

# **Power Plant Engineering**

## **Lecture 9**

### **Steam Condensers, Condensate-Feed-water and Circulating Water Systems**

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# ***Lecture learning outcomes:***

At the end of this lecture, you will be able to:

- i. Explain the role of steam condensers in thermal power plants and their impact on cycle efficiency.
- ii. Identify the components, functions, and operational requirements of condensate and feed-water systems.
- iii. Evaluate the design and operation of circulating water systems used for condenser cooling, including open and closed-loop configurations.
- iv. Analyze how steam condensers, feed-water, and circulating water systems interact and affect overall plant efficiency.
- v. Assess strategies for performance monitoring, routine maintenance, and operational optimization of condenser systems.

# Content

1. Introduction to Steam Condensers
2. Condensate Feed-Water Systems
3. Circulating Water Systems for Condensers
4. Integration of Steam Condensers with Feed-Water and Circulating Systems
5. Maintenance, Performance Monitoring, and Optimization

Summary

References

# 1. Introduction to Steam Condensers

- Steam condensers are essential components in thermal power plants and various industrial processes.
- A **steam condenser** is a closed vessel or heat exchanger designed to **condense the exhaust steam** from a turbine back into **water (condensate)** by rejecting its latent heat to a cooling medium, which can then be reused in the cycle [1].
- This not only conserves water but also significantly improves the **efficiency of steam turbines** by maintaining a low backpressure at the turbine exhaust.
- The condenser facilitates the **phase change** of the exhaust steam from a vapor to a liquid.

# 1. Introduction to Steam Condensers

- A steam condenser has the following major objectives:
  - It maintains a **low pressure** (below atmospheric pressure) so as to obtain maximum possible energy from steam and thus to secure high efficiency.
  - It supplies **pure feed water** to the hot well, from where it is pumped back to boiler.
  - It enables **removal of air** and non-condensable gases from steam.
- Steam condensers are vital for **energy conservation, turbine efficiency**, and **water reuse** in thermal power systems.

## Principles of Condensation

- Condensation is the **phase change of steam from vapor to liquid** as it releases latent heat.
- The condensation process inside a condenser is a heat transfer phenomenon.
- Condensation occurs at nearly **constant pressure**.
- The condensation process is **exothermic** (releases heat).
- Efficient condensation lowers the **turbine exhaust pressure**, which increases turbine work output according to the Rankine cycle.

# 1. Introduction to Steam Condensers

Cont...

- Condensation involves **two** key principles:

## a. Latent Heat Transfer

- When steam comes into contact with a surface colder than its saturation temperature, it **condenses**.
- The energy released is not used to change temperature but to change state from gas to liquid.
- This latent heat is much larger than the sensible heat involved in simply cooling water.

## b. Vacuum Creation

- When steam condenses into a much smaller volume of water, it creates a vacuum.
- This vacuum is crucial because it lowers the **turbine exhaust pressure**, also known as **condenser back-pressure**.

## Types of Steam Condensers

- Steam condensers can be classified based on the method of condensation and cooling, i.e. how the exhaust steam and the cooling medium interact

# 1. Introduction to Steam Condensers

Cont...

- The main types are:

## 1. Surface Condenser

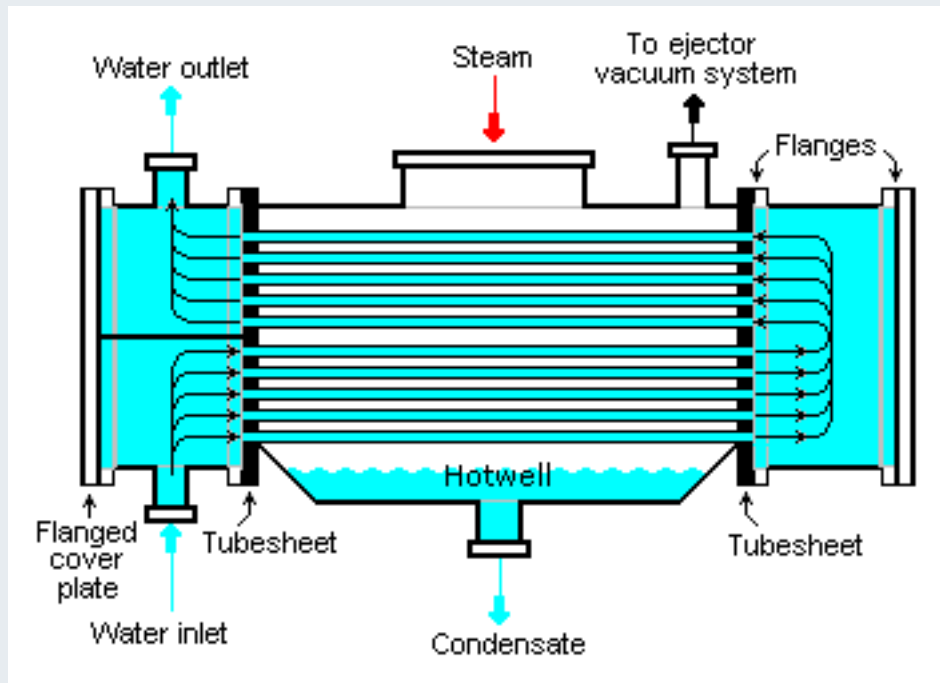
- Steam **does not mix** with cooling water. The condensate is collected separately.
- Consists of a **shell-and-tube** arrangement where steam flows over tubes carrying cold water.
- **Advantages:**
  - ✓ High thermal efficiency.
  - ✓ Produces clean condensate suitable for reuse.
  - ✓ Prevents contamination of feedwater.
- Common in thermal power plants with high-quality feedwater requirements.

# 1. Introduction to Steam Condensers

Cont...

## ■ Disadvantages:

- Large, bulky, and expensive.
- Requires a separate circulating water system.



**Figure 1:** Surface Condenser, Mbeychok. (2007).

[url: https://upload.wikimedia.org/wikipedia/commons/8/8b/Surface\\_Condenser.png](https://upload.wikimedia.org/wikipedia/commons/8/8b/Surface_Condenser.png)

# 1. Introduction to Steam Condensers

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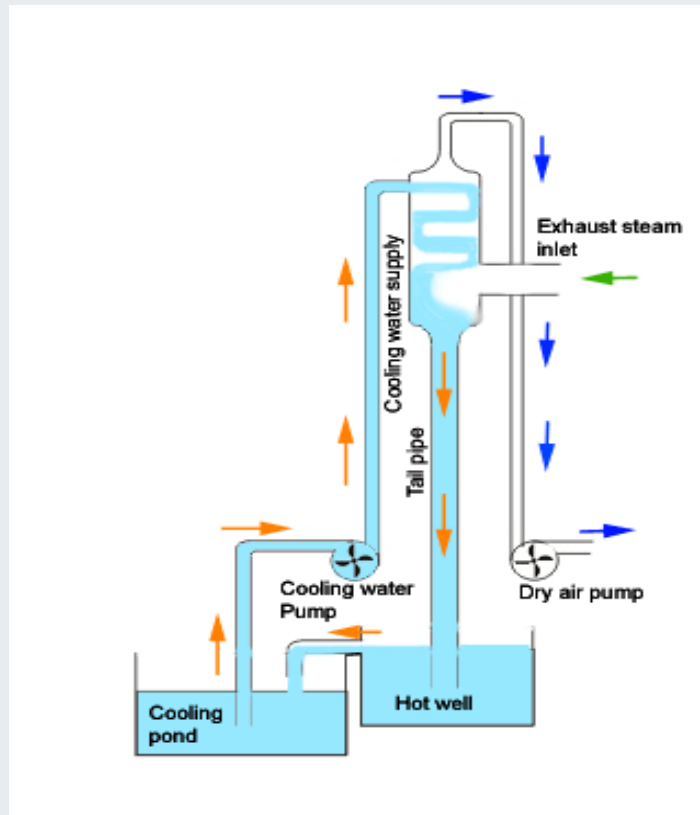
## 2. Jet Condenser (Contact Condenser)

- Exhaust steam and cooling water are brought into **direct physical contact**.
- The cooling water is sprayed into the steam, causing instantaneous condensation.
- There are two types of Jet condensers:
  - ✓ **Direct jet condenser**: Steam is directly sprayed into cold water.
  - ✓ **Ejector condenser**: Uses a vacuum pump to assist condensation.
- **Advantages**:
  - ✓ Simpler construction and lower cost.
  - ✓ Compact design.
  - ✓ High condensing efficiency due to direct contact.

# 1. Introduction to Steam Condensers

Cont...

- The **disadvantage** of jet condenser is it contaminates condensate and cannot be reused directly as feedwater.
- It is applied for small-scale plants or older installations where water quality is less critical.



**Figure 2:** Jet Condenser, Electrical4U, (2012)

[url: https://www.electrical4u.com/images/high-level-jet-condenser.gif](https://www.electrical4u.com/images/high-level-jet-condenser.gif)

## 3. Air-Cooled Condenser

- Uses **ambient air** as the cooling medium instead of water.
- Exhaust steam flows through finned tubes, and large fans force air over the tubes to remove the latent heat.
- Steam is condensed by **air flowing over finned tubes** instead of water, i.e., no water consumption for cooling.
- **Advantages:**
  - Ideal for locations with water scarcity.
  - Eliminates the need for large water sources and water treatment plants.

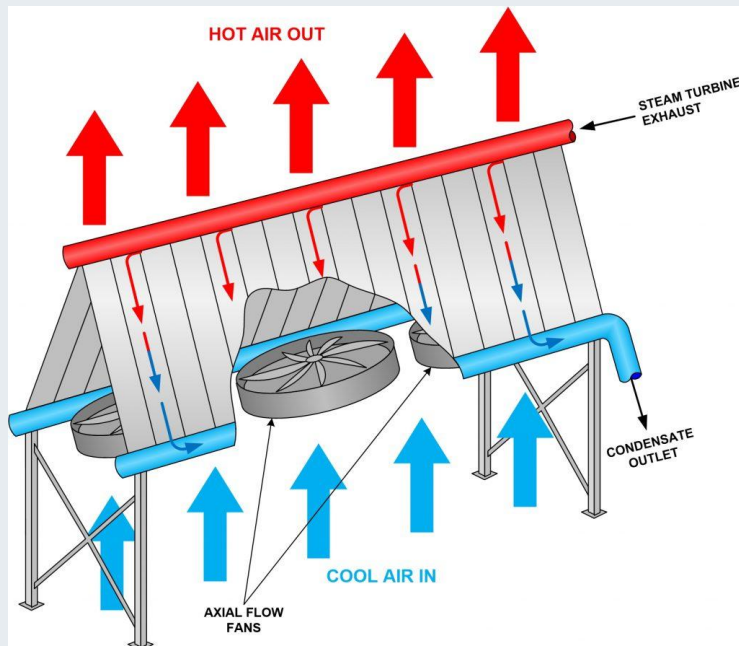
# 1. Introduction to Steam Condensers

Cont...

## ■ Disadvantages:

- ✓ Larger size and higher capital cost.
- ✓ Lower efficiency, especially in hot ambient conditions, leading to higher back-pressure and reduced plant output.

- Its application areas are in nuclear power plants and desert locations.

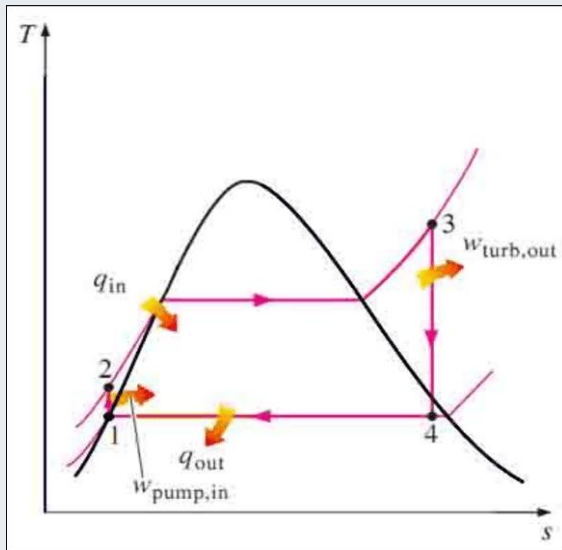


**Figure 3:** Air-Cooled Condenser, Filar, A. (2020),  
[url: https://www.fossilconsulting.com/wp-content/uploads/2020/10/ACC-Markup-2-1024x894-1.jpeg](https://www.fossilconsulting.com/wp-content/uploads/2020/10/ACC-Markup-2-1024x894-1.jpeg)

# 1. Introduction to Steam Condensers

Cont...

- The condenser's role is not to add energy but to enable a much larger energy extraction in the turbine.
- Let's analyze the simplified Temperature-Entropy (T-S) diagram below:



- **Process 3-4: Turbine Expansion** - Steam expands isentropically (ideally) from high pressure/temperature to low pressure.
- **Process 4-1: Condensation** - Exhaust steam is condensed at constant pressure and temperature back into liquid.

**Figure 4:** T-s diagram of a Rankine Cycle,  
Alhwayzee, M., Kadhim, H. J., & Rashid, F. L.  
(2021).

url:  
<https://www.researchgate.net/publication/336647595/figure/fig1/AS:815342993547265@1571404326643/deal-Rankine-Cycle.png>

# 1. Introduction to Steam Condensers

Cont...

- Condensers play a crucial role in the overall efficiency of the Rankine cycle:
  - i. **Lowers Turbine Exhaust Pressure (Back-Pressure)**
    - By condensing exhaust steam at a low pressure, the turbine can expand the steam more, converting more thermal energy into mechanical work.
  - ii. **Heat Recovery**
    - The condensate is returned to the boiler as feedwater, reducing the energy required to heat the water to steam.
    - Minimizes fuel consumption and improves thermal efficiency.
  - iii. **Maintenance of Vacuum**
    - Condensers maintain a vacuum at the turbine exhaust, ensuring smooth operation and preventing air ingress into the system.

## 2. Condensate Feed-Water Systems

- The condensate feed-water system forms a critical part of a steam power plant.
- It is responsible for **collecting the condensate** (condensed steam) from the condenser and returning it to the boiler as feed-water after proper **heating, purification, and pressurization [2]**.
- This closed-loop system minimizes losses, conserves energy, and enhances the thermal efficiency of the power plant.
- In summary, the functions of the condensate and feed-water systems are:
  1. **Condensate collection** from the steam condenser.
  2. **Deaeration** – removal of dissolved gases (oxygen, CO<sub>2</sub>)  
to prevent corrosion.

## 2. Condensate Feed-Water Systems

Cont...

3. **Feed-water heating** using steam from various turbine extraction points.
4. **Pressurization** – supplying feed-water at high pressure to the boiler drum or economizer.
5. **Water treatment and purification** to maintain boiler water quality.
6. **Energy recovery and conservation** by utilizing waste heat in heaters.

## Components of a Feed-Water System

- The system is a series of components that work in sequence to move, heat, and purify the water.
- A modern feed-water system typically includes the following major components:

### 1. Condensate Extraction Pump

- Located at the condenser outlet.
- Lifts the condensate from the low-pressure region of the condenser to the next stage (e.g., low-pressure heater).
- Must handle high temperatures and operate reliably under vacuum conditions.

# 2. Condensate Feed-Water Systems

Cont...

## 2. Condensate Polishing Unit

- Removes impurities and dissolved solids that enter with condensate.
- Usually contains ion-exchange resins or filters to maintain high purity.

## 3. Low-Pressure (LP) Feedwater Heaters

- These are shell-and-tube heat exchangers that use steam extracted from the low-pressure stages of the steam turbine to heat the condensate.
- This extraction steam is called **bleed steam** or **extraction steam**.
- Increase water temperature gradually before it reaches the deaerator, improving cycle efficiency.

### 4. Deaerator

- The deaerator is the **transition point** between the low-pressure and high-pressure sections of the feed-water system.
- It removes **dissolved oxygen and CO<sub>2</sub>** from feed-water, preventing corrosion in the boiler and piping system.
- Usually combines mechanical and thermal methods using steam injection.
- Also serves as a **feed-water storage tank** and maintains steady pressure.

## 2. Condensate Feed-Water Systems

Cont...

### 5. Feed-Water Pump (FWP)

- Draws deaerated water from the deaerator and delivers it at boiler pressure.
- Usually a multi-stage centrifugal pump.
- Must overcome the boiler drum pressure and line friction losses.

### 6. High-Pressure Heaters

- Receive feed-water from the feed pump and use **high-pressure extraction steam** from the turbine to raise its temperature close to saturation before entering the economizer.
- Improve overall **thermal efficiency** by utilizing waste steam energy.

# 2. Condensate Feed-Water Systems

Cont...

## 7. Valves and Control Devices

- Regulate flow, maintain pressure balance, and ensure safe operation.
- Include check valves, pressure-reducing valves, control valves, and bypass valves for operational flexibility.

# 3. Circulating Water Systems for Condensers

- In thermal power plants, refineries, chemical plants, and large HVAC systems for commercial buildings, the **circulating water system (CWS)** plays a vital role in **transferring waste heat** from the **condenser** to the environment [3].
- The condenser converts turbine exhaust steam into water by cooling it with circulating water.
- They manage heat dissipation efficiently, ensuring equipment longevity and operational stability.
- The efficiency of this system directly affects **turbine performance**, **condenser vacuum**, and **overall plant efficiency**.

The fundamental principle of a CWS is:

- A working fluid (e.g., steam in a turbine condenser) absorbs heat from a process and needs to be cooled and condensed to complete the cycle.
- The Circulating Water System provides a cooler medium (water) to absorb this waste heat and dissipate it, ensuring the primary process operates efficiently and continuously [3].
- The main functions of a CWS include:

## 1. Heat Rejection

- To remove low-grade waste heat from the condenser and discharge it to the cooling medium (water or air).

# 3. Circulating Water Systems for Condensers

Cont...

## 2. Maintaining Process Temperature

- To control and maintain optimal operating temperatures for various equipment like heat exchangers, intercoolers, and reactors.

## 3. Recycling of Cooling Water (in closed systems)

- Allows reuse of water, minimizing consumption and reducing environmental impact.

## 4. Environmental Protection

- Designed to minimize **thermal pollution** and **water wastage**.

## Types of Circulating Water Systems

The circulating water system can be broadly classified into three types:

### 1. Once-Through System (Open-Cycle)

- Water is drawn from a natural source (river, lake, or sea), circulated through the condenser, and discharged back to the source after absorbing heat.

The **operation procedure** is:

- Water is pumped from an intake structure.
- It passes through condenser tubes, cooling the steam.
- Warmed water is returned to the source.

# 3. Circulating Water Systems for Condensers

Cont...

## 2. Closed-Loop System (Recirculating or Cooling Tower System)

- The same water is recirculated repeatedly.
- The heated water returning from the process is cooled in a cooling tower by evaporating a small portion of the water into the atmosphere.
- The cooled water is then collected and pumped back to the process.

The **operation procedure** is:

- Hot water from the condenser goes to the cooling tower.
- Cooling tower releases heat to the atmosphere.
- Cooled water returns to the condense

## 3. Hybrid / Wet-Surface Cooling System

- It is a combination of once-through (open cycle) and closed-loop systems.
- Often used in areas where the primary water source is too warm for efficient once-through cooling or during peak load conditions.
- It may involve a smaller cooling tower to assist in heat rejection.

## Design Considerations for Water Flow and Temperature Control

- Proper design of the circulating water system ensures **efficient condenser cooling** and minimal energy loss.

# 3. Circulating Water Systems for Condensers

Cont...

- The key design parameters include:

## 1. Water Flow Rate Determination

- The objective is to provide sufficient flow rate to keep condenser pressure low while minimizing pumping power.
- The rate of heat removal from the condenser is given by:

$$Q = \dot{m}c_p(T_{out} - T_{in})$$

Where:

$Q$  = Heat load (kJ/s)

$\dot{m}$  = *Mass flow rate of cooling water (kg/s)*

$c_p$  = *Specific heat of water*

$T_{in}, T_{out}$  = *Inlet and outlet water temperatures*

## 2. Temperature Control

- **Inlet Temperature:** Should be as low as possible for good vacuum (typically 25–30°C).
- **Outlet Temperature:** Must be below environmental discharge limits (usually < 40°C).
- **Flow Regulation:** Achieved through valves, variable-speed pumps, or bypass control.

## 3. Pump Selection and Head Losses

- Use **axial-flow or mixed-flow pumps** for large flow and low head applications.
- Consider **pipe friction losses, elevation, and condenser pressure drop** when determining total dynamic head.

# 3. Circulating Water Systems for Condensers

Cont...

## 4. Cooling Tower Sizing: Factors affecting cooling tower design:

- Heat load
- Wet-bulb temperature of air
- Desired range and approach
- Type of tower (natural or mechanical draft)
- Site conditions (humidity, altitude)

## 5. Energy Efficiency Considerations

- Optimize pump efficiency (typically 80–85%).
- Minimize pipe friction by proper sizing and smooth internal surfaces.
- Use variable frequency drives (VFDs) to match flow with load demand.

## Materials and Corrosion Issues

- Circulating water systems operate in a **corrosive environment** due to the presence of dissolved oxygen, salts, suspended solids, and biological growth.
- Selecting appropriate materials and controlling corrosion are critical for reliability and long service life.

## The major corrosion mechanisms include:

- **Galvanic Corrosion** - Occurs when dissimilar metals are in contact in water.
- **Pitting Corrosion** - Localized attack forming small pits, often due to chlorides.
- **Erosion-Corrosion** - Accelerated wear due to high water velocity or suspended solids.

# 3. Circulating Water Systems for Condensers

Cont...

The common materials used are [4]:

Component	Typical Material	Properties
Condenser Tubes	Copper alloys (Admiralty brass, Cu-Ni), stainless steel, titanium	High thermal conductivity and corrosion resistance
Piping	Carbon steel, ductile iron, FRP (fiberglass-reinforced plastic)	Strength, cost-effective, easy fabrication
Pumps & Valves	Cast iron or stainless steel	Corrosion and erosion resistance
Cooling Tower Structure	Reinforced concrete, FRP, treated wood	Durability in humid and wet environments

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

- In a steam power plant, **several systems** work together to convert heat energy into mechanical and then electrical energy.
- Among them, the **steam condenser, feed-water system, and circulating water system** form the **heat rejection and recovery section** of the plant.
- Their **integration** ensures that:
  - ✓ Exhaust steam is condensed effectively,
  - ✓ Condensate is recovered and purified as feed-water, and
  - ✓ Cooling water circulates continuously to remove the rejected heat.

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

Cont...

- The **efficient** integration of these three systems is paramount for achieving:
  - ✓ High cycle efficiency
  - ✓ Maximum turbine power output
  - ✓ Plant reliability and availability
- They form the **back end** of the Rankine cycle:
  - **Exhaust Steam from Turbine → Condenser**: Steam releases latent heat and condenses into water.
  - **Condensate → Feed-Water System**: Condensate is pumped, purified, and heated before entering the boiler again.
  - **Circulating Water → Condenser**: Circulating water absorbs rejected heat and carries it to a cooling tower or discharge.

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

## Cont...

- The process integration steps are:

### 1. Condensation

- Turbine exhaust steam enters the condenser and condenses on the outer surface of cooling tubes.
- Cooling water inside tubes absorbs the heat.

### 2. Condensate Recovery

- Condensed water collects in the hotwell at the bottom of the condenser.
- Condensate extraction pump transfers it to the feed-water system.

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

Cont...

## 3. Feed-Water Heating and Return:

- The condensate passes through **low-pressure heaters** and **deaerator** to remove dissolved gases.
- Then it is pressurized by the **Boiler Feed Pump** and further heated in **high-pressure heaters** before returning to the boiler.

## 4. Cooling Water Circulation:

- Circulating pumps draw water from a **cooling source** (river or cooling tower basin).
- Water passes through condenser tubes, absorbing heat, and returns to the source or cooling tower for reuse.

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

Cont...

Role of Integration in Efficiency Improvement

## 1. Enhanced Turbine Efficiency:

- Maintaining a low condenser pressure through effective cooling increases the turbine output.

## 2. Energy Recovery through Feed-Water Heating:

- Using recovered condensate and regenerative feed-water heating reduces fuel consumption in the boiler.

## 3. Reduced Water Consumption:

- Closed-loop circulation and condensate reuse minimize makeup water requirements.

# 4. Integration of Steam Condensers with Feed-Water and Circulating Systems

Cont...

## 4. Lower Environmental Impact:

- Reduced thermal discharge to natural water bodies and improved resource utilization.

## 5. Stable Operation:

- Properly integrated systems provide steady condenser temperature and pressure control, improving reliability.

## 5. Maintenance, Performance Monitoring, and Optimization Cont...

- A perfectly designed system can fail without proper **operation** and **maintenance**.
- The **steam condenser, circulating water system, and feed-water system** operate continuously under **high load** and **harsh environmental conditions** [5].
- Efficient operation of these systems is vital for maintaining low condenser pressure, high turbine efficiency, and reliable power generation.
- However, operational issues such as air leakage, scaling, corrosion, and mechanical failures can degrade performance.
- Thus, systematic operation, maintenance, and troubleshooting are essential for reliability and long service life.

## ■ Common Operational Problems

### 1. Air Leakage

- It is entry of non-condensable gases (mainly air) into the condenser, reducing vacuum quality and heat transfer efficiency.
- The remedies are:
  - ✓ Tighten or replace gaskets and seals.
  - ✓ Regular vacuum testing.
  - ✓ Maintain air ejectors or vacuum pumps properly.
  - ✓ Conduct periodic leak detection tests.

## 2. Scaling and Fouling

- It is a deposition of impurities (salts, suspended solids, biological matter) on tube surfaces, impeding heat transfer.
- The prevention and removal methods are:
  - ✓ Chemical treatment (phosphate, lime softening, dispersants).
  - ✓ Mechanical cleaning (brushing, sponge-ball system).
  - ✓ Maintaining water velocity within design range.
  - ✓ Biocide dosing for biological fouling.

## 3. Corrosion

- Gradual deterioration of metal surfaces due to electrochemical reactions with water, oxygen, or salts.
- The prevention methods include:
  - ✓ Proper material selection (Cu-Ni alloys, stainless steel, titanium).
  - ✓ Cathodic protection using sacrificial anodes.
  - ✓ Water chemistry control (pH, oxygen scavengers).
  - ✓ Use of protective coatings

## Maintenance Practices

### 1. Preventive Maintenance

- Performed at regular intervals to prevent failures and ensure reliability.

### 2. Predictive Maintenance

- Based on condition monitoring to predict failures before they occur.

### 3. Corrective Maintenance

- Performed after failure or during scheduled overhaul.

## Performance Test Procedure

1. Record inlet and outlet temperatures of cooling water.
2. Measure vacuum pressure in the condenser.
3. Determine condensate temperature and flow rate.
4. Calculate heat rejected and overall heat transfer coefficient.
5. Compare with design values to assess condition.

# Summary

- Steam condensers convert exhaust steam from turbines back into water under vacuum, improving thermal efficiency and enabling condensate reuse.
- The condenser is the link between two essential auxiliary systems: the Circulating Water System and the Feed-Water System.
- Circulating systems (once-through or closed-loop) supply cooling water to the condenser, maintaining low exhaust pressure and efficient condensation through temperature control.
- The condenser, feed-water, and circulating water systems operate as a closed thermal loop—recovering heat, conserving energy, and ensuring stable turbine and boiler performance.
- Regular inspection, cleaning, and performance testing help prevent air leakage, scaling, and corrosion, ensuring reliable operation, reduced losses, and sustained power plant efficiency.

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Thank you !