

Power Plant Engineering

Lecture 8

Steam Turbines

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Lecture learning outcomes:

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

- i. Explain the effect of friction on steam turbine blade efficiency and identify factors influencing friction losses.
- ii. Analyze the relationship between blade efficiency and overall energy conversion in steam turbines.
- iii. Evaluate key performance parameters of steam turbines such as power output, efficiency, and specific steam consumption.
- iv. Describe various governing methods used in steam turbines and their role in maintaining constant speed under varying loads.
- v. Assess the combined impact of friction, efficiency, and governing mechanisms on the overall performance and operation of steam turbines.

Content

1. Effect of Friction on Blade Efficiency
2. Blade Efficiency and Energy Conversion
3. Performance of Steam Turbines
4. Governing of Steam Turbines
5. Combined Effect on Turbine Operation and Efficiency

Summary

References

1. Effect of Friction on Blade Efficiency

Definition and Causes of Blade Friction

- In a steam turbine, steam expands and flows over the blades, transferring energy to the rotor.
- Ideally, this flow is **frictionless**, allowing maximum energy transfer. However, in practical situations, friction between the **steam and blade surfaces** reduces the relative velocity of steam, leading to losses in efficiency.
- **Blade friction** refers to the **resistance to motion** experienced by steam (or gas) as it flows over the surface of turbine blades [1].
- This friction arises due to **viscous forces** between the moving steam and the blade surface, causing loss of kinetic energy and a reduction in the relative velocity of steam.

1. Effect of Friction on Blade Efficiency

Cont...

Causes of Blade Friction

1. Surface roughness of blades

- Uneven or rough blade surfaces increase turbulence and energy loss.

2. High steam velocity

- Increased relative velocity leads to higher shear forces and frictional losses.

3. Steam wetness

- Presence of water droplets in wet steam increases drag and erosion, enhancing friction.

4. Blade geometry and shape

- Poor aerodynamic design causes flow separation and vortex formation.

1. Effect of Friction on Blade Efficiency

Cont...

5. Contamination or deposits

- Dust, oil, or corrosion products increase surface resistance.

6. Operating conditions

- Changes in steam temperature and pressure can alter viscosity and frictional behavior.

Impact of Friction on Velocity Diagrams

▪ Ideal (Frictionless) Condition

- Steam enters and leaves the blade with **no loss** in relative velocity.
- The velocity triangles (at inlet and outlet) are **sharp** and **geometrically accurate**.
- Work output is **maximum** for a given set of velocities.

1. Effect of Friction on Blade Efficiency

Cont...

- **Actual (with friction)**

- Due to **friction**, the relative velocity of steam decreases as it passes over the blade surface.
- If V_{r1} is the relative velocity at inlet, and V_{r2} at outlet:
$$V_{r2} = kV_{r1}$$
, where k = blade velocity coefficient (typically 0.8–0.9).
- The outlet velocity triangle becomes **smaller** (flattened) due to the reduced V_{r2} .
- The direction of outlet velocity also changes slightly, affecting the exit angle and resulting in less turning of steam.

1. Effect of Friction on Blade Efficiency

Cont...

Reduction in Blade Efficiency Due to Friction

Blade Efficiency (η_b) - refers to how effectively a blade converts **fluid energy** (air or water) into mechanical work [2].

- Blade or diagram efficiency is defined as:

$$\eta_b = \frac{\text{Work done on blades}}{\text{Kinetic energy supplied to blades}} = \frac{\text{Work done on blades}}{\frac{V_1^2}{2}}$$

$$\eta_b = \frac{2U_b (V_{w1} + V_{w2})}{V_1^2}$$

Since V_{w2} is smaller due to friction, the efficiency reduces accordingly.

Where:

V_1 = Absolute velocity of steam at inlet

U_b = Blade velocity

V_{w1} = Tangential component of inlet steam velocity

V_{w2} = Tangential component of outlet steam velocity

1. Effect of Friction on Blade Efficiency

Cont...

Effect of Friction

- Blade friction is a major cause of efficiency loss in steam turbines.
- Friction reduces the **kinetic energy available** for conversion into work.
- Since $V_{r2} < V_{r1}$, the exit velocity component decreases, leading to lower work done per kg of steam.
- The outlet triangle becomes smaller, indicating loss of kinetic energy.
- The whirl component V_{w2} decreases, reducing work output.

1. Effect of Friction on Blade Efficiency

Cont...

Methods to Minimize Frictional Losses

1. **Improved surface finish** - Polished or mirror-finished blades reduce boundary layer thickness and flow resistance.
2. **Lubrication** - moisture control and anti-corrosive coatings act as indirect lubrication.
3. **Selection of blade materials** - Selection of smooth surface properties, high resistance to erosion and corrosion, stable microstructure materials.
4. **Steam quality control** - Ensure superheated steam to prevent droplet impact and erosion and drain moisture from steam lines before entry to turbine.
5. **Aerodynamic blade design** - Optimize blade curvature and thickness to maintain laminar flow.

2. Performance of Steam Turbines

Key Performance Parameters

- These are the primary metrics used to gauge the **effectiveness** and **economic value** of a steam turbine.
- The performance of a steam turbine is evaluated using several important parameters that describe how effectively it converts steam energy into mechanical work.

1. Efficiency

- Efficiency is the ratio of useful **energy output** to the **energy input**.
- In steam turbines, several types of efficiencies are considered:

2. Performance of Steam Turbines

Cont...

a. Blade or Diagram Efficiency, η_b

- **Blade Efficiency (η_b)** is a measure of how effectively the blades (buckets) of a turbine rotor convert the kinetic energy of the steam jet into useful mechanical work (shaft work) [3].
- It is a crucial internal performance parameter that focuses solely on the energy conversion happening at the rotor blades.

$$\eta_b = \frac{\text{Work done on blades}}{\text{Kinetic energy supplied to blades}} = \frac{2U (V_{w1} + V_{w2})}{V_1^2}$$

2. Performance of Steam Turbines

Cont...

b. Stage Efficiency, η_{st}

- **Stage Efficiency (η_{st})** is a measure of how efficiently a single stage of the turbine converts the available energy in the steam into useful mechanical work on the turbine shaft [3].
- It accounts for all the **losses** that occur within that particular stage, including **nozzle losses, blade friction, leakage, and shock losses**.

$$\eta_{st} = \frac{\text{Actual work done per kg of steam per stage}}{\text{Isentropic energy (enthalpy) drop available in the stage}}$$

- Stage efficiency indicates how close the actual performance of a stage is to the ideal **isentropic performance**.

2. Performance of Steam Turbines

Cont...

Mathematically,

$$\eta_{st} = \frac{h_1 - h_2}{h_1 - h'_2}$$

Where,

h_1 = enthalpy of steam at stage inlet

h'_2 = enthalpy at stage exit for isentropic expansion

h_2 = actual enthalpy at stage exit

$h_1 - h_2$ = represents the **actual energy** converted to mechanical work in the stage.

$h_1 - h'_2$ = represents the **maximum possible** (ideal isentropic) energy conversion.

2. Performance of Steam Turbines

Cont...

c. Mechanical Efficiency, η_m

- Mechanical efficiency of a steam turbine is the ratio of the **useful power available** at the turbine shaft to the **power developed** by the steam on the turbine blades.
- It accounts for mechanical (frictional) losses that occur in the moving parts of the turbine, such as bearings, glands, and shaft friction.
- The causes of mechanical losses include **bearing friction, windage losses, gland leakage losses**, coupling and shaft alignment losses.

$$\eta_m = \frac{\text{Brake Power}}{\text{Power developed by blades}}$$

2. Performance of Steam Turbines

Cont...

- Mechanical efficiency determines how effectively the turbine converts blade-developed energy into usable mechanical output.
- High mechanical efficiency implies **good lubrication**, **proper alignment**, and **minimal wear**, which are vital for reliable long-term turbine operation.

d. Nozzle Efficiency, η_n

- Nozzle efficiency is a measure of how effectively a **steam nozzle** converts the enthalpy (heat energy) of steam into **kinetic energy**.

$$\eta_n = \frac{\text{Actual kinetic energy of steam at nozzle exit}}{\text{Isentropic kinetic energy}}$$

2. Performance of Steam Turbines

Cont...

- Mathematically,

$$\eta_n = \frac{h_1 - h_2}{h_1 - h'_2}$$

- Where,

h_1 = enthalpy of steam at nozzle inlet

h'_2 = enthalpy at nozzle exit for isentropic expansion (ideal case)

h_2 = enthalpy at nozzle exit for actual expansion (real case)

- Velocity form,

$$\eta_n = \frac{V_{actual}^2}{V_{isentropic}^2}$$

V_{actual} = Actual velocity of steam at nozzle exit

$V_{isentropic}$ = Velocity for isentropic expansion

2. Performance of Steam Turbines

Cont...

- In steam turbines, nozzles are used to expand high-pressure steam and convert its thermal energy into **high-velocity jets** that strike the turbine blades to produce mechanical work.
- Nozzle efficiency determines the **velocity** of steam jets entering the turbine blades.
- The factors affecting nozzle efficiency includes:
 - **Surface friction** between steam and nozzle walls,
 - **Shock losses** due to sudden changes in steam direction,
 - **Heat losses** to the surroundings,
 - **Steam wetness** (moisture reduces expansion efficiency),
 - **Poor nozzle design** or rough internal surface finish.

2. Performance of Steam Turbines

Cont...

e. Generator Efficiency, η_g

- The **generator efficiency** of a steam turbine refers to the efficiency with which the **mechanical power** delivered by the turbine shaft is converted into **electrical power** by the generator.

$$\eta_m = \frac{\text{Electrical power output of generator (kW)}}{\text{Mechanical power input from turbine (kW)}}$$

- **Electrical power output:** The actual electrical power produced by the generator connected to the turbine.
- **Mechanical power input:** The shaft power delivered by the steam turbine, after accounting for losses due to friction, bearings, and coupling.

2. Performance of Steam Turbines

Cont...

f. Overall Efficiency, $\eta_{overall}$

- The **overall (thermal) efficiency** of a steam turbine is a measure of how effectively the **thermal energy of steam** supplied to the turbine is converted into **useful mechanical (shaft) work** or **electrical power output**.
- It represents the **combined performance** of all turbine components - including nozzles, blades, mechanical parts, and stage - in converting heat energy into usable work.

$$\eta_m = \frac{\text{Useful power output (shaft or electrical)}}{\text{Heat energy supplied to the turbine}}$$

2. Performance of Steam Turbines

Cont...

- In terms of **enthalpy**, the overall enthalpy is:

$$\eta_{overall} = \frac{\dot{m}(h_1 - h_2) \times \eta_m \times \eta_g}{\dot{Q}_{in}}$$

Where:

\dot{Q}_{in} = is the rate of heat supplied to the steam (usually in the boiler).

h_1 = Enthalpy of steam entering the turbine

h_2 = Enthalpy of steam leaving the turbine

\dot{m} = Mass flow rate of steam (kg/s)

2. Performance of Steam Turbines

Cont...

- The total efficiency is the **product** of individual component efficiencies:

$$\eta_{overall} = \eta_n \times \eta_b \times \eta_{st} \times \eta_m \times \eta_g$$

Where:

η_n = Nozzle Efficiency

η_b = Blade Efficiency

η_{st} = Stage Efficiency

η_m = Mechanical Efficiency

η_g = Generator Efficiency

2. Performance of Steam Turbines

Cont...

Factors Affecting Turbine Performance

- The performance of a steam turbine is influenced by several factors that affect its **efficiency, power output, and operational reliability** [4].
- Understanding these factors helps in improving design, optimizing operation, and maintaining efficiency throughout the turbine's life.
- The factors that influence the actual performance of a steam turbine include:
 1. **Blade friction and surface roughness**
 - Friction between steam and blade surfaces causes energy loss.
 - It reduces the relative velocity of steam as it passes over the blades.
 - Surface roughness due to corrosion or erosion increases drag and turbulence.

2. Performance of Steam Turbines

Cont...

2. Steam leakage

- Leakage occurs through blade tips, seals, and between stages.
- It occurs through clearances between stationary and moving parts (e.g., at the shaft seals, blade tips, and casing joints).
- Results in reduced steam flow through the intended paths and decreases output.

3. Moisture content

- In low-pressure stages, steam expands below the saturation line, forming water droplets.
- Droplets strike the blades, causing erosion, efficiency loss, and unbalanced forces.
- Moisture also reduces kinetic energy conversion since part of the flow is liquid.

2. Performance of Steam Turbines

Cont...

4. Mechanical losses

- Include friction in bearings, glands, and shaft couplings.
- Lead to loss of mechanical efficiency.

5. Steam flow and pressure losses

- Steam experiences **pressure losses** in nozzles, blades, and pipelines due to resistance.
- Non-optimal flow angles (inlet/outlet) cause velocity triangles to deviate from ideal design.
- Leads to reduced stage efficiency.

2. Performance of Steam Turbines

Cont...

6. Throttling and nozzle losses

- Imperfect expansion of steam in nozzles reduces kinetic energy supplied to blade.

6. Heat losses

- Through casing and piping by conduction and radiation.
- Prevented by proper insulation and lagging.

7. Steam quality and conditions

- Turbine performance depends strongly on inlet steam pressure, temperature, and degree of superheat.
- Any drop in these parameters leads to less available enthalpy for work conversion.

3. Governing of Steam Turbines

- Steam turbines are designed to operate efficiently at a specific **speed** and **load**.
- However, in practical applications — especially when driving electrical generators or mechanical loads — the load on the turbine continuously **varies**.
- To maintain a **constant speed** and ensure **stable operation** under changing load conditions, a **governing system** is employed.
- **Governing** of a steam turbine refers to the process of **controlling** and **regulating** or **adjusting** the flow of steam to the turbine in order to maintain its speed constant, irrespective of variations in load [5].

3. Governing of Steam Turbines

Cont...

Objectives of Governing

- The main purposes of governing in steam turbines are:
 1. To maintain **constant turbine speed** despite load changes.
 2. To prevent **over-speeding** when the load suddenly decreases.
 3. To ensure **efficient utilization** of steam.
 4. To maintain **steady output** in coupled electrical generators.
 5. To protect the turbine and connected equipment from **mechanical damage** due to excessive speed.

3. Governing of Steam Turbines

Cont...

Principle of Governing

- The governing system works on the principle of **speed feedback control**.
- When the **load** on the turbine **increases** → the **speed** tends to **fall**.
 - ✓ The governor detects the speed drop and increases the steam supply.
- When the **load decreases** → the **speed** tends to **rise**.
 - ✓ The governor detects the speed rise and reduces the steam supply.
- This automatic regulation is achieved using a **centrifugal governor** mechanism that senses the turbine speed and adjusts the steam control valve position accordingly.

3. Governing of Steam Turbines

Cont...

Components of a Governing System

- A typical governing system consists of the following parts:
 - **Governor (mechanical, hydraulic, or electronic)** - Senses turbine speed and generates control signal.
 - **Linkages and relay mechanism** - Transmit motion from governor to the control valve.
 - **Steam control valve** - Regulates the amount of steam entering the turbine.
 - **Servomotor or actuator** - Uses hydraulic or pneumatic power to move the control valve as per governor signal.
 - **Oil pump and piping system** - Provide pressurized oil for hydraulic operation.

3. Governing of Steam Turbines

Cont...

Components of a Governing System

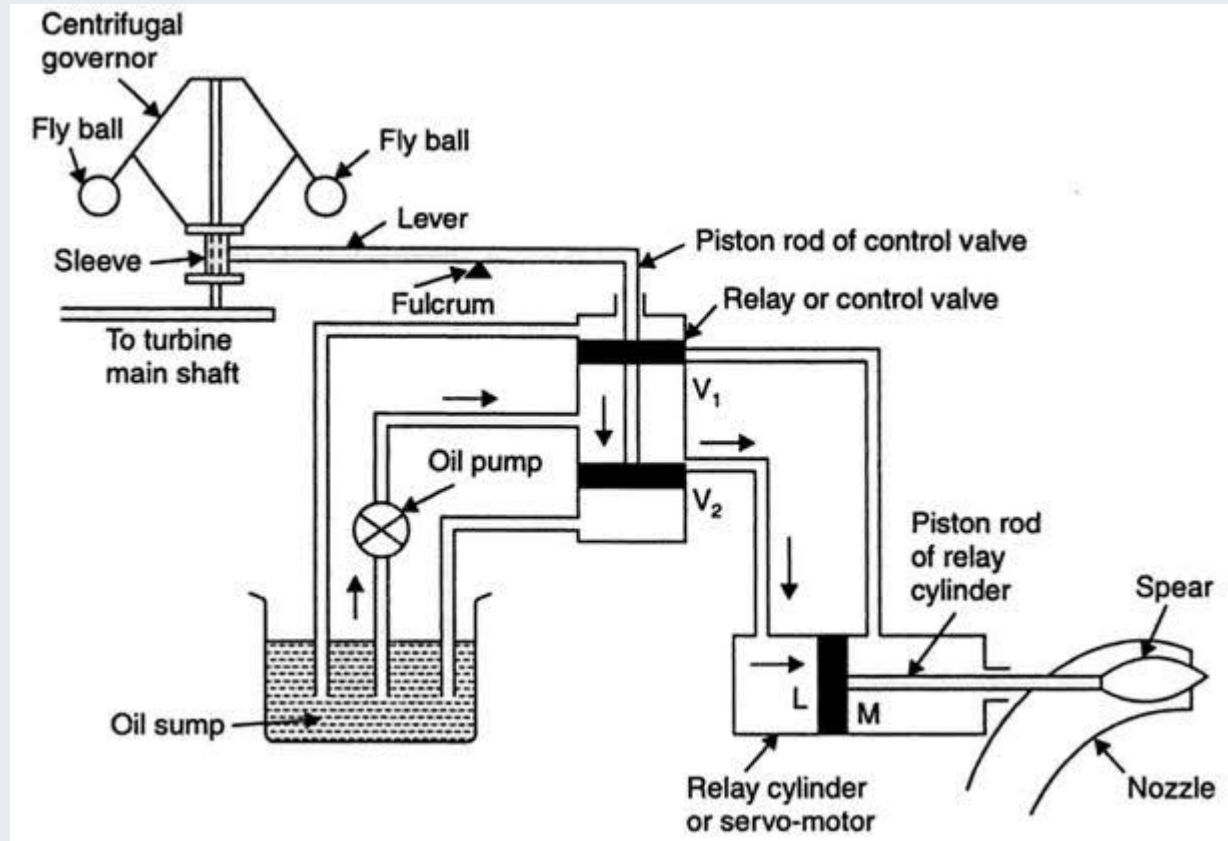


Figure 1: Main Components of Governing of Impulse Turbine, Fluid Mechanics and Hydraulic Machines, R. K Bansal, 2010.

[url: https://figures.academia-assets.com/52582534/figure_033.jpg](https://figures.academia-assets.com/52582534/figure_033.jpg)

Types of Governing in Steam Turbines

- Depending on how the steam flow is controlled, turbine governing can be classified into three main types:

1. Throttle governing

- The simplest and most common method used in small and medium turbines.
- The flow of steam to the turbine is regulated by **throttling**, i.e., by partially closing the throttle valve.
- Used in small power plants or auxiliary turbines where efficiency is not very critical.

3. Governing of Steam Turbines

Cont...

2. Nozzle control governing

- Used in large impulse turbines (like the Curtis and Rateau types).
- Instead of throttling, the **number of nozzles** through which steam flows is varied.
- Steam is admitted through a group of nozzles controlled by separate valves.
- At full load: all nozzle groups are **open**.
- At part load: some nozzle groups are **closed**.
- Pressure remains constant at the nozzle inlet — only mass flow rate is reduced.

3. Bypass governing

- Used in large reaction turbines.
- A portion of the steam is diverted (bypassed) directly to later stages of the turbine when load increases suddenly.
- At **normal load**: steam passes through all stages normally.
- When **load increases**: extra steam is supplied by opening bypass valves to later stages.
- When **load reduces**: bypass valves close to restrict steam flow.

Modern Governing Systems

- Modern steam turbines use **electro-hydraulic** or **electronic governing** systems that provide:
 - ✓ Faster response and higher precision.
 - ✓ Integration with automatic control systems.
 - ✓ Digital feedback using sensors and servo-actuators.
- Proper governing ensures **steady turbine speed, load sharing**, and **safe operation**.
- Malfunctioning governors can lead to overspeed accidents and mechanical failure.

2. Exhaust pressure

- Lowering P_2 (the condenser back pressure) significantly increases work output and efficiency.
- However, it is limited by the temperature of the cooling medium (river, sea, or air) and the escalating size and cost of the condenser.

3. Reheat

- Steam is expanded part-way in the High-Pressure (HP) turbine, returned to the boiler for reheating, and then expanded in the Intermediate-Pressure (IP) and Low-Pressure (LP) turbines.

4. Combined Effect on Turbine Operation and Efficiency

Cont...

- Reheating increases the **average temperature** of heat addition.
- Crucially, reheating reduces the **moisture content** in the LP turbine stages, which protects blades from erosion and improves the internal efficiency of the LP turbine.
- The combined effect of reheating is a net gain in cycle efficiency.

4. Regeneration (Feedwater heating)

- Bleeding off small quantities of steam at various stages of the turbine to preheat the boiler feedwater.
- This reduces the amount of heat that must be added in the boiler (Q_{in}) for the same turbine work output.

4. Combined Effect on Turbine Operation and Efficiency

Cont...

- While regeneration slightly reduces the total mass flow through the LP stages (slightly less work), the reduction in (Q_{in}) is greater, leading to a significant improvement in cycle thermal efficiency.
- Therefore, **combined effect on turbine operation and efficiency** results from the interplay of thermodynamic, mechanical, and aerodynamic factors.
- Optimizing each component — nozzle, blade, and mechanical systems — can significantly improve **overall turbine efficiency** and **power plant performance**.

The Combined Effect - The Interaction of Parameters

1. The Efficiency vs. Load Characteristic

- A turbine's efficiency is **not constant** across its operating range.
- It is typically highest at its **Economic Load** or **Valve-Wide-Open (VWO)** point and drops off at both higher and lower loads.

2. Combined Effect of Exhaust Pressure and Load

- At high loads, a rise in exhaust pressure (e.g., due to poor condenser performance or high cooling water temperature)

has a **severe negative impact** on efficiency and output.

4. Combined Effect on Turbine Operation and Efficiency

Cont...

- At low loads, the same rise in exhaust pressure has a less pronounced but still significant negative effect.
- The turbine is operating less efficiently overall, and the back-pressure effect compounds this.

3. Combined Effect of Reheat and Initial Temperature

- High initial temperature T_1 is beneficial, but its effect is magnified when combined with reheat.
- A high reheat temperature ensures the benefits of reheat (moisture reduction, efficiency gain) are fully realized.

4. The Regeneration-Reheat-Moisture Nexus

This is a critical combined effect in modern power plants.

- **Reheat's Role:** Reheat dries the steam entering the LP turbine.
- **Regeneration's Role:** Regeneration improves cycle efficiency but removes mass flow from the turbine. The steam bled for the last feedwater heater is often taken from the LP turbine's wet region.
- The **combination** of Reheat + Regeneration (Regenerative-Reheat Cycle) represents the peak of conventional steam cycle design.

4. Combined Effect on Turbine Operation and Efficiency

Cont...

To summarize the combined effect of different parameters on turbine performance,

- Turbine operation is a complex balancing act.
- The final efficiency and output are the result of the combined, non-linear interaction of:
 - ✓ Initial conditions (P_1, T_1)
 - ✓ Final condition (P_2)
 - ✓ Cycle modifications (Reheat, Regeneration)
 - ✓ Load demand (Governor valve position)
 - ✓ Internal health (Isentropic efficiency)

Summary

- Friction between steam and blade surfaces reduces kinetic energy transfer, lowering turbine blade efficiency and increasing thermal losses.
- Blade design, steam velocity, and pressure gradients directly influence how effectively steam energy is converted into mechanical work.
- Speed and load regulation through governing systems (like throttle or nozzle control) ensure stable turbine operation under varying demand.
- Frictional losses can interfere with governing accuracy, requiring compensation mechanisms to maintain optimal performance and prevent overspeed.
- The synergy between blade design, friction control, and precise governing determines overall turbine efficiency, reliability, and energy output.

References

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Thank you !