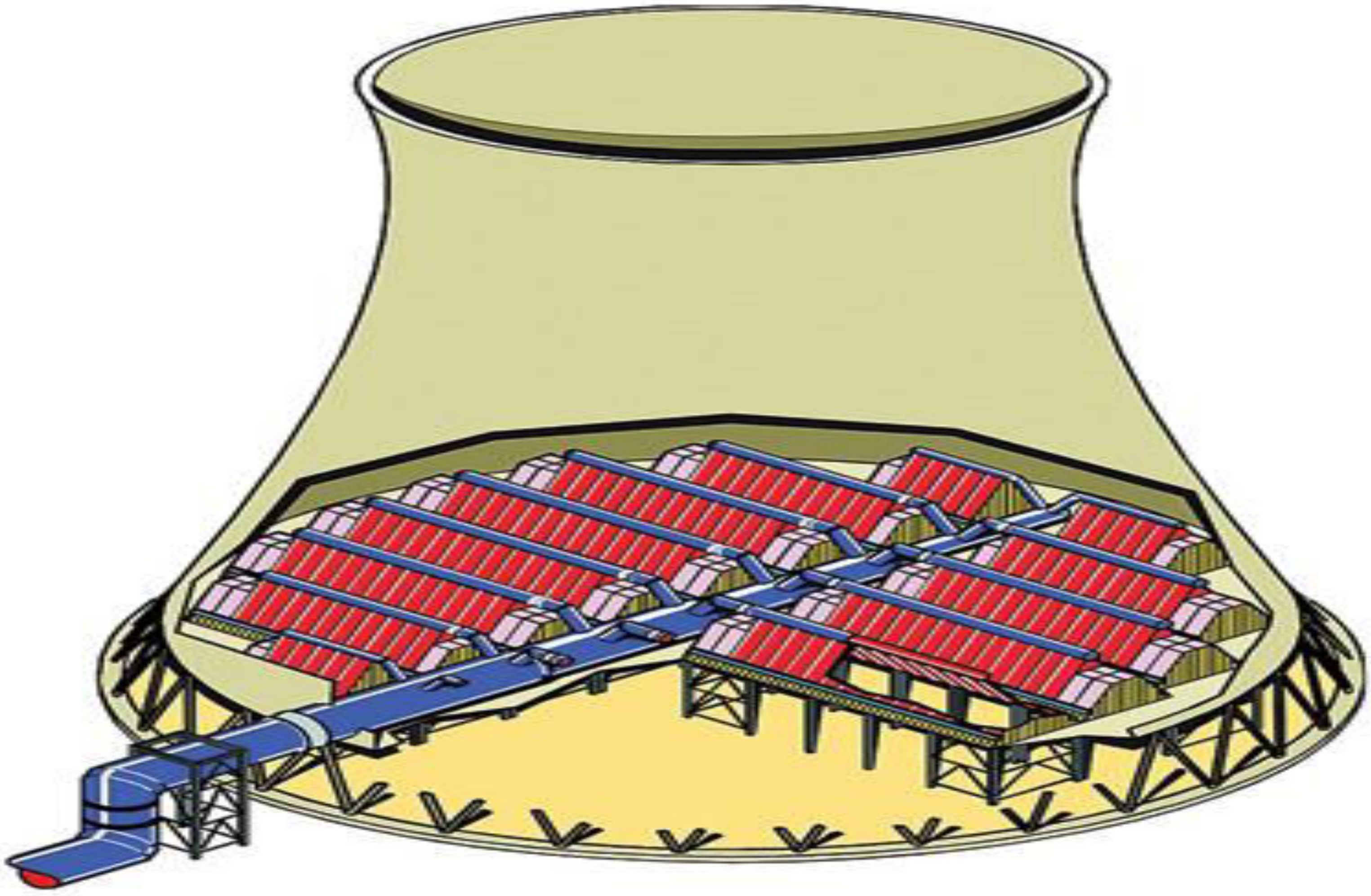
Dry cooling towers



Natural draft type, dry cooling tower

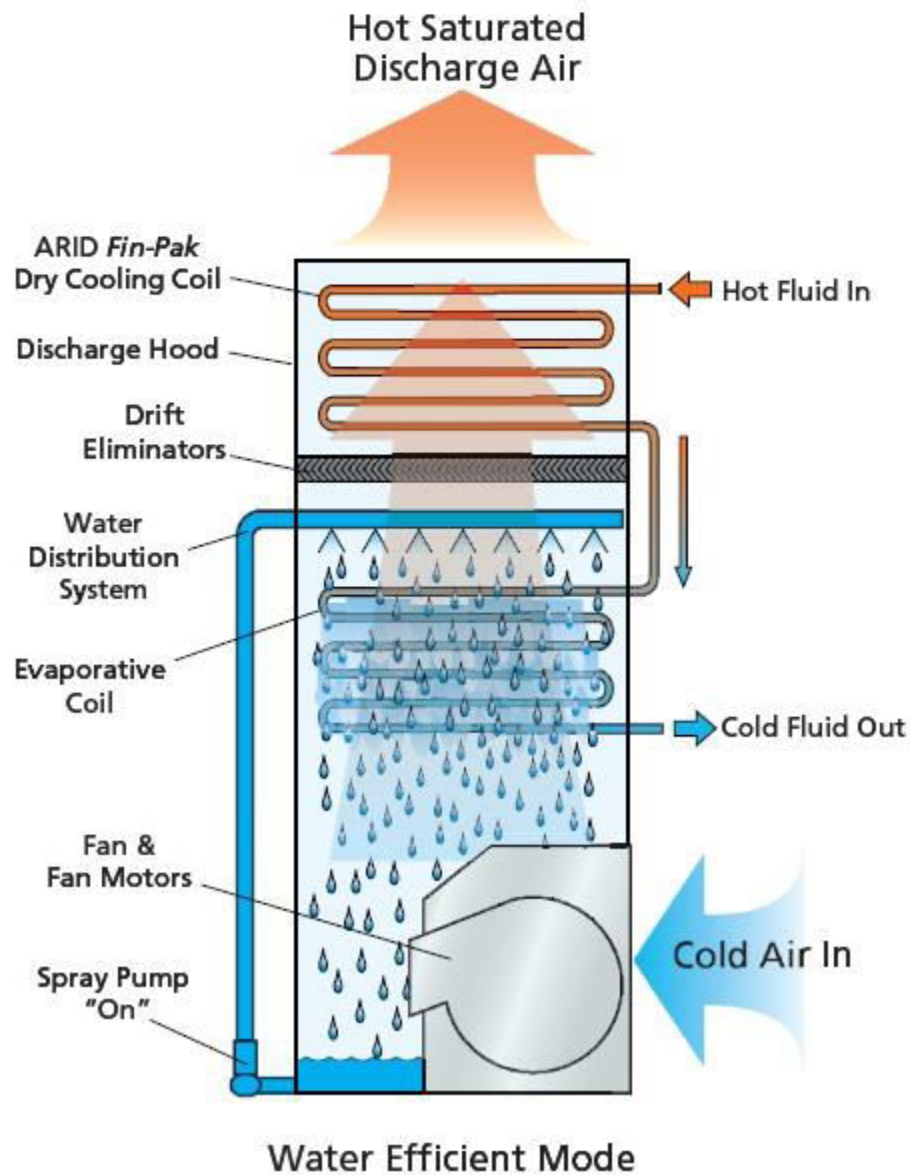
- However, they are less efficient compared to wet cooling towers

Hybrid cooling tower

- In a **hybrid cooling tower**, **depending upon season**, the condenser cooling water is cooled:

1. **Only by sensible cooling** in **dry cooling tower** mode,
2. **Both by sensible and heat transfer** modes in wet cooling tower mode

- The **dry mode** is used when the ambient temperature is normal or less than normal
- The **wet mode** is used when the ambient temperature is high

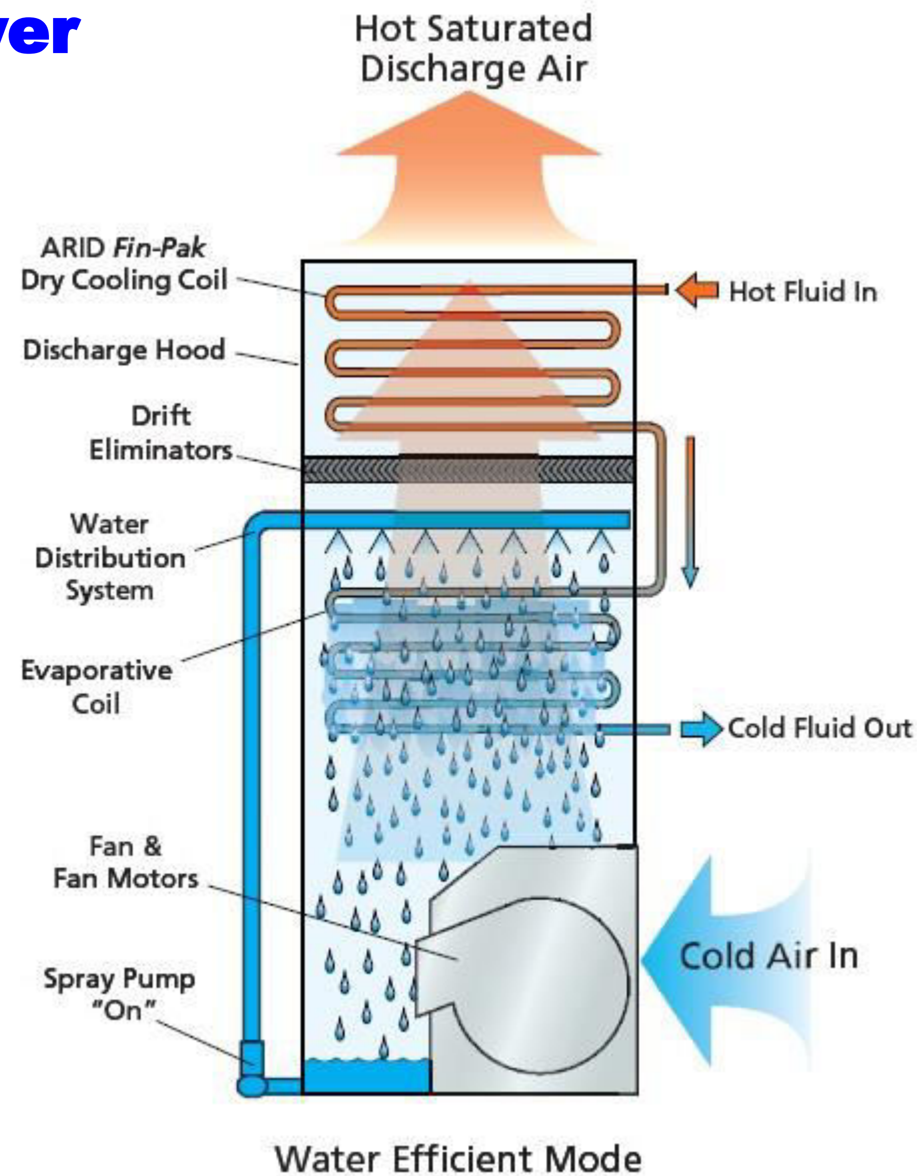


Hybrid cooling tower

Hybrid cooling tower

The **hybrid cooling tower** offers the following **advantages**:

1. The **cooling tower plume formation** can be **minimized** as air leaving the wet tower portion is heated in the dry portion
2. **Evaporation losses are reduced**
3. In **cold weather**, the tower can be operated only in **dry mode**



Hybrid cooling tower

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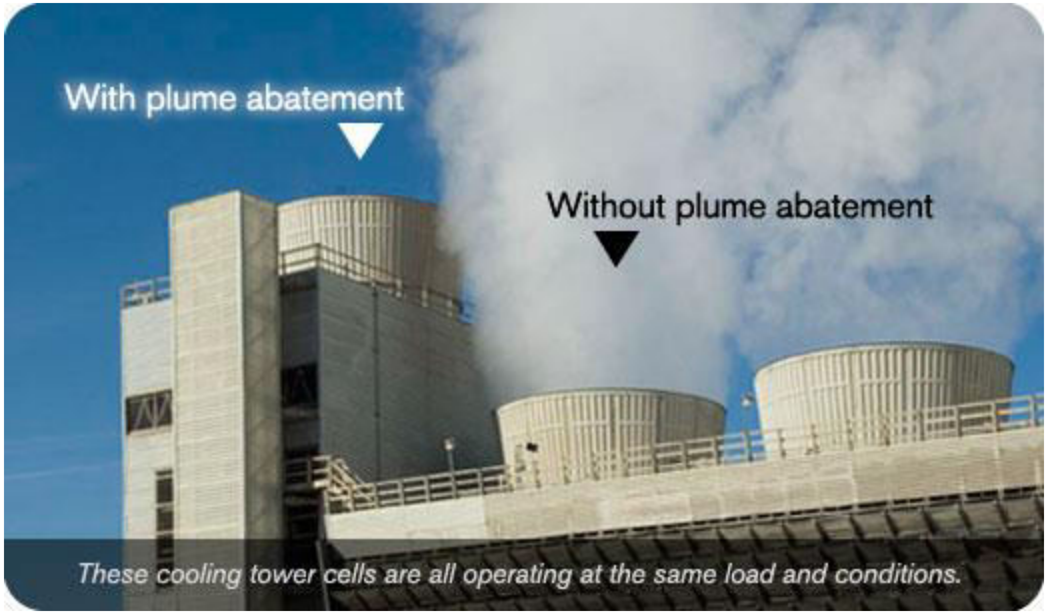
Cooling Tower Plumes



These cooling tower cells are all operating at the same load and conditions.

End of Module 5