Thermal Engineering II – Unit 1: Gas Turbines

Course: Diploma in Mechanical/Engineering • **Semester:** 4th • **Author:** Dr. Parvesh Antil • **Based on AICTE Model Curriculum**

📘 **Chapter Overview:** This unit covers the fundamentals of gas turbines, their working principles, classification, comparison with other engines, and detailed study of jet propulsion systems including turbojet, ramjet, and rocket engines.

1. UNIT SPECIFICS

This unit provides foundational knowledge of gas turbines and jet propulsion systems, essential for understanding modern power generation and aviation technology.

Topics Covered:

- Basics of gas turbines, working principles, p-v and T-s diagrams
- Various types/layouts of gas turbines (open & closed cycle)
- Comparison with IC engines and steam turbines
- Principle of jet propulsion, fuels used, and applications
- Working of turbojet, ramjet, and rocket engines
- Performance parameters and efficiency calculations

📐 ***Key Diagrams to Study:*** *Fig. 1.1 to Fig. 1.11 – Air-standard gas turbine, Brayton cycle diagrams, open/closed cycle layouts, turbojet, ramjet, and rocket schematics.*

2. RATIONALE – WHY STUDY GAS TURBINES?

Gas turbines play a crucial role in industrial growth and technological advancement. They are used in:

- **Power Generation:** Convert mechanical energy to electrical energy via generators
- **Aviation:** Primary power source for jet propulsion in aircraft
- **Marine & Locomotive:** Propulsion for ships and trains
- **Industrial Applications:** Drive compressors, pumps, and other machinery
- **Oil & Gas Industry:** Used in drilling and pipeline operations

Modern jet fighters fly at supersonic speeds, commercial airliners reach higher altitudes and longer distances, and rockets launch satellites into space – all thanks to gas turbine and jet propulsion technology.

3. PRE-REQUISITES

Before studying this unit, students should review:

- **Physics – Thermodynamics (Class XII):** Laws of thermodynamics, heat transfer, cycles
- **Basic Mechanical Engineering (MEPC102):** Fundamentals of engines, energy conversion

4. UNIT OUTCOMES

After completing this unit, students will be able to:

- **U1-O1:** Understand basics of gas turbines and operating cycles
- **U1-O2:** Compare effectiveness of gas turbines with steam turbines and IC engines
- **U1-O3:** Understand layout of gas turbines based on operating cycle
- **U1-O4:** Learn about jet propulsion and turbine engines

- **U1-O5:** Understand working of ramjet and rocket engines

5. AIR STANDARD CYCLES

Definition: Air standard cycles are simplified thermodynamic cycles used to analyze the performance of internal combustion engines and gas turbines by assuming air as the working fluid and ideal conditions.

5.1 Purpose and Assumptions

- Simplify complex engine processes for analysis
- Assume working fluid is **air** (ideal gas properties)
- Combustion process replaced by **external heat addition**
- Exhaust process replaced by **heat rejection**
- All processes are **internally reversible**
- Neglect friction, heat losses, and chemical changes

5.2 Types of Air Standard Cycles

- **Otto Cycle:** For petrol/spark-ignition engines (constant volume heat addition)
- **Diesel Cycle:** For diesel/compression-ignition engines (constant pressure heat addition)
- **Brayton Cycle:** For gas turbines and jet engines (constant pressure heat addition & rejection)

6. BRAYTON CYCLE (GAS TURBINE CYCLE)

Refer to Fig. 1.1: *Air-standard gas turbine schematic and* ***Fig. 1.2:*** *p-V and T-s Diagrams for Brayton Cycle*

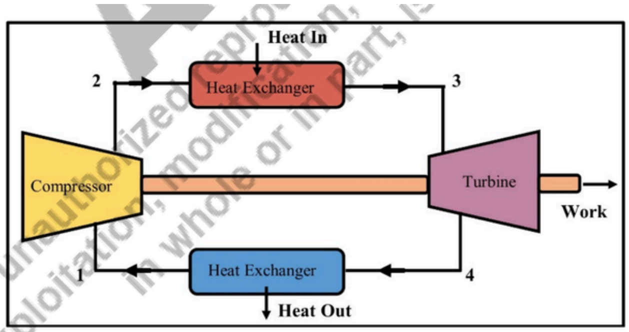


Fig. 1.1 Air-standard gas turbine

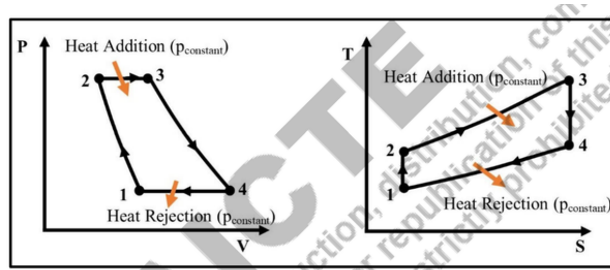


Fig. 1.2 p-V and T-s Diagrams for Brayton Cycle

6.1 Components

- **Compressor:** Increases air pressure (isentropic compression)
- **Combustion Chamber/Heat Exchanger:** Adds heat at constant pressure
- **Turbine:** Expands hot gases to produce work (isentropic expansion)
- **Cooler/Heat Exchanger:** Rejects heat at constant pressure

6.2 Four Processes of Brayton Cycle

1. **Process 1-2: Isentropic Compression** – Air compressed in compressor (pressure ↑, temperature ↑)
2. **Process 2-3: Constant Pressure Heat Addition** – Fuel burned in combustion chamber (temperature ↑)
3. **Process 3-4: Isentropic Expansion** – Hot gases expand in turbine (pressure ↓, work output)
4. **Process 4-1: Constant Pressure Heat Rejection** – Heat rejected to surroundings (temperature ↓)

6.3 Energy Analysis Formulas

$$\text{Heat added: } q_{in} = h_3 - h_2 = C_p(T_3 - T_2)$$

$$\text{Heat rejected: } q_{out} = h_4 - h_1 = C_p(T_4 - T_1)$$

$$\text{Turbine work: } W_T = h_3 - h_4 = C_p(T_3 - T_4)$$

$$\text{Compressor work: } W_C = h_2 - h_1 = C_p(T_2 - T_1)$$

$$\text{Net work output: } W_{net} = W_T - W_C = q_{in} - q_{out}$$

Where:

- h = Enthalpy (kJ/kg)
- C_p = Specific heat at constant pressure (kJ/kg·K)
- T = Temperature (K)
- W = Work (kJ/kg)
- q = Heat transfer (kJ/kg)

Step 2: Net Work Output

$$\text{Net Work} = \text{Turbine Work} - \text{Compressor Work}$$
$$W_{net} = W_T - W_C$$
$$W_{net} = C_p(T_3 - T_4) - C_p(T_2 - T_1)$$
$$W_{net} = C_p[(T_3 - T_4) - (T_2 - T_1)]$$

Step 3: Thermal Efficiency Definition

$$\eta_{th} = \text{Net Work Output}/\text{Heat Input}$$
$$\eta_{th} = W_{net}/q_{in}$$

$$\eta_{th} = \frac{C_p[(T_3 - T_4) - (T_2 - T_1)]}{C_p(T_3 - T_2)}$$

$$\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \quad \text{............ (Equation 1)}$$

Step 4: Applying Isentropic Relations

For isentropic processes 1-2 and 3-4:

For process 1-2: $\frac{T_2}{T_1} = \frac{P_2}{P_1}^{(\gamma-1)/\gamma} = r_p^{(\gamma-1)/\gamma}$

For process 3-4: $\frac{T_3}{T_4} = \frac{P_3}{P_4}^{(\gamma-1)/\gamma} = \frac{P_2}{P_1}^{(\gamma-1)/\gamma} = r_p^{(\gamma-1)/\gamma}$

Where:

- r_p = Pressure ratio = $P_2/P_1 = P_3/P_4$
- γ = Ratio of specific heats = C_p/C_v

Step 5: Expressing Temperatures in Terms of T_1 and r_p

From isentropic relation: $T_2 = T_1 \times r_p^{(\gamma-1)/\gamma}$

Also: $\frac{T_3}{T_4} = r_p^{(\gamma-1)/\gamma} \Rightarrow T_3 = T_4 \times r_p^{(\gamma-1)/\gamma}$

Step 6: Substituting into Efficiency Equation

From Equation 1: $\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$

Substitute $T_2 = T_1 r_p^{(\gamma-1)/\gamma}$ and $T_3 = T_4 r_p^{(\gamma-1)/\gamma}$:

$$\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_4 r_p^{(\gamma-1)/\gamma} - T_1 r_p^{(\gamma-1)/\gamma})}$$

$$\eta_{th} = 1 - \frac{(T_4 - T_1)/r_p^{(\gamma-1)/\gamma}}{(T_4 - T_1)}$$

$$\eta_{th} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

Step 7: Final Efficiency Formula

Brayton Cycle Thermal Efficiency:

$$\eta_{th} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

Step 8: Important Notes

Key Points from Derivation:

1. **Efficiency depends only on pressure ratio (r_p) and specific heat ratio (γ)**
2. **Independent of maximum temperature (T_3) in ideal Brayton cycle**
3. **Higher pressure ratio → Higher efficiency**
4. **Practical limit: Material strength limits maximum temperature**
5. **For air: γ ≈ 1.4, so $\eta_{th} = 1 - 1/r_p^{0.2857}$**

6.4 Thermal Efficiency Formula

$$\eta_{th} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

Where:

- η_{th} = Thermal efficiency

- r_p = Pressure ratio = P_2/P_1
- γ = Ratio of specific heats (C_p/C_v) ≈ 1.4 for air
- P_1 = Inlet pressure, P_2 = Outlet pressure

Key Point: Higher pressure ratio → Higher thermal efficiency. But practically limited by material strength and temperature constraints.

7. CLASSIFICATION OF GAS TURBINES

7.1 Open Cycle Gas Turbines

Refer to Fig. 1.4: *Open cycle gas turbine schematic*

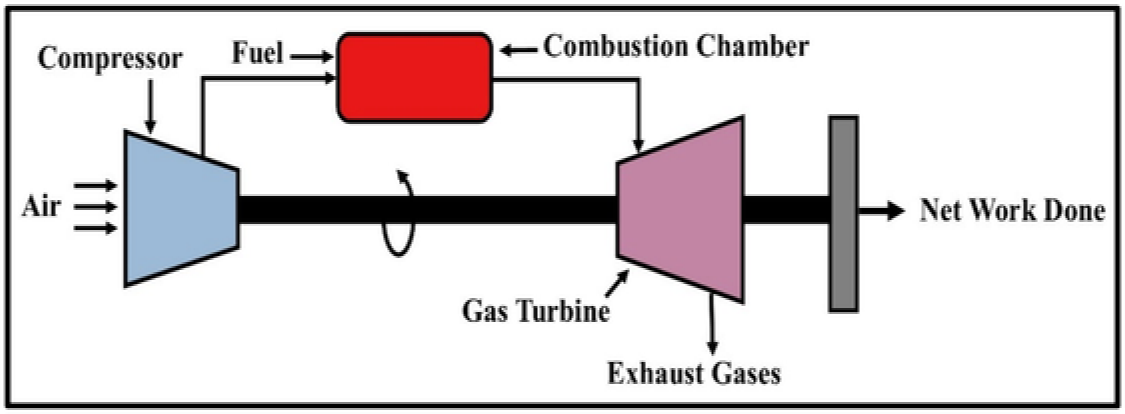


Fig. 1.4 Open cycle gas turbine

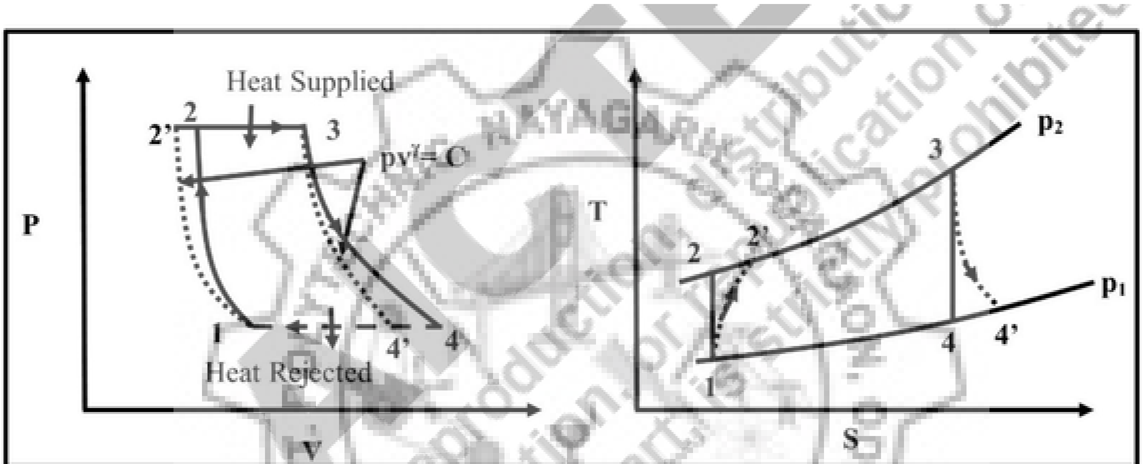


Fig. 1.6 p-V and T-s Diagram of open cycle gas turbine

- **Working Fluid:** Atmospheric air (continuously replaced)
- **Process:** Air drawn → Compressed → Fuel burned → Expanded → Exhaust released
- **Characteristics:**
  - Simple construction
  - Lower initial cost
  - Used where water is scarce
  - Lower efficiency compared to closed cycle
- **Applications:** Aircraft engines, peak-load power plants, industrial drives

7.2 Closed Cycle Gas Turbines

> ***Refer to Fig. 1.5:*** *Closed cycle gas turbine schematic*

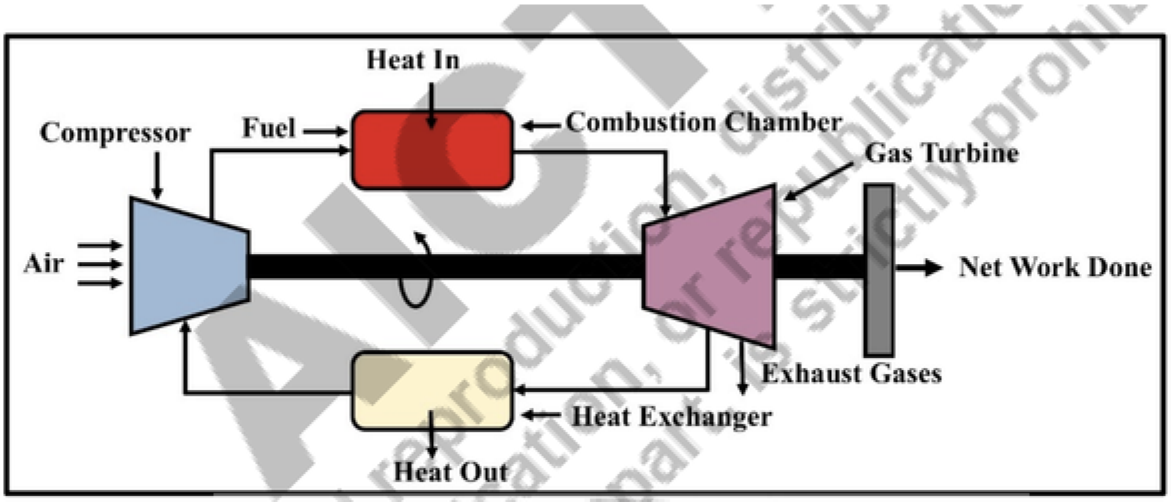


Fig. 1.5 Closed cycle gas turbine

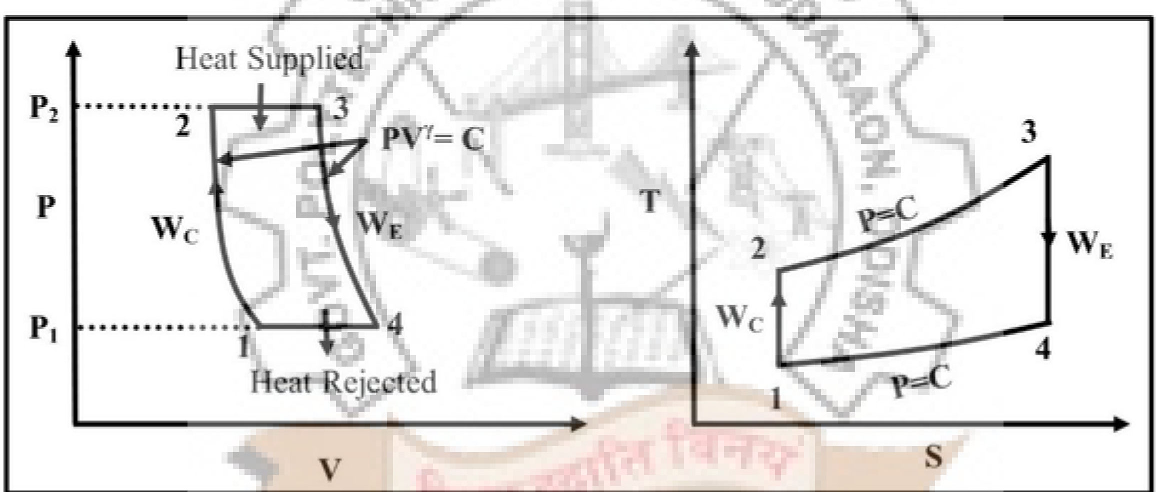


Fig. 1.7 p-V and T-s diagrams

- **Working Fluid:** Air, helium, argon (recirculated in closed loop)
- **Process:** Fluid compressed → Heated externally → Expanded → Cooled externally → Recirculated
- **Characteristics:**
  - Higher efficiency at part-load
  - Can use any fuel (external combustion)
  - Lower maintenance (clean working fluid)
  - Higher initial cost

- **Applications:** Base-load power plants, nuclear power systems, industrial processes

- T-S Diagram of Actual Gas Turbine

8. COMPARATIVE ANALYSIS

8.1 Gas Turbine vs. Reciprocating IC Engine

Parameter	Gas Turbine	IC Engine
Mechanical Efficiency	Higher (≈95%) – rotating parts, less friction	Lower (≈85%) – reciprocating parts, more friction
Flywheel Requirement	Not required – uniform torque	Required – fluctuating torque
Weight per kW	Lower (lightweight construction)	Higher (heavy components)
Power per kg of Air	Higher	Lower
Starting	Difficult (needs starter motor)	Easier
Exhaust Emissions	Cleaner (complete combustion)	More pollutants
Maintenance	Less frequent but specialized	More frequent but simpler

8.2 Gas Turbine vs. Steam Turbine

Parameter	Gas Turbine	Steam Turbine
Working Fluid	Combustion gases	Steam (water)
Combustion	Internal (in combustion chamber)	External (in boiler furnace)
Pressure Ratio	Lower (5:1 to 20:1)	Higher (up to 200:1)
Thermal Efficiency	Lower (25–40%)	Higher (35–45%)
Start-up Time	Short (minutes)	Long (hours)
Footprint	Compact	Large (needs boiler, condenser, etc.)
Cooling Requirement	Only blade cooling	Condenser with cooling water
Fuel Flexibility	Limited (clean fuels)	High (any fuel including coal, biomass)

9. JET PROPULSION SYSTEMS – DETAILED STUDY

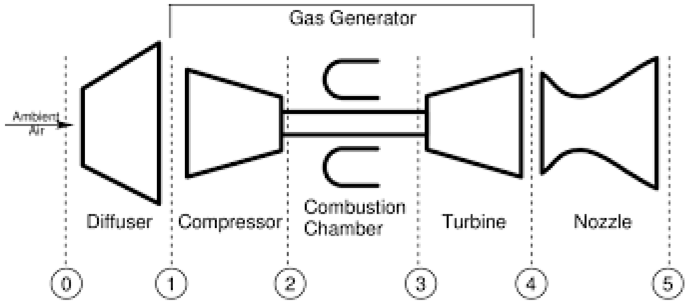
Principle: Jet propulsion works on Newton's Third Law – "For every action, there is an equal and opposite reaction." When hot gases are expelled backward at high speed, the reaction force pushes the engine forward.

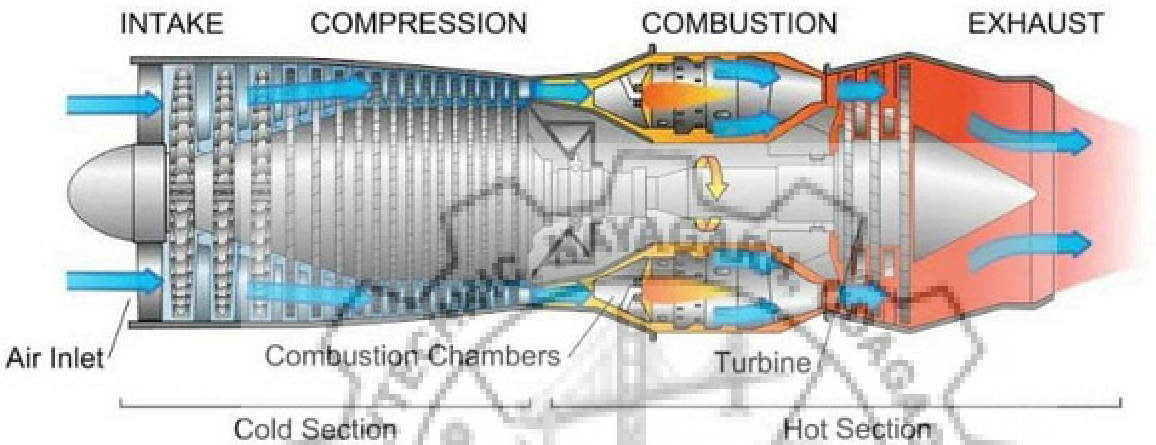
9.1 Turbojet Engine

> ***Refer to Fig. 1.8:*** *Schematic diagram of Turbojet Engine and* ***Fig. 1.9:*** *T-s Diagram of turbojet engine*

Components:

- **Inlet/Diffuser:** Slows down air, increases pressure (ram effect)
- **Compressor:** Axial or centrifugal type, further compresses air
- **Combustion Chamber:** Fuel injected and burned at constant pressure
- **Turbine:** Extracts energy to drive compressor
- **Nozzle:** Accelerates exhaust gases to produce thrust


Gas Generator
Ambient Air
Diffuser
Compressor
Combustion Chamber
Turbine
Nozzle
0
1
2
3
4
5


INTAKE
COMPRESSION
COMBUSTION
EXHAUST
Air Inlet
Combustion Chambers
Turbine
Cold Section
Hot Section

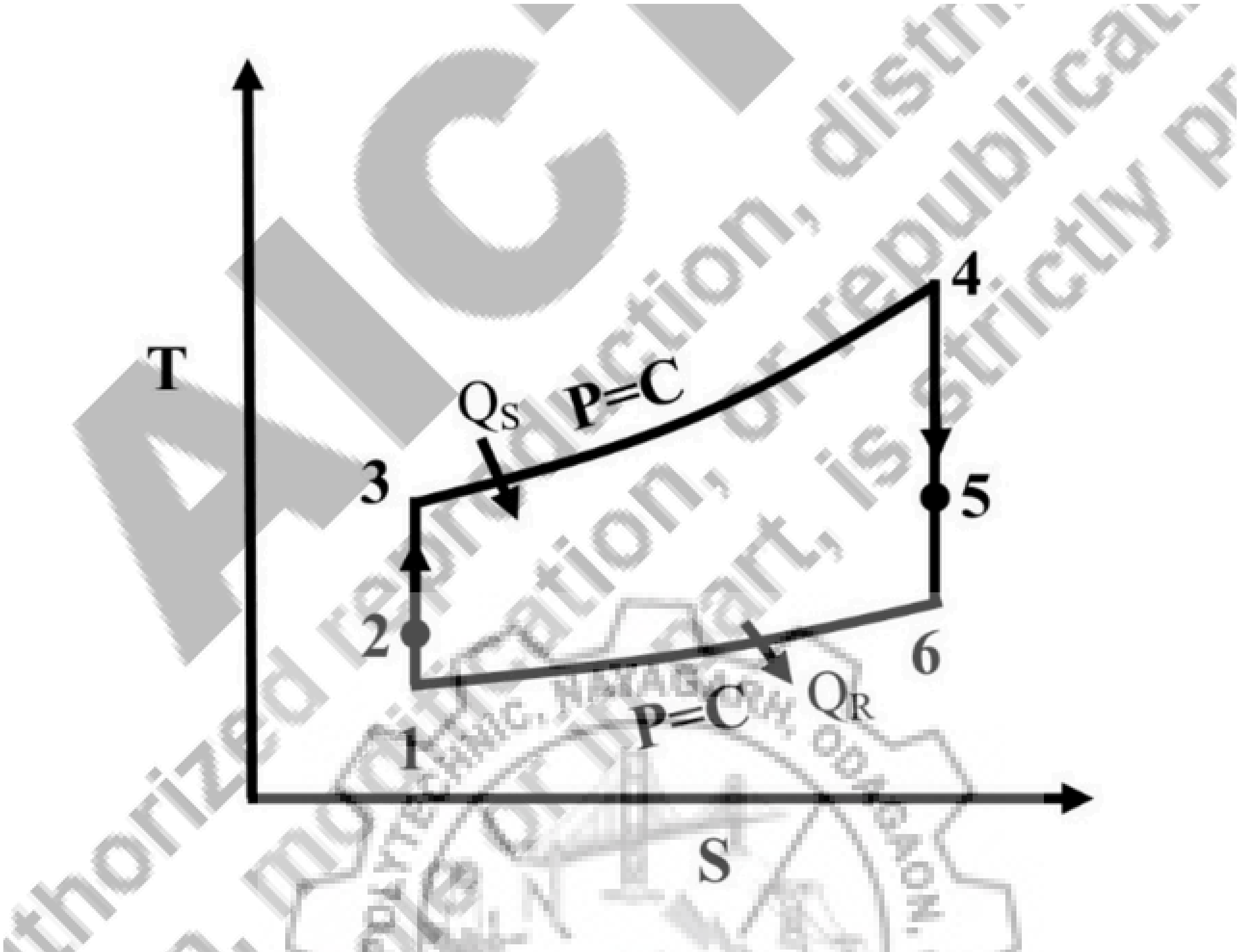


Fig 1.9. T-s Diagram of turbojet engine

Working (Step-by-Step):

1. Air enters inlet at high speed
2. Diffuser slows air, increases pressure
3. Compressor further increases pressure (3–4 bar)
4. Compressed air enters combustion chamber, fuel injected and burned
5. Temperature rises to 900–1500°C
6. Hot gases expand through turbine – just enough to drive compressor
7. Remaining gases expand through nozzle, accelerate to high velocity
8. High-speed exhaust produces thrust (Newton's Third Law)

Applications:

- Military fighter aircraft (MiG, Sukhoi)
- Early commercial jets (Boeing 707, Concorde)
- Missiles and drones

9.2 Ramjet Engine

> ***Refer to Fig. 1.10:*** *Schematic diagram of ramjet engine*

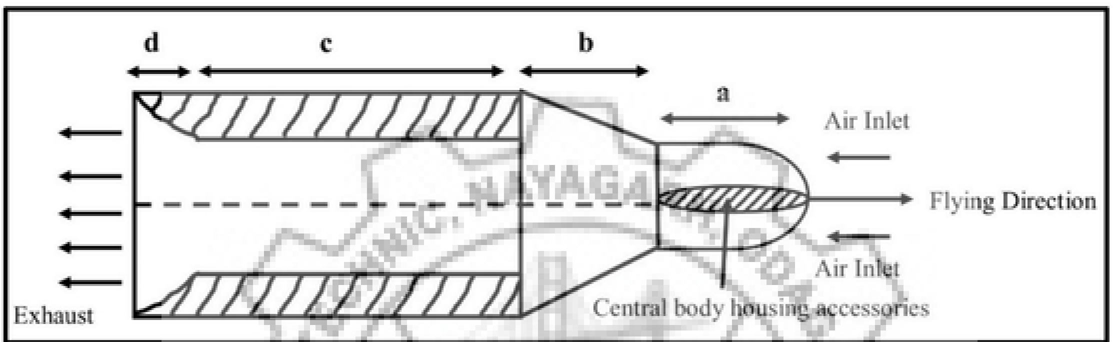


Fig. 1.10 Schematic diagram of ramjet engine

Special Feature: No moving parts (no compressor, no turbine)

How It Works:

1. Uses **forward speed** to compress incoming air (ram effect)
2. At high speeds (above Mach 0.5), air entering engine is already compressed
3. Air slows down in diffuser, pressure increases further
4. Fuel injected and burned in combustion chamber
5. Hot gases expand through nozzle, accelerate to produce thrust

Key Characteristics:

- **Cannot start from rest** – needs booster (rocket or aircraft) to reach operating speed
- Most efficient at **supersonic speeds** (Mach 2–5)
- Simple, lightweight, reliable (no moving parts)
- Fuel flexibility (can use various fuels)

Applications:

- Supersonic missiles (BrahMos, Meteor)
- Experimental aircraft (X-43A, HIFiRE)
- Scramjet (supersonic combustion ramjet) for hypersonic vehicles

9.3 Rocket Engine

> ***Refer to Fig. 1.11:*** *Schematic diagram of rocket jet*

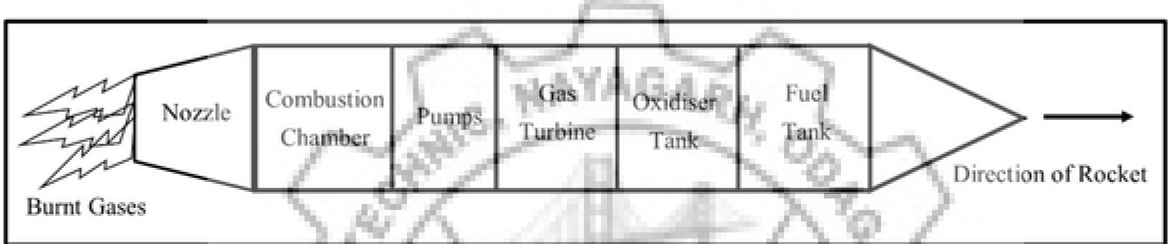


Fig. 1.11 Schematic diagram of rocket jet

Fundamental Difference: Carries its own oxidizer (can operate in vacuum)

Types:

- **Solid Propellant Rocket:**
  - Fuel and oxidizer mixed together in solid form
  - Once ignited, burns until exhausted
  - Cannot be stopped or throttled
  - Examples: Space shuttle boosters, fireworks, missile boosters
- **Liquid Propellant Rocket:**
  - Fuel and oxidizer stored separately as liquids
  - Pumped into combustion chamber where they mix and burn
  - Can be throttled, stopped, and restarted
  - Examples: SpaceX Falcon 9, ISRO GSLV, Saturn V

Working Principle:

1. Propellants (fuel + oxidizer) fed into combustion chamber
2. Ignited – produces high-pressure, high-temperature gases
3. Gases expand through converging-diverging nozzle
4. Accelerate to extremely high velocities (up to 4500 m/s)
5. Expulsion of mass creates thrust in opposite direction

Applications:

- Space launch vehicles (ISRO's GSLV, SpaceX Starship)
- Ballistic missiles
- Satellite orbit adjustment
- Spacecraft propulsion
- Escape systems, braking rockets

9.4 Comparison of Jet Propulsion Systems

Feature	Turbojet	Ramjet	Rocket
Oxidizer Source	Atmospheric air	Atmospheric air	Carries own oxidizer
Moving Parts	Compressor, turbine	None	Pumps (liquid rockets only)
Operating Speed	Subsonic to supersonic	Supersonic only (Mach 0.5+)	Any speed (including vacuum)
Static Thrust	Yes (can start from rest)	No (needs initial speed)	Yes

Efficiency at High Speed	Good	Excellent	Good in vacuum, poor in atmosphere
Complexity	High	Low	Very high (liquid rocket)
Applications	Aircraft, missiles	Supersonic missiles	Spacecraft, ballistic missiles

10. PERFORMANCE PARAMETERS & FORMULAS

10.1 Thrust Formula

$$\text{Thrust } (F) = \dot{m} \times (V_{exit} - V_{inlet})$$

Where:

- $\dot{m}$ = Mass flow rate of air (kg/s)
- V_{exit} = Exit velocity of exhaust gases (m/s)
- V_{inlet} = Inlet velocity of air (m/s)
- Unit: Newtons (N) or pounds-force (lbf)

10.2 Specific Fuel Consumption (SFC)

$$SFC = \text{Fuel flow rate (kg/hr)} / \text{Thrust (N)}$$

Where:

- SFC = Specific Fuel Consumption
- Unit: kg/N·hr
- **Lower SFC = Better fuel efficiency**

10.3 Thermal Efficiency (Brayton Cycle)

$$\eta_{th} = 1 - 1/r_p^{(\gamma-1)/\gamma}$$

Typical Values:

- Simple cycle gas turbines: 30–40%
- Combined cycle plants: 60%+
- Modern aircraft engines: 40–50%

10.4 Work Ratio

$$\text{Work Ratio} = W_{net}/W_T$$

Where:

- W_{net} = Net work output
- W_T = Turbine work output

- Higher work ratio indicates better performance

11. APPLICATIONS & LIMITATIONS

11.1 Applications of Gas Turbines

- **Power Generation:** Base-load and peak-load power plants
- **Aviation:** Commercial, military, and private aircraft
- **Marine:** Naval ships, cruise liners, high-speed boats
- **Industrial:** Drive compressors, pumps, generators
- **Oil & Gas:** Pipeline compression, drilling operations
- **Automotive:** Some tanks, experimental cars
- **Emergency Power:** Backup generators for hospitals, data centers

11.2 Limitations of Gas Turbines

- Lower thermal efficiency than advanced IC engines
- High initial cost
- Specialized maintenance required
- Sensitive to air quality (dust, sand)
- Poor efficiency at part-load operation
- High noise levels (requires silencing)
- Temperature limitations on turbine blades

12. UNIT SUMMARY – KEY POINTS TO REMEMBER

1. **Gas turbine is a rotary internal combustion engine operating on Brayton cycle**
2. **Brayton cycle has 4 processes: isentropic compression, constant pressure heat addition, isentropic expansion, constant pressure heat rejection**
3. **Thermal efficiency depends on pressure ratio: $\eta_{th} = 1 - 1/r_p^{(\gamma-1)/\gamma}$**
4. **Two main types: Open cycle (atmospheric air) and Closed cycle (recirculating fluid)**
5. **Gas turbines have higher mechanical efficiency, lower weight per kW compared to IC engines**
6. **Jet propulsion works on Newton's Third Law (action-reaction)**
7. **Turbojet has compressor and turbine, uses atmospheric air**
8. **Ramjet has no moving parts, needs high initial speed**
9. **Rocket carries own oxidizer, works in vacuum**
10. **Main applications: power generation, aviation, marine propulsion**

13. EXAM PREPARATION GUIDE

Important Topics for Exams:

- **Definition and classification** of gas turbines
- **Brayton cycle processes** with p-v and T-s diagrams
- Formula for **thermal efficiency** of Brayton cycle
- Comparison: Gas turbine vs IC engine vs Steam turbine
- **Working principles** of turbojet, ramjet, rocket
- **Applications and limitations** of each system
- Numerical problems on **efficiency and work output**

13.1 Expected Question Types

- **Short Answer (2-3 marks):** Definitions, comparisons, listings
- **Long Answer (5-10 marks):** Working principles with diagrams, comparative analysis
- **Numerical Problems (3-5 marks):** Efficiency calculations, work output
- **Diagram Drawing (3-4 marks):** Brayton cycle, turbojet, ramjet layouts

13.2 Common Exam Questions

1. Explain Brayton cycle with p-v and T-s diagrams
2. Differentiate between open and closed cycle gas turbines
3. Compare gas turbine with reciprocating IC engine
4. Explain working of turbojet engine with neat sketch
5. Why ramjet cannot start from rest? Explain its working
6. Differentiate between jet propulsion and rocket propulsion
7. Calculate thermal efficiency for given pressure ratio
8. List applications and limitations of gas turbines

14. ADDITIONAL RESOURCES

14.1 Recommended Textbooks

- **Thermal Engineering** by B.R. Sarkar (McGraw-Hill)
- **Thermal Engineering** by R.K. Rajput (Laxmi Publications)
- **A Textbook of Thermal Engineering** by R.S. Khurmi & J.K. Gupta (S. Chand)

14.2 Online Resources (via QR codes in textbook)

- NPTEL Course on "Gas Turbines" – IIT Roorkee
- NPTEL Course on "Introduction to Rocket Propulsion" – IIT Kanpur
- Video lectures on jet propulsion systems

14.3 Real-World Examples to Study

- **ISRO GSLV:** Uses liquid and solid rocket engines
- **BrahMos Missile:** Ramjet powered, supersonic cruise missile
- **GE 9X:** World's largest commercial aircraft engine (for Boeing 777X)
- **Pratt & Whitney F135:** Fighter jet engine (F-35 Lightning II)

Final Study Tips:

- Practice drawing **all diagrams** without looking
- Memorize the **comparison tables** – they cover many questions
- Understand the **physics behind each principle** (not just memorization)
- Solve **numerical problems** from textbook exercises
- Relate concepts to **real-world examples** you know
- Review the **Unit Summary** before exam

These comprehensive notes cover **Unit 1: Gas Turbines** as per AICTE Diploma curriculum.

Best of luck for your exams! Study regularly and practice diagrams.

Thermal Engineering II – Unit 2: Properties of Steam ## **Complete Lecture Notes (Exam-Focused)** ```html

Thermal Engineering II – Unit 2: Properties of Steam

Course: Diploma in Mechanical/Engineering • **Semester:** 4th • **Author:** Dr. Parvesh Antil • **Based on AICTE Model Curriculum**

📘 **Chapter Overview:** This unit covers the fundamental properties of steam, its formation processes, thermodynamic properties, use of Mollier chart, various thermodynamic processes involving steam, and methods for measuring steam quality using calorimeters.

1. UNIT SPECIFICS

This unit provides comprehensive understanding of steam properties essential for thermal engineering applications in power plants, industrial processes, and HVAC systems.

Topics Covered:

- Formation of steam under constant pressure and industrial applications
- Key definitions related to liquid and vapor lines
- Determination of enthalpy, internal energy, and entropy
- Use of Mollier chart for various thermodynamic processes
- Types of calorimeters and numerical problems
- Thermodynamic processes involving steam (isochoric, isobaric, isothermal, etc.)

📐 ***Key Diagrams to Study:*** *Fig. 2.1 to Fig. 2.16 – Steam generation, formation processes, T-h diagrams, p-h diagrams, P-T diagrams, T-v diagrams, Mollier chart, and various calorimeters.*

2. RATIONALE – WHY STUDY STEAM PROPERTIES?

Steam is a crucial working fluid in thermal engineering due to its unique properties and widespread applications:

- **High Energy Carrier:** Steam can hold 5-6 times more potential energy than equivalent mass of water
- **Easy Transport:** Can be easily transported through insulated pipes
- **Versatile Applications:** Used in power generation, heating, sterilization, drying, and industrial processes
- **Thermodynamic Efficiency:** Essential for Rankine cycle in power plants
- **Quality Control:** Understanding steam quality is vital for equipment efficiency and safety

3. PRE-REQUISITES

Before studying this unit, students should review:

- **Physics – Thermodynamics (Class XII):** Laws of thermodynamics, heat transfer, phase changes
- **Basic Mechanical Engineering (MEPC102):** Fundamentals of thermodynamics, properties of substances

4. UNIT OUTCOMES

After completing this unit, students will be able to:

- **U2-O1:** Understand basics of steam formation and uses
- **U2-O2:** Learn about various terms used in steam analysis
- **U2-O3:** Understand steam quality measuring techniques
- **U2-O4:** Learn about Mollier chart for various processes
- **U2-O5:** Understand types of steam calorimeter

5. STEAM - BASIC CONCEPTS

Definition: Steam is water in the gaseous phase, consisting of microscopic droplets of water floating in air after being converted from liquid to vapor phase.

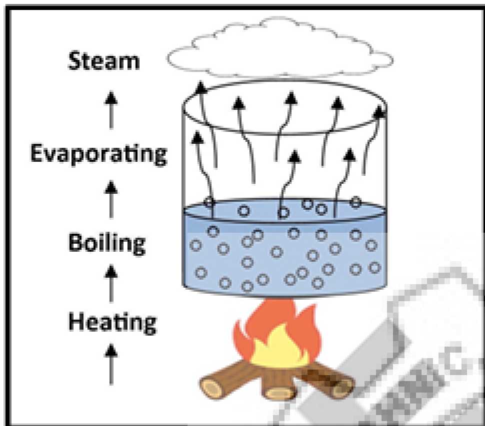


Figure 2.1 Steam generation

Refer to Fig. 2.1: *Steam generation*

5.1 Types of Steam

Type	Definition	Characteristics	Applications
Wet Steam	Mixture of steam and liquid water droplets	• Exists at saturation temperature • Water content > 5% • Two-phase mixture	Initial stages of steam generation, some industrial processes

		• Lower heat transfer capacity	
Dry Steam	Saturated steam without water droplets	• Moisture < 0.5% • High dryness fraction • Superior heat exchange capacity • No corrosion issues	Power generation, heating applications, sterilization
Superheated Steam	Steam heated above saturation temperature	• Temperature > saturation temperature • Single phase (vapor only) • Highest energy content • No condensation during transport	Steam turbines, high-temperature processes

6. FORMATION OF STEAM

> ***Refer to Fig. 2.2:*** *Stages of formation of Steam*

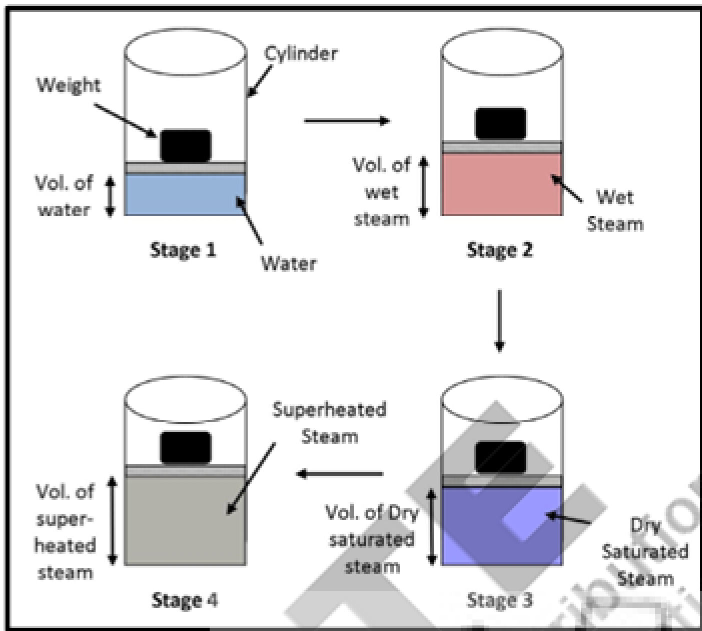


Figure 2.2 Stages of formation of Steam

6.1 Four Stages of Steam Formation

1. **Stage 1 (Initial State):**
    - 1 kg of water at 0°C in cylinder with frictionless piston
    - Weight on piston creates constant pressure P
    - Water starts at absolute 0°C
2. **Stage 2 (Sensible Heating):**
    - Heat applied to raise water temperature from 0°C to T°C
    - Only sensible heat added (no phase change)
    - Water remains in liquid state
3. **Stage 3 (Latent Heating/Vaporization):**
    - Heat added causes phase change from liquid to vapor
    - Temperature remains constant (saturation temperature)
    - Water converts to steam
    - Piston moves upward due to volume increase
4. **Stage 4 (Superheating):**

- Additional heating after complete vaporization
- Temperature rises above saturation temperature
- Volume increases further
- Forms superheated steam

7. FORMATION OF STEAM UNDER CONSTANT PRESSURE

> ***Refer to Fig. 2.3:*** *Formation of steam under constant pressure*

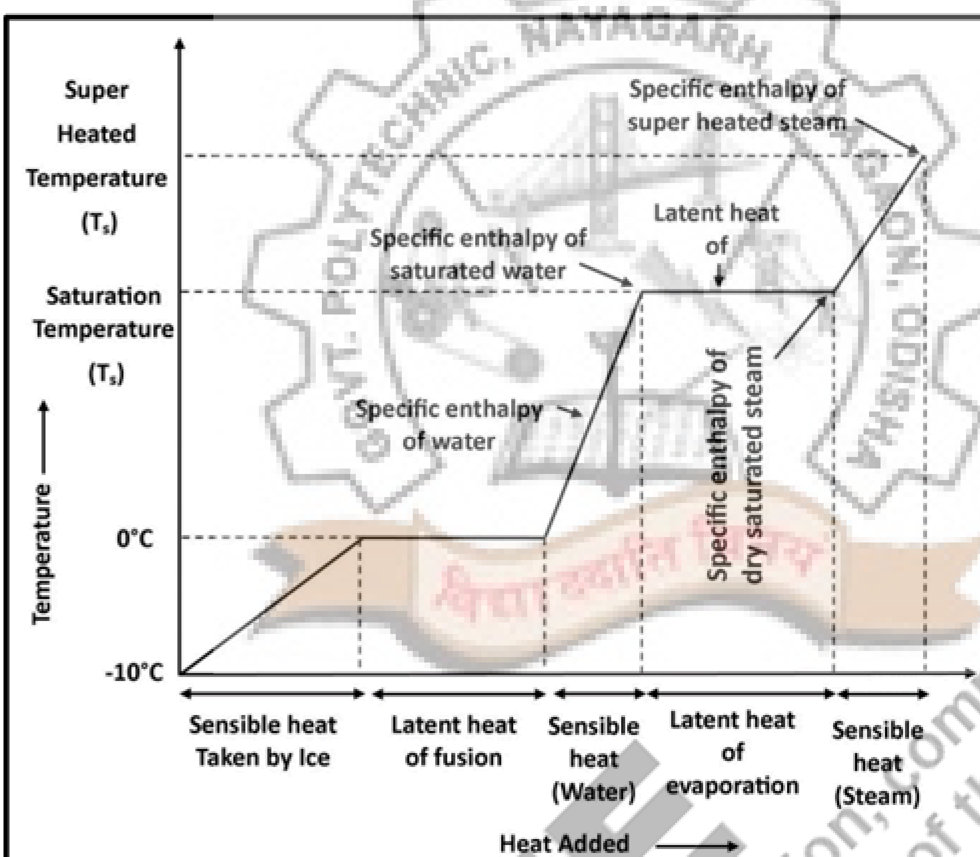


Figure 2.3 Formation of steam under constant pressure

7.1 Complete Process (Starting from Ice)

1. **Ice Heating (-10°C to 0°C):**
   - Sensible heat added to ice

- Temperature rises to melting point (0°C)

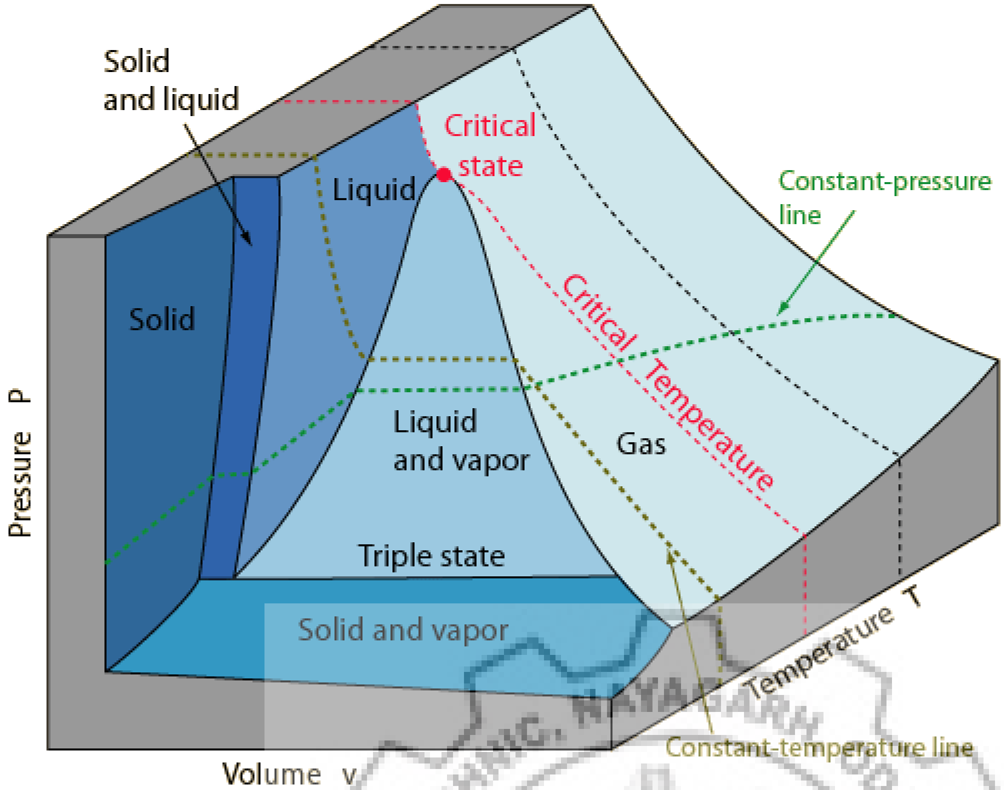
2. **Melting (0°C):**
   - Latent heat of fusion absorbed
   - Ice transforms to water at 0°C
   - Temperature remains constant
3. **Water Heating (0°C to Ts):**
   - Sensible heat added to water
   - Temperature rises to saturation temperature (Ts)
   - Ts depends on pressure P
4. **Vaporization (Ts):**
   - Latent heat of vaporization absorbed
   - Water transforms to dry saturated steam
   - Temperature remains constant at Ts
   - Intermediate state: Wet steam (mixture)
5. **Superheating (Above Ts):**
   - Sensible heat added to dry steam
   - Temperature rises above Ts
   - Forms superheated steam
   - Degree of superheat = $T_{sup} - T_s$

Key Point: At constant pressure, saturation temperature (T_s), latent heat, and other properties remain constant. These properties change only when pressure changes.

8. INDUSTRIAL APPLICATIONS OF STEAM

8.1 Major Applications

1. **Steam for Heating:**
   - *Direct Heating:* Steam directly contacts material (pharmaceuticals, food processing)
   - *Indirect Heating:* Through heat exchangers, jacketed vessels
2. **Steam for Atomization:**
   - Converts fuels to fine particles in burners
   - Increases surface area for efficient combustion
   - Reduces smoke formation
3. **Steam for Drying:**
   - Removes moisture from products
   - More economical than hot air
   - Maintains product quality
4. **Steam for Power Generation:**
   - Used in Rankine cycle-based power plants
   - Drives steam turbines to generate electricity
   - Superheated steam preferred for higher efficiency
5. **Steam for Sterilization & Disinfection:**
   - High-temperature steam kills microorganisms
   - Used in pharmaceuticals, food processing, hospitals
   - Ensures clean and safe working environment



9. KEY DEFINITIONS IN STEAM ANALYSIS

9.1 Saturated Liquid Line and Saturated Vapor Line

> ***Refer to Fig. 2.4:*** *T-h diagram showing saturated liquid and saturated vapour lines*

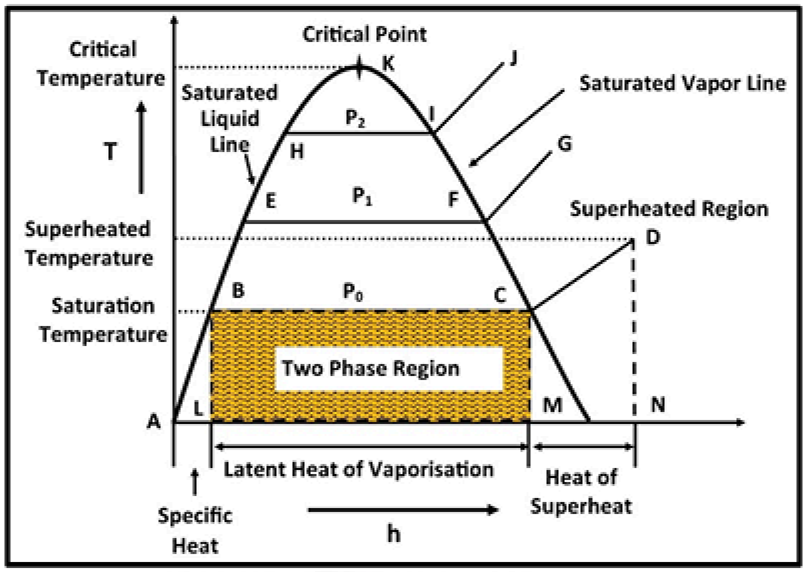


Figure 2.4 T-h diagram showing saturated liquid and saturated vapour lines

- **Saturated Liquid Line:** Boundary between compressed liquid and saturated mixture
- **Saturated Vapor Line:** Curve where all mixture has completely vaporized
- Below saturated liquid line: Pure liquid
- Between the two lines: Wet region (liquid-vapor mixture)
- Above saturated vapor line: Superheated vapor

9.2 Phase Regions on p-h Diagram

> ***Refer to Fig. 2.5:*** *p-h diagram showing various regions (phases) of water*

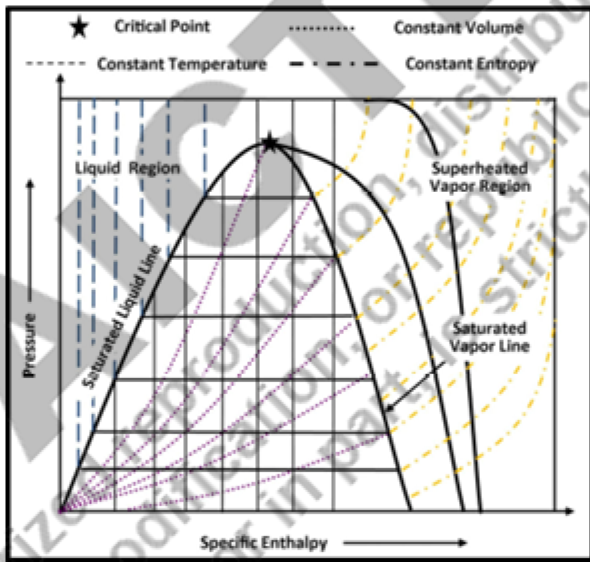


Figure 2.5 p-h diagram showing various regions (phases) of water

- **Subcooled Liquid Region:** Left of saturated liquid line
- **Wet Region:** Between saturated liquid and vapor lines
- **Superheated Vapor Region:** Right of saturated vapor line
- **Critical Point:** Intersection of saturated liquid and vapor lines

9.3 Critical Point

> ***Refer to Fig. 2.6:*** *P-T diagram showing critical point*

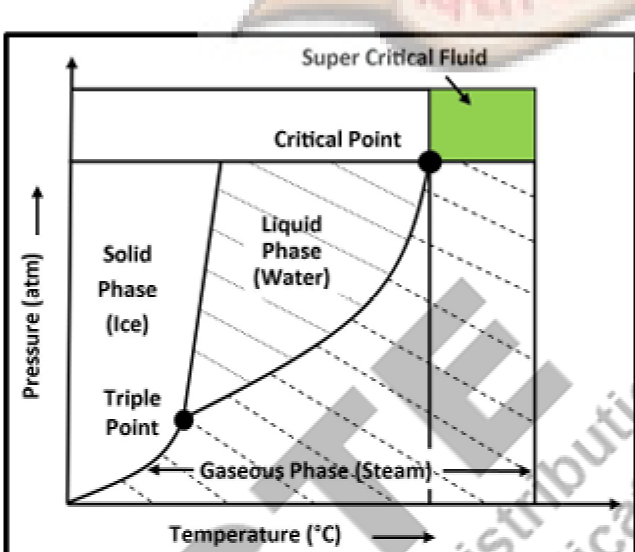


Figure 2.6 P-T diagram showing critical point

- **Definition:** Point where liquid and gas phases become indistinguishable
- **Critical Pressure (P_c):** 221.2 bar for water
- **Critical Temperature (T_c):** 374.15°C for water
- **Properties at Critical Point:**
  - Latent heat of vaporization = 0
  - No phase boundary exists
  - Liquid instantly converts to vapor

9.4 Saturated States

> ***Refer to Fig. 2.7:*** *T-v diagram saturated stages*

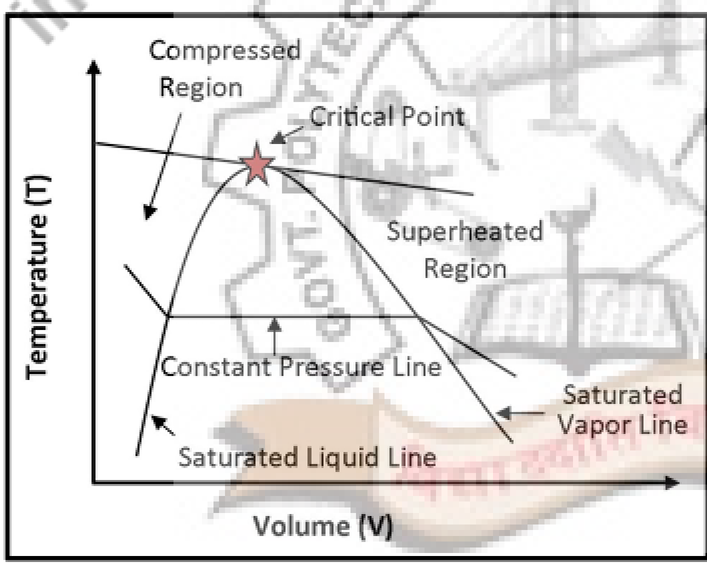


Figure 2.7 T-*v* diagram saturated stages

- **Saturated Liquid:** Liquid at saturation temperature and pressure
- **Saturated Vapor:** Vapor at saturation temperature and pressure
- **Dry Saturated Vapor:** Saturated vapor without liquid particles
- **Saturation Temperature:** Temperature at which liquid transforms to vapor at given pressure

9.5 Heat Definitions

- **Sensible Heat:** Heat that changes temperature without phase change
- **Latent Heat:** Heat required for phase change at constant temperature
    - Latent heat of fusion: Solid to liquid
    - Latent heat of vaporization: Liquid to vapor
- **Specific Heat:** Heat required to raise temperature of unit mass by 1°C

9.6 Dryness Fraction and Wetness Fraction

Dryness Fraction (x):

$$x = \frac{m_s}{m_s + m_w}$$

Where:

- m_s = Mass of dry steam (kg)
- m_w = Mass of water particles in suspension (kg)
- Range: 0 (saturated liquid) to 1 (dry saturated steam)

Wetness Fraction:

$$\text{Wetness fraction} = 1 - x = \frac{m_w}{m_s + m_w}$$

Example 9.1: Calculate Dryness Fraction

Problem: A steam sample contains 85 kg of dry steam and 1.25 kg of water. Find dryness fraction.

Step 1: Total mass = 85 + 1.25 = 86.25 kg

Step 2: Dryness fraction x = 85 / 86.25

Step 3: x = 0.985

Answer: Dryness fraction = 0.985

9.7 Superheated Steam Parameters

- **Superheated Steam:** Steam heated above saturation temperature
- **Degree of Superheat:** $T_{sup} - T_s$
- **Specific Heat of Superheated Steam (C_{ps}):** 2.0 to 2.1 kJ/kg·K (depends on pressure and temperature)

10. ENTHALPY OF STEAM

Definition: Enthalpy (H) is a thermodynamic property defined as the sum of internal energy (U) and the product of pressure and volume (PV).

Refer to Fig. 2.8: *Enthalpy*

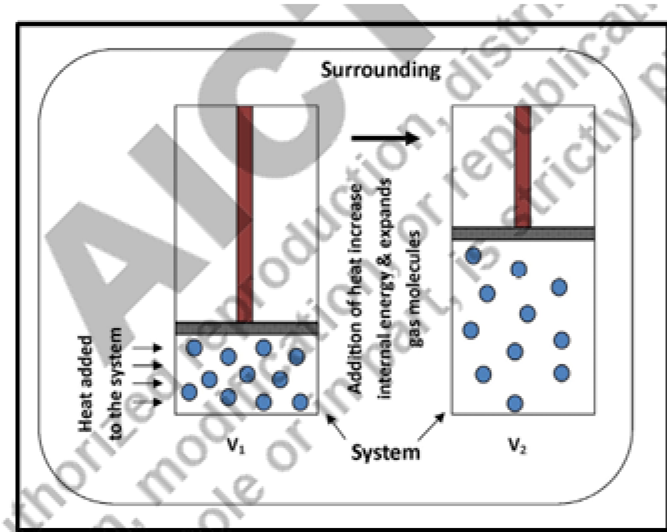


Figure 2.8 Enthalpy

10.1 Fundamental Enthalpy Formula

$$H = U + PV$$

$$\Delta H = \Delta U + \Delta (PV)$$

For constant pressure process: $\Delta H = \Delta U + P\Delta V$

From First Law: $q = \Delta U + P\Delta V = \Delta H$

Where:

- H = Enthalpy (kJ/kg)
- U = Internal energy (kJ/kg)
- P = Pressure (kPa)
- V = Volume (m^3/kg)
- q = Heat transfer (kJ/kg)

10.2 Enthalpy Formulas for Different Steam States

For Wet Steam:

$$h = h_f + xh_{fg}$$

For Dry Saturated Steam:

$$h_g = h_f + h_{fg}$$

For Superheated Steam:

$$h_{sup} = h_f + h_{fg} + C_{ps}(T_{sup} - T_s)$$

$$h_{sup} = h_g + C_{ps}(T_{sup} - T_s)$$

Where:

- h_f = Enthalpy of saturated liquid (sensible heat)
- h_{fg} = Enthalpy of vaporization (latent heat)
- h_g = Enthalpy of dry saturated steam
- x = Dryness fraction
- C_{ps} = Specific heat of superheated steam
- T_{sup} = Temperature of superheated steam
- T_s = Saturation temperature

Example 10.1: Enthalpy Calculation

Problem: Calculate enthalpy of 1 kg steam at 8 bar pressure with dryness fraction 0.8.

Step 1: From steam tables at 8 bar: h_f = 720.9 kJ/kg, h_{fg} = 2046.5 kJ/kg

Step 2: $h = h_f + xh_{fg}$ = 720.9 + 0.8 × 2046.5

Step 3: h = 720.9 + 1637.2 = 2358.1 kJ/kg

Answer: Enthalpy = 2358.1 kJ/kg

11. INTERNAL ENERGY OF STEAM

Definition: Internal energy (U) is the sum of microscopic forms of energy including sensible heat and internal latent heat. It represents the energy stored in molecular motion and molecular forces.

Refer to Fig. 2.9: *Internal Energy*

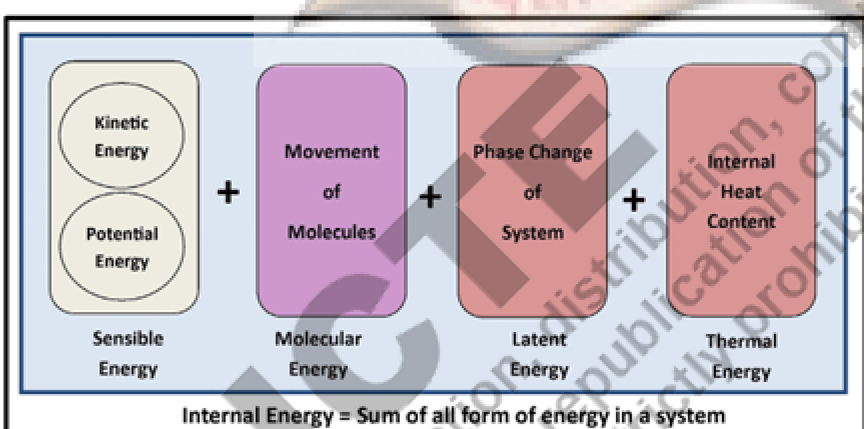


Figure 2.9 Internal Energy

11.1 Internal Energy Formulas

General: $U = H - PV$

For Wet Steam:

$$u = (h_f + xh_{fg}) - 100P(xv_g)$$

For Dry Saturated Steam:

$$u_g = h_g - 100Pv_g$$

For Superheated Steam:

$$u_{sup} = h_g + C_{ps}(T_{sup} - T_s) - 100Pv_g\frac{T_{sup}}{T_s}$$

Note: Pressure P is in bar, factor 100 converts bar to kPa for consistent units.

11.2 Internal and External Latent Heat

- **Total Latent Heat (L):** Sum of internal and external latent heat
- **Internal Latent Heat (L_i):** Used to overcome intermolecular forces during phase change
- **External Latent Heat (L_e):** Used to do work against external pressure during volume expansion
- **Relationship:** $L = L_i + L_e$

Example 11.1: Internal Energy Change

Problem: Steam expands from 10 bar, 300°C to 1.5 bar, 0.9 dryness. Find change in internal energy.

Step 1: From steam tables at 10 bar, 300°C: u_1 = 2793.2 kJ/kg

Step 2: At 1.5 bar: u_f = 466.92 kJ/kg, u_{fg} = 2052.7 kJ/kg

Step 3: $u_2 = u_f + x_2u_{fg}$ = 466.92 + 0.9 × 2052.7 = 2314.35 kJ/kg

Step 4: $\Delta u = u_2 - u_1$ = 2314.35 - 2793.2 = -478.85 kJ/kg

Answer: Internal energy decreases by 478.85 kJ/kg

12. ENTROPY OF STEAM

Definition: Entropy (S) is a measure of molecular disorder or randomness. It represents the unavailable energy in a thermodynamic system.

Refer to Fig. 2.10: *Representation of entropy change*

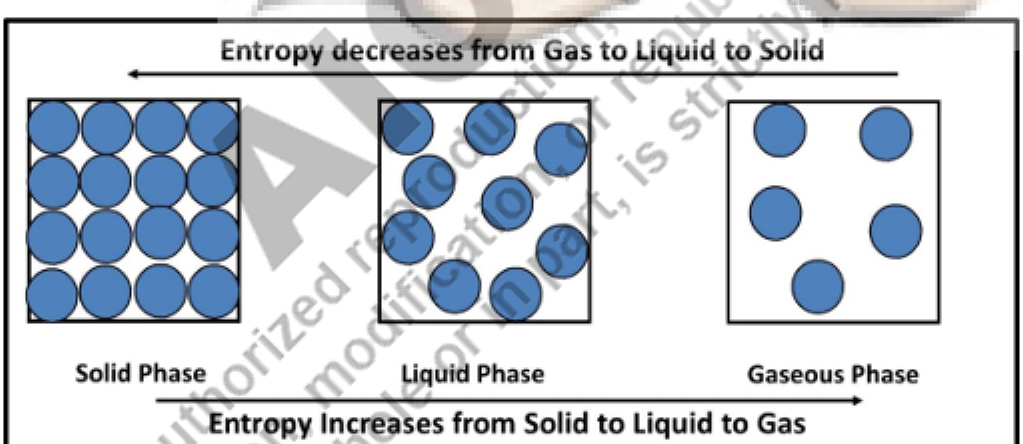


Figure 2.10 Representation of entropy change

12.1 Entropy Change Formula

$$\text{For reversible process: } dS = \frac{\delta Q}{T}$$

$$\text{For irreversible process: } dS \geq \frac{\delta Q}{T}$$

Principle of Increase of Entropy: $(dS)_{universe} \geq 0$

12.2 Entropy Formulas for Different Steam States

For Wet Steam:

$$s = s_f + x s_{fg}$$

For Dry Saturated Steam:

$$s_g = s_f + s_{fg}$$

For Superheated Steam:

$$s_{sup} = s_f + s_{fg} + C_{ps} \ln \frac{T_{sup}}{T_s}$$

Where:

- s_f = Entropy of saturated liquid
- s_{fg} = Entropy change during evaporation
- x = Dryness fraction
- C_{ps} = Specific heat of superheated steam
- T_{sup} = Superheated temperature (K)
- T_s = Saturation temperature (K)

Example 12.1: Entropy Calculation

Problem: Calculate entropy of 1 kg superheated steam at 12 bar, 250°C. C_{ps} = 2.1 kJ/kg·K.

Step 1: From steam tables at 12 bar: T_s = 188 + 273 = 461 K, h_{fg} = 1984.3 kJ/kg

Step 2: T_{sup} = 250 + 273 = 523 K

Step 3: $s_{sup} = C_{pw} \ln(T_s/273) + h_{fg}/T_s + C_{ps} \ln(T_{sup}/T_s)$

Step 4: s_{sup} = 4.18 ln(461/273) + 1984.3/461 + 2.1 ln(523/461)

Step 5: s_{sup} = 2.190 + 4.304 + 0.265 = 6.759 kJ/kg·K

Answer: Entropy = 6.759 kJ/kg·K

13. MOLLIER CHART (h-s DIAGRAM)

Definition: The Mollier chart is a graphical representation of steam properties with enthalpy (h) on vertical axis and entropy (s) on horizontal axis. Developed by Dr. Richard Mollier in 1904.

> ***Refer to Fig. 2.11:*** *Mollier Chart*

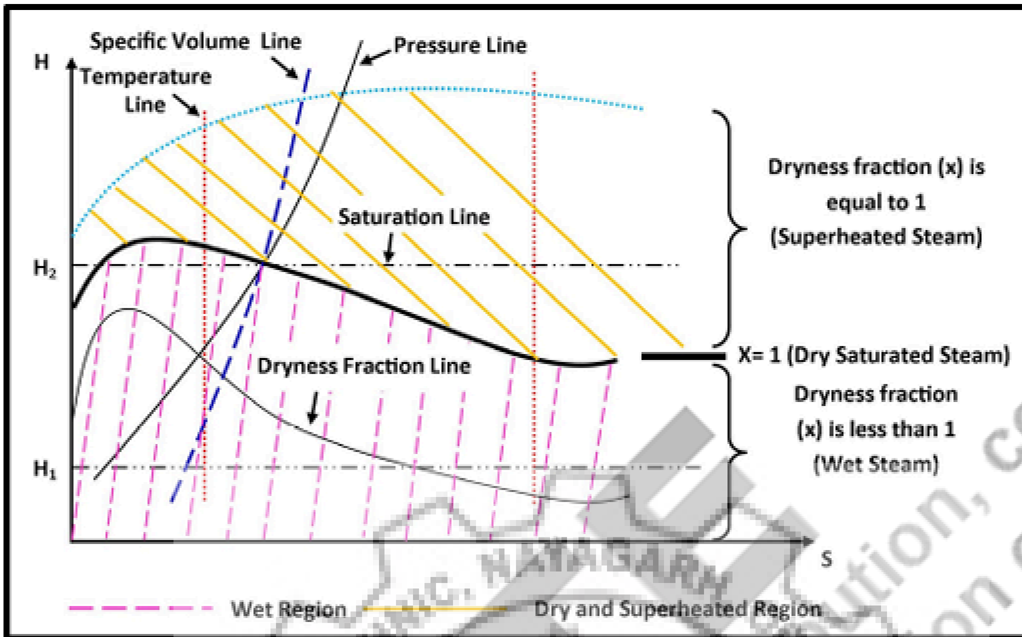


Figure 2.11 Mollier Chart

> ***Refer to Fig. 2.12:*** *Enthalpy - Entropy Plot*

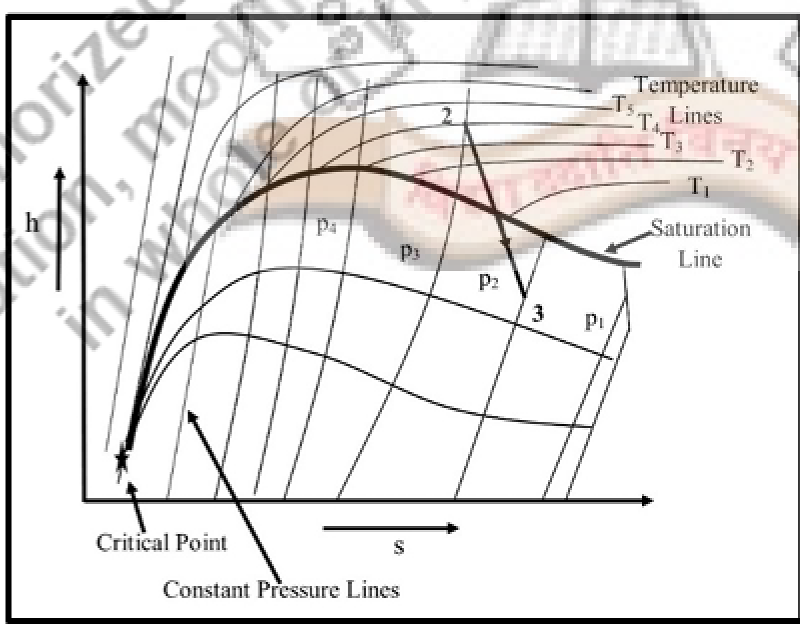


Figure 2.12 Enthalpy - Entropy Plot

13.1 Features of Mollier Chart

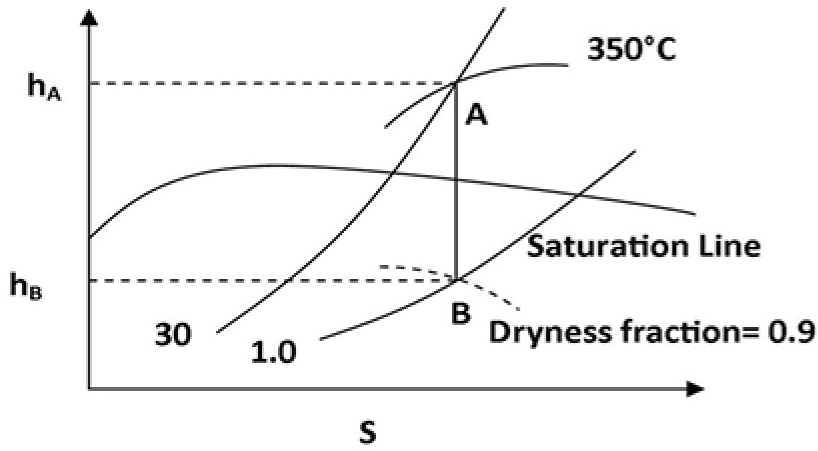
- **Saturation Line:** Thick curve separating wet and superheated regions
- **Wet Region (Below saturation line):**
  - Lines of constant pressure are straight
  - Lines of constant temperature coincide with constant pressure lines
  - Lines of constant dryness fraction (x) are shown
- **Superheated Region (Above saturation line):**
  - Lines of constant pressure are curved
  - Lines of constant temperature are shown
  - Lines of constant specific volume are shown
- **Critical Point:** Highest point on saturation line (221.2 bar, 374.15°C for water)

13.2 Uses of Mollier Chart

1. Determine properties of steam at any state (h, s, T, P, x, v)
2. Analyze isentropic processes (vertical lines on chart)
3. Analyze throttling processes (constant enthalpy, horizontal lines)
4. Determine heat drop in turbines
5. Find final state after expansion or compression
6. Calculate work output in thermodynamic cycles

Example 13.1: Using Mollier Chart

Problem: Steam expands isentropically from 30 bar, 350°C to 1 bar. Find enthalpy drop using Mollier chart.



Step 1: Locate point A at intersection of P=30 bar and T=350°C lines

Step 2: Draw vertical line (constant entropy) to P=1 bar line (point B)

Step 3: Read h_A = 3120 kJ/kg, h_B = 2450 kJ/kg

Step 4: Enthalpy drop = h_A - h_B = 3120 - 2450 = 670 kJ/kg

Answer: Enthalpy drop = 670 kJ/kg

14. THERMODYNAMIC PROCESSES WITH STEAM

14.1 Types of Processes

1. Constant Volume (Isochoric) Process
2. Constant Pressure (Isobaric) Process
3. Constant Temperature (Isothermal) Process
4. Hyperbolic Process
5. Constant Entropy (Isentropic) Process
6. Polytropic Process (PV^n = Constant)
7. Constant Enthalpy (Throttling) Process

14.2 Constant Volume (Isochoric) Process

Condition: V = constant, dV = 0

Work done: W = PΔV = 0

Heat transfer: $q = u_2 - u_1$

Volume relation: $x_1 v_{g1} = x_2 v_{g2}$

$$\therefore x_2 = x_1 \frac{v_{g1}}{v_{g2}}$$

14.3 Constant Pressure (Isobaric) Process

Condition: P = constant, dP = 0

Work done: $W = 100P(v_2 - v_1)$ kJ/kg (P in bar)

Heat transfer: $q = h_2 - h_1$

Internal energy change: $\Delta u = (h_2 - h_1) - 100P(v_2 - v_1)$

14.4 Isentropic Process

Condition: s = constant, $q = 0$

Work done: $W = u_1 - u_2$

Entropy relation: $s_{f1} + x_1 s_{fg1} = s_{f2} + x_2 s_{fg2}$

For superheated steam: $s_{g1} + C_{ps} \ln \frac{T_1}{T_{s1}} = s_{g2} + C_{ps} \ln \frac{T_2}{T_{s2}}$

14.5 Throttling Process (Constant Enthalpy)

Condition: h = constant, $q = 0$, $W = 0$

Enthalpy relation: $h_1 = h_2$

For wet steam: $h_{f1} + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2}$

$$\therefore x_2 = \frac{h_{f1} + x_1 h_{fg1} - h_{f2}}{h_{fg2}}$$

> For superheated steam after throttling: $h_{f1} + x_1 h_{fg1} = h_{g2} + C_{ps}(T_{sup2} - T_{s2})$

15. STEAM CALORIMETERS

Steam calorimeters are instruments used to determine the dryness fraction (quality) of steam.

15.1 Types of Calorimeters

Type	Principle	Formula for Dryness Fraction	Applications/Limitations
Barrel Calorimeter	Steam condensed in cold water, temperature rise measured	$x = \frac{M}{m} \frac{C_p(t_2-t_1) - C_p(t_s-t_2)}{L}$	Simple but inaccurate due to heat losses
Separating Calorimeter	Mechanically separates water from steam	$x = \frac{m_g}{m_g + m_w}$	Good for very wet steam, doesn't give accurate dryness fraction

Throttling Calorimeter	Steam throttled to lower pressure, becomes superheated	$h_{f1} + xh_{fg1} = h_{g2} + C_{ps}(T_2 - T_{sat2})$	Accurate for steam with x > 0.95
Combined Separating & Throttling	First separates water, then throttles remaining steam	$x = x_1 \times x_2$ where x_1 = from separator x_2 = from throttling	Most accurate, used for steam with x < 0.95

Refer to Fig. 2.13: *Barrel Calorimeter*

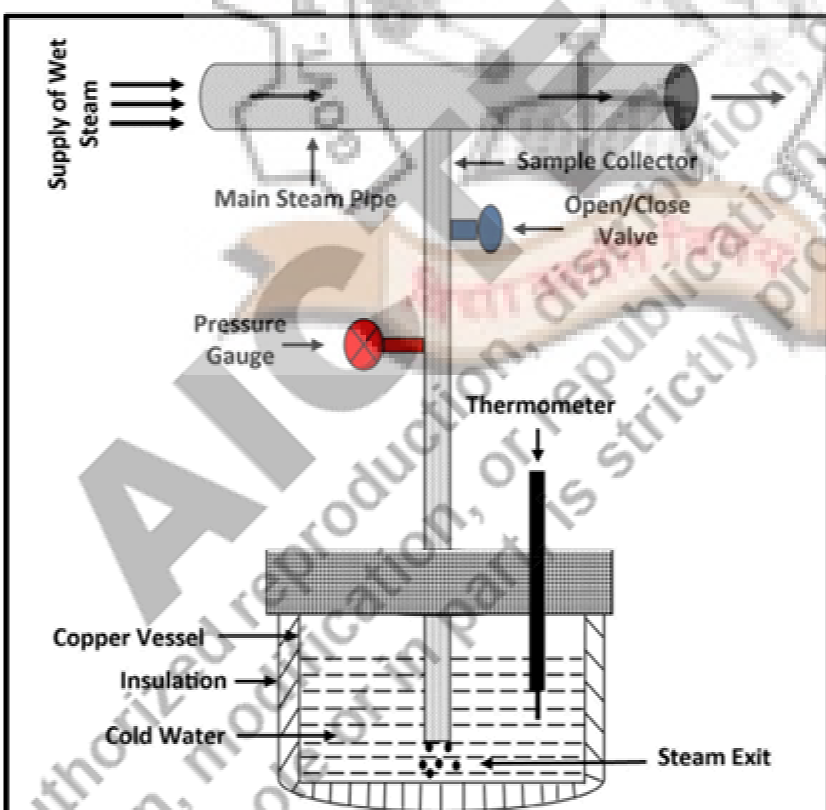


Figure 2.13 Barrel Calorimeter

Refer to Fig. 2.14: *Separating Calorimeter*

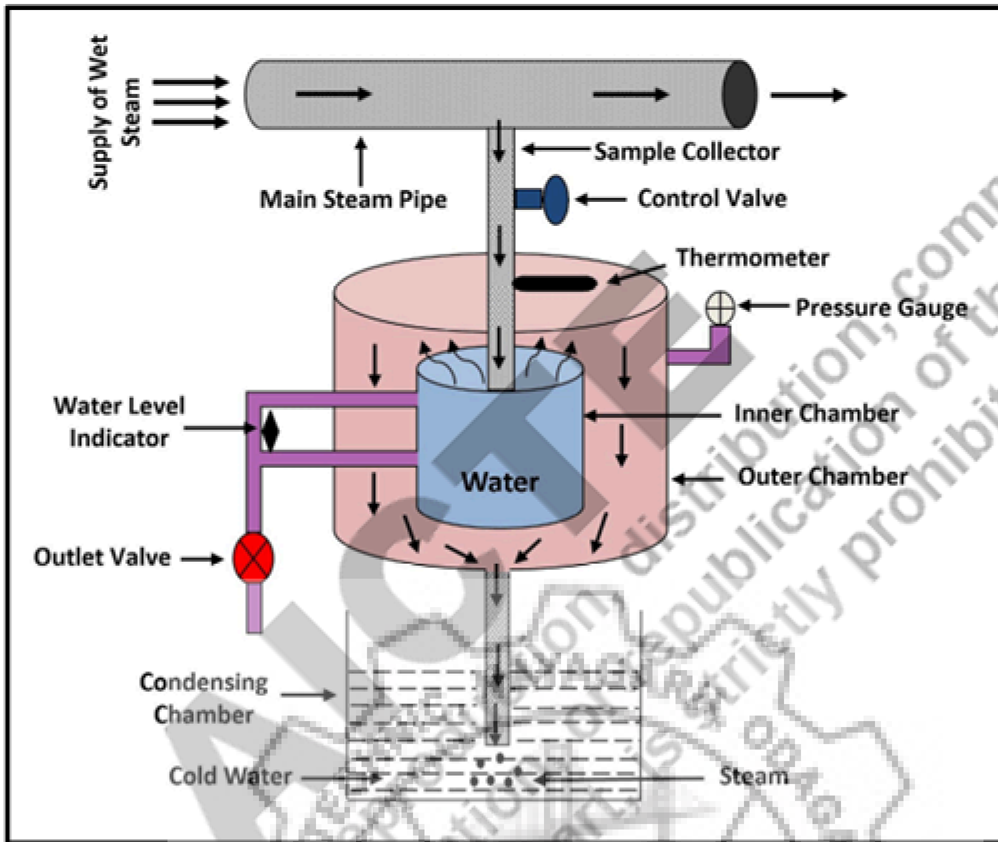


Figure 2.14 Separating Calorimeter

Refer to

Fig. 2.15: *Throttling Calorimeter*

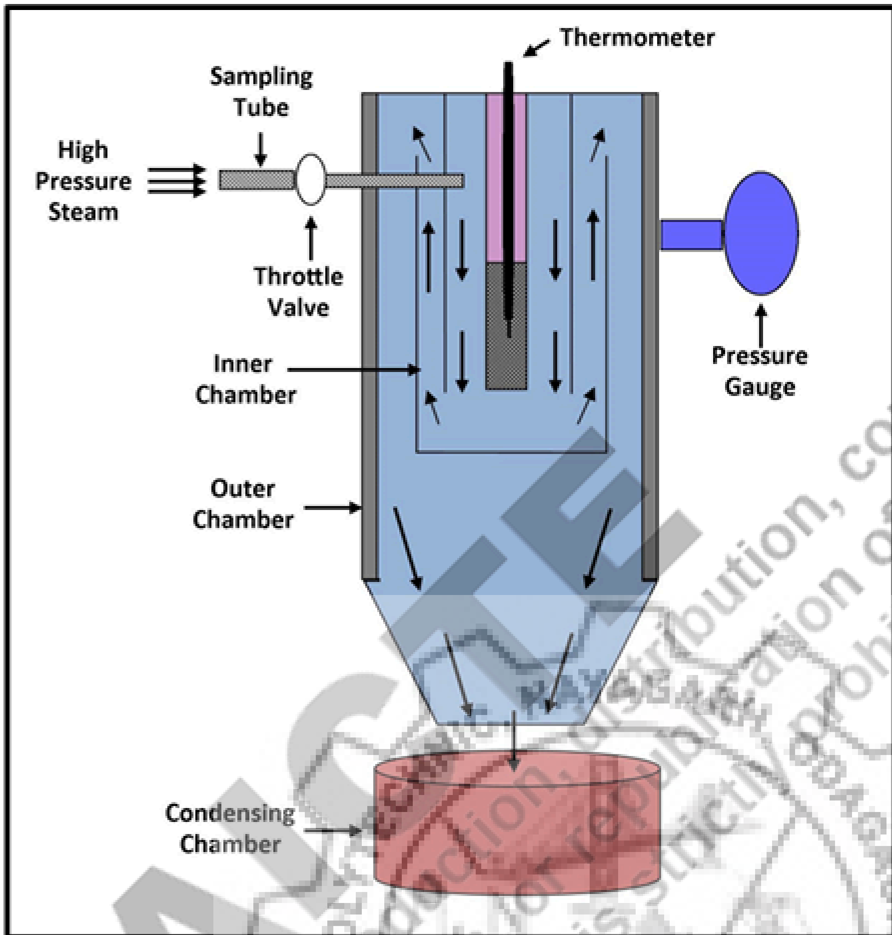


Figure 2.15 Throttling Calorimeter

Refer to Fig. 2.16:

Combined Separating and Throttling Calorimeter

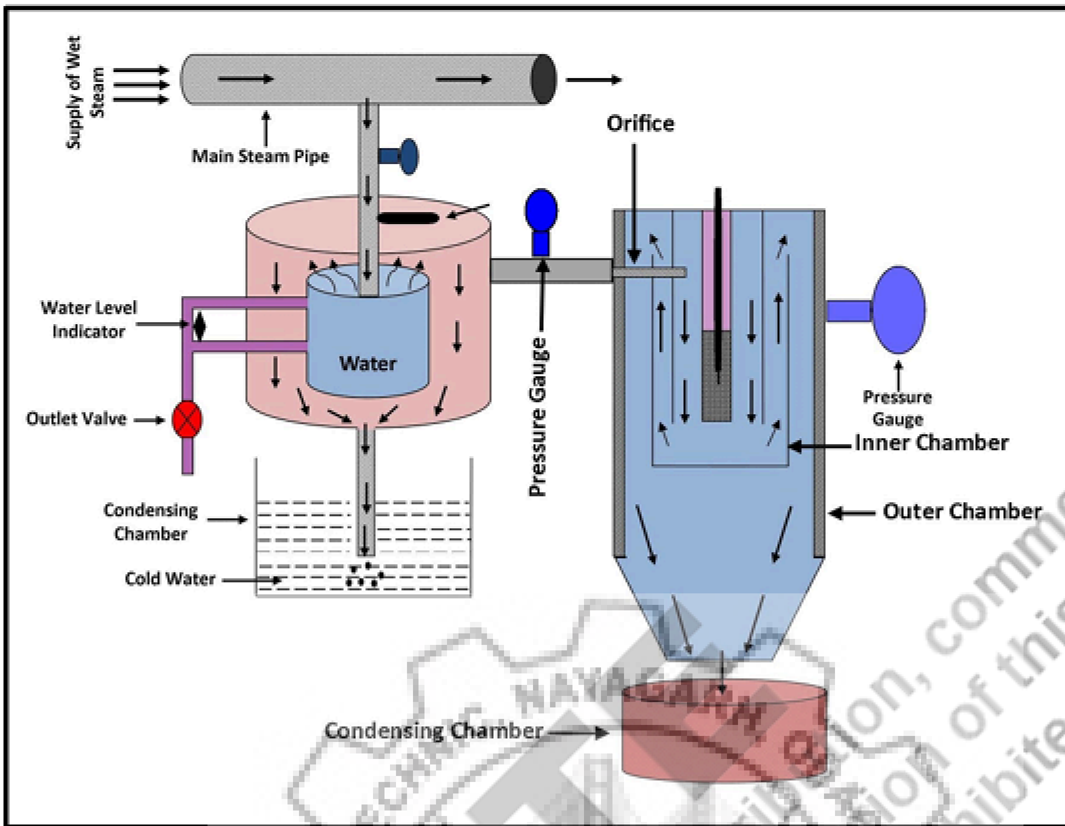


Figure 2.16 Combined Separating and Throttling Calorimeter

Example 15.1: Throttling Calorimeter

Problem: Steam at 10 bar throttled to 1.01325 bar, 110°C. C_{ps} = 2.2 kJ/kg·K. Find dryness fraction.

Step 1: From steam tables at 10 bar: h_{f1} = 762.81 kJ/kg, h_{fg1} = 2014.3 kJ/kg

Step 2: At 1.01325 bar: h_{g2} = 2676 kJ/kg, T_{sat2} = 100°C

Step 3: $h_1 = h_2$ (constant enthalpy)

Step 4: 762.81 + x × 2014.3 = 2676 + 2.2(110-100)

Step 5: 762.81 + 2014.3x = 2676 + 22 = 2698

Step 6: 2014.3x = 2698 - 762.81 = 1935.19

Step 7: x = 1935.19/2014.3 = 0.961

Answer: Dryness fraction = 0.961

Numerical 2.14: Combined Separating and Throttling Calorimeter

Problem Statement:
The dryness fraction of steam passing through a steam main at a pressure of 9 bar was measured using a combination separating and throttling calorimeter. After throttling, steam had a pressure of 1.25 bar and a temperature of 115°C. After throttling, 2.2 kg of steam condensed, and 0.20 kg of water was collected in the separator. Calculate the primary steam's dryness fraction. Consider the specific heat of superheated steam as 2.1 kJ/kg·K.

Given Data:

Mass of water collected in separator (m_w)	= 0.20 kg
Mass of steam condensed after throttling (m_s)	= 2.2 kg
Initial pressure (p_1)	= 9 bar
Pressure after throttling (p_2)	= 1.25 bar
Temperature after throttling (T_2)	= 115°C
Specific heat of superheated steam (C_{ps})	= 2.1 kJ/kg·K

Step 1: Find dryness fraction from separating calorimeter (x_1)

The dryness fraction from separating calorimeter is:

$$x_1 = \frac{m_s}{m_w + m_s}$$

Substituting values:

$$x_1 = \frac{2.2}{0.20 + 2.2} = \frac{2.2}{2.4}$$

$$x_1 = 0.9167$$

Step 2: Steam table values at initial pressure (9 bar)

From steam tables at $p_1 = 9$ bar:

$$h_{f1} = 742.83 \text{ kJ/kg}$$

$$h_{fg1} = 2031.1 \text{ kJ/kg}$$

Step 3: Steam table values after throttling (1.25 bar)

From steam tables at $p_2 = 1.25$ bar:

$$T_{sat2} = 106°C$$

$$h_{g2} = 2685.4 \text{ kJ/kg}$$

Step 4: Calculate enthalpy after throttling (h_2)

For superheated steam after throttling:

$$h_2 = h_{g2} + C_{ps}(T_2 - T_{sat2})$$

$$h_2 = 2685.4 + 2.1 \times (115 - 106)$$

$$h_2 = 2685.4 + 2.1 \times 9$$

$$h_2 = 2685.4 + 18.9 = 2704.3 \text{ kJ/kg}$$

Step 5: Apply constant enthalpy condition ($h_1 = h_2$)

Enthalpy before throttling (h_1) is:

$$h_1 = h_{f1} + x_2 h_{fg1}$$

Since $h_1 = h_2$:

$$742.83 + x_2 \times 2031.1 = 2704.3$$

Step 6: Solve for x_2

$$x_2 \times 2031.1 = 2704.3 - 742.83$$

$$x_2 \times 2031.1 = 1961.47$$

$$x_2 = \frac{1961.47}{2031.1}$$

$$x_2 = 0.9657$$

Step 7: Calculate overall dryness fraction (x)

For combined calorimeter:

$$x = x_1 \times x_2$$

$$x = 0.9167 \times 0.9657$$

$$x = 0.885$$

Final Answer: The dryness fraction of the primary steam is 0.885 or 88.5%

Note: *The combined calorimeter method is more accurate than using either calorimeter alone because:*

- *The separating calorimeter removes most moisture from very wet steam*
- *The throttling calorimeter accurately measures the dryness of relatively dry steam*
- *The product of the two gives the true dryness fraction of the original steam*

16. UNIT SUMMARY – KEY POINTS

1. **Steam exists in three states: wet steam (liquid-vapor mixture), dry saturated steam (pure vapor at saturation), and superheated steam (vapor above saturation temperature)**

2. **Dryness fraction (x) is the ratio of mass of dry steam to total mass of wet steam**
3. **Critical point is where liquid and vapor phases become indistinguishable (221.2 bar, 374.15°C for water)**
4. **Enthalpy formulas:**
   - **Wet steam:** $h = h_f + xh_{fg}$
   - **Superheated steam:** $h_{sup} = h_g + C_{ps}(T_{sup} - T_s)$
5. **Internal energy:** $u = h - Pv$ **(with proper unit conversion)**
6. **Entropy formulas:**
   - **Wet steam:** $s = s_f + xs_{fg}$
   - **Superheated steam:** $s_{sup} = s_g + C_{ps} \ln(T_{sup}/T_s)$
7. **Mollier chart is h-s diagram used for graphical analysis of steam processes**
8. **Thermodynamic processes: Know formulas for isochoric, isobaric, isentropic, and throttling processes**
9. **Steam calorimeters measure dryness fraction:**
   - **Barrel calorimeter: Simple but inaccurate**
   - **Separating calorimeter: Good for very wet steam**
   - **Throttling calorimeter: Accurate for x > 0.95**
   - **Combined calorimeter: Most accurate, used for x < 0.95**

17. EXAM PREPARATION GUIDE

Important Topics for Exams:

- Definitions of steam properties and states
- Formulas for enthalpy, internal energy, entropy

- Use of steam tables and Mollier chart
- Calculations involving dryness fraction
- Working principles of different calorimeters
- Numerical problems on steam properties
- Thermodynamic processes with steam

17.1 Expected Question Types

- **Short Answer (2-3 marks):** Definitions, comparisons, working principles
- **Long Answer (5-10 marks):** Derivation of formulas, working of calorimeters, thermodynamic processes
- **Numerical Problems (3-5 marks):** Calculations using steam tables, enthalpy, entropy, dryness fraction
- **Diagram Drawing (3-4 marks):** Steam formation processes, calorimeters, Mollier chart

17.2 Common Exam Questions

1. Define: dry saturated steam, wet steam, superheated steam, dryness fraction
2. Explain formation of steam under constant pressure with diagram
3. Derive formula for enthalpy of wet steam
4. Explain working of throttling calorimeter with diagram
5. Differentiate between separating and throttling calorimeters
6. Calculate enthalpy, internal energy, entropy for given steam conditions
7. Explain use of Mollier chart for isentropic expansion
8. Describe constant volume and constant pressure processes with steam

18. ADDITIONAL RESOURCES

18.1 Recommended Textbooks

- **Thermal Engineering** by B.R. Sarkar (McGraw-Hill)
- **Thermal Engineering** by R.K. Rajput (Laxmi Publications)
- **A Textbook of Thermal Engineering** by R.S. Khurmi & J.K. Gupta (S. Chand)

18.2 Online Resources (via QR codes in textbook)

- Lectures on Steam formation and Properties - Engineering Funda
- NPTEL Course on "Property of pure substance and Steam Table" - IIT Kharagpur
- Lectures on calorimeters - Mechanical Engineering Tutorials

18.3 Important Values to Remember

- Critical point of water: P_c = 221.2 bar, T_c = 374.15°C
- Latent heat of vaporization at atmospheric pressure: 2257 kJ/kg
- Specific heat of water: C_{pw} = 4.18 kJ/kg·K
- Specific heat of superheated steam: C_{ps} = 2.0-2.1 kJ/kg·K
- Triple point of water: 0.01°C, 0.00611 bar

Final Study Tips:

- Practice using **steam tables** - know how to interpolate values
- Memorize key **formulas** for enthalpy, internal energy, entropy
- Understand the **physical meaning** of each property
- Solve numerical problems from textbook exercises
- Practice drawing and interpreting **Mollier chart**
- Review the **Unit Summary** before exam
- Focus on applications of each concept in real engineering systems

These comprehensive notes cover **Unit 2: Properties of Steam** as per AICTE Diploma curriculum.

Best of luck for your exams! Practice numerical problems regularly.

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Chapter 3: Steam Generators

📘 **Chapter Overview:** This chapter covers steam boilers (steam generators), their classification, working principles, construction details, accessories, mountings, efficiency calculations, and draught systems. Essential for power plant engineering and industrial applications.

3.0 UNIT SPECIFICS

This unit provides comprehensive understanding of steam generators (boilers), their types, components, performance parameters, and applications in power generation and industrial processes.

Topics Covered:

- Function and classification of steam boilers using schematic diagrams
- Comparison of water tube and fire tube boilers
- High-pressure boilers: Lamont and Benson boilers
- Boiler mountings and accessories
- Calculation of boiler efficiency, boiler horsepower, equivalent evaporation

- Draught systems: Natural, forced, induced, and balanced draught

> 📐 ***Key Diagrams to Study:*** *Fig. 3.1 to Fig. 3.10 – Schematic diagrams of boilers, Cochran boiler, Babcock & Wilcox boiler, Lamont boiler, Benson boiler, and draught systems.*

3.1 RATIONALE – IMPORTANCE OF STEAM GENERATORS

Steam boilers are critical components in energy systems and industrial processes:

- **Power Generation:** Convert water to high-pressure steam to drive turbines
- **Industrial Heating:** Provide steam for manufacturing, drying, sterilization
- **HVAC Systems:** Used for heating in residential, commercial, and industrial buildings
- **Process Industries:** Essential in chemical, pharmaceutical, food processing industries
- **Energy Efficiency:** Understanding boiler design and operation maximizes energy utilization

3.2 PRE-REQUISITES

Before studying this unit, students should review:

- **Basic Mechanical Engineering (MEPC102):** Thermodynamics, heat transfer, fluid mechanics
- **Properties of Steam (Chapter 2):** Steam formation, enthalpy, entropy concepts

3.3 UNIT OUTCOMES

After completing this unit, students will be able to:

- **U3-O1:** Understand boilers and their classification and function
- **U3-O2:** Explain Cochran, Babcock and Wilcox boilers with diagrams
- **U3-O3:** Compare water tube and fire tube boilers and describe high-pressure boilers
- **U3-O4:** Learn about boiler mountings, accessories and performance measuring terms

- **U3-O5:** Understand types of draught system

3.4 STEAM BOILERS – BASIC CONCEPTS

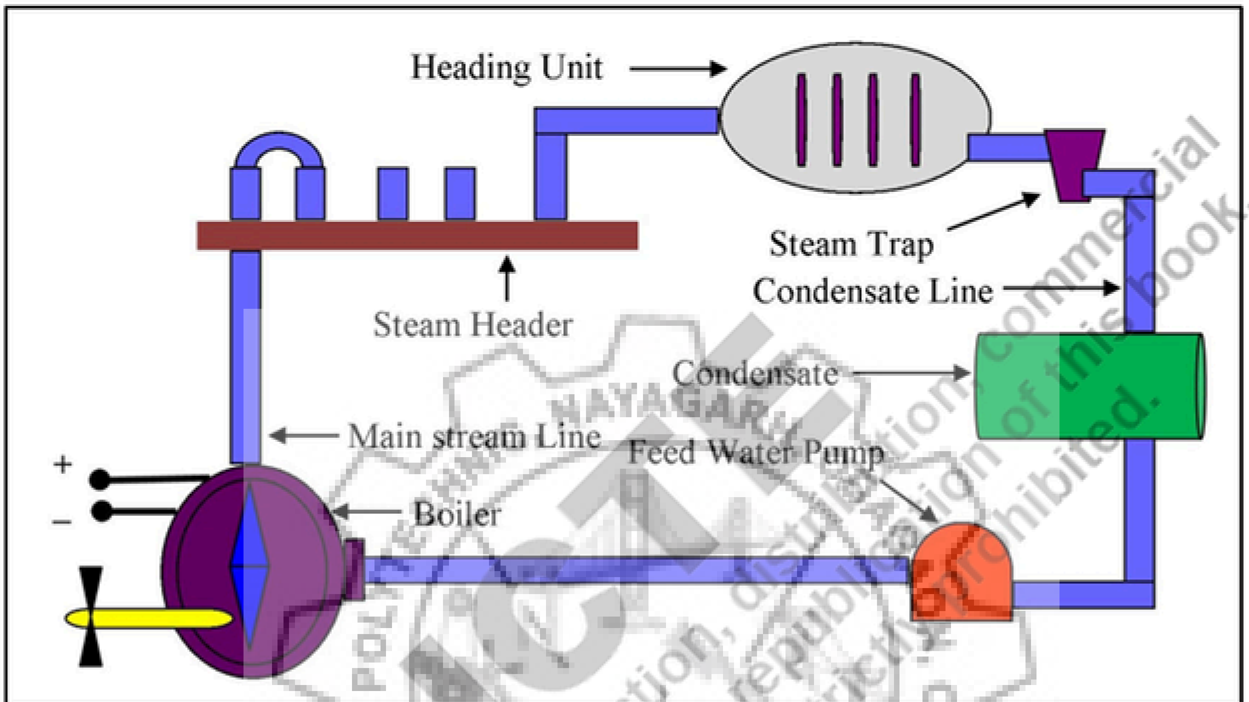


Fig. 3.1 Schematic Diagram of Steam Boiler

Definition: A boiler is a closed vessel in which water is heated by combustion of fuel to produce steam or hot water. It consists of three main parts: furnace, heat transfer surfaces, and steam space.

> ***Refer to Fig. 3.1:*** *Schematic Diagram of Steam Boiler*

3.4.1 Function and Uses of Steam Boilers

- **Primary Function:** Convert water into steam using heat from fuel combustion
- **Applications:**
  - Power generation (steam turbines)
  - Industrial processes (sterilization, drying, chemical processing)
  - Heating systems (residential, commercial)

- Marine propulsion
- Locomotive engines

3.5 CLASSIFICATION OF STEAM BOILERS

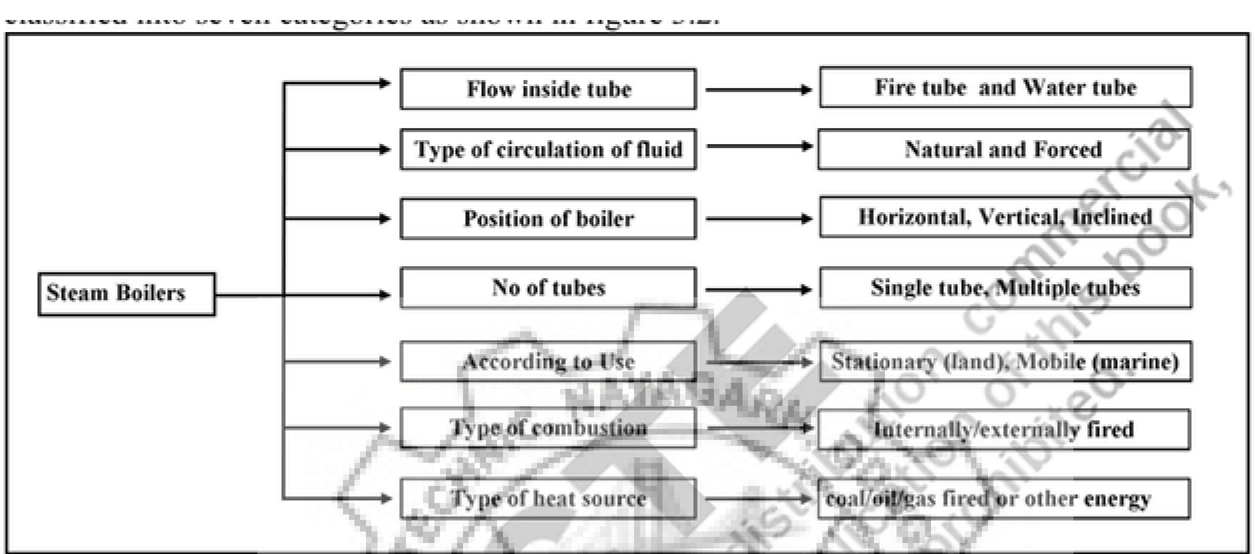


Fig. 3.2 Classification of Boilers

Refer to Fig. 3.2: *Classification of Boilers*

3.5.1 Classification Basis

Basis of Classification	Types	Examples
Flow Inside Tubes	• Fire Tube Boiler • Water Tube Boiler	• Cochran, Lancashire (Fire tube) • Babcock & Wilcox (Water tube)

Circulation of Fluid	• Natural Circulation • Forced Circulation	• Lancashire (Natural) • LaMont, Benson (Forced)
Position of Boiler	• Horizontal • Vertical • Inclined	• Babcock & Wilcox (Horizontal) • Cochran (Vertical)
Number of Tubes	• Single Tube • Multi-tube	• Simple Vertical (Single) • Cochran (Multi-tube)
Use/Application	• Stationary • Mobile	• Power Plant Boilers • Marine, Locomotive
Type of Combustion	• External Combustion • Internal Combustion	• Most boilers (External) • Lancashire (Internal)
Heat Source	• Coal-fired • Oil-fired • Gas-fired • Electric • Nuclear	• Traditional power plants • Modern industrial boilers

3.6 COCHRAN BOILER

Definition: Cochran boiler is a vertical, multi-tubular, fire tube boiler with hemispherical shell and firebox. It is a type of internally fired, natural circulation boiler.

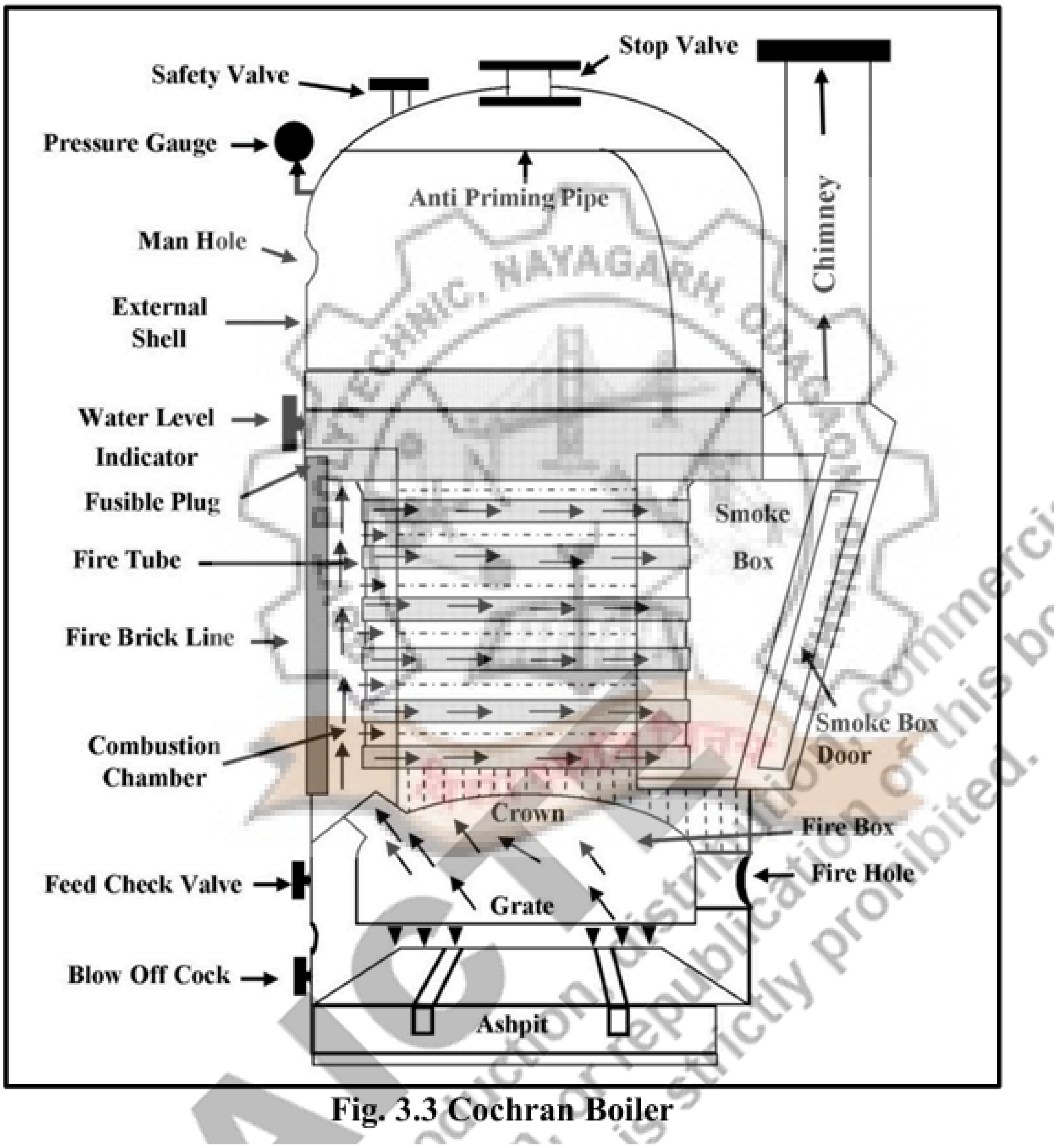


Fig. 3.3 Cochran Boiler

Cochran Boiler

3.6.1 Construction and Main Parts

1. **Boiler Shell:** Cylindrical vessel made of steel plates
2. **Combustion Chamber:** Where fuel burns to produce heat
3. **Grate:** Platform for fuel combustion
4. **Furnace:** Area below boiler shell where fuel is burned
5. **Fire Tubes:** Horizontal tubes carrying hot gases
6. **Fire Hole:** Opening for fuel ignition
7. **Chimney:** Exhaust for flue gases
8. **Manhole:** For inspection and cleaning
9. **Flue Pipe:** Connects firebox to combustion chamber

3.6.2 Working Principle

1. Fuel burned on grate → hot gases → flue pipes → combustion chamber
2. Hot gases pass through fire tubes, heating surrounding water
3. Water converts to steam, rises to dome
4. Steam dried by anti-priming pipe
5. Dry steam supplied to turbines via steam stop valve
6. Exhaust gases pass to smokebox → chimney
7. **Fusible plug** melts if temperature exceeds limit, water extinguishes fire

3.6.3 Advantages and Disadvantages

Advantages	Disadvantages

• Low initial cost • Compact design, less floor space • Simple operation and control • Portable • Multi-fuel capability	• Low steam production rate • Limited pressure handling capacity • Difficult maintenance and inspection • Lower efficiency compared to water tube boilers

3.6.4 Applications

- Power stations (steam production: 500 kg/s at 160 bar, 550°C)
- Refining units
- Paper production factories
- Chemical processing industries
- Various process applications

3.7 BABCOCK AND WILCOX BOILER

Definition: Babcock & Wilcox boiler is a horizontal, water tube, externally fired, natural circulation boiler operating at high pressure. Invented in 1967 by George Herman Babcock and Stephen Wilcox.

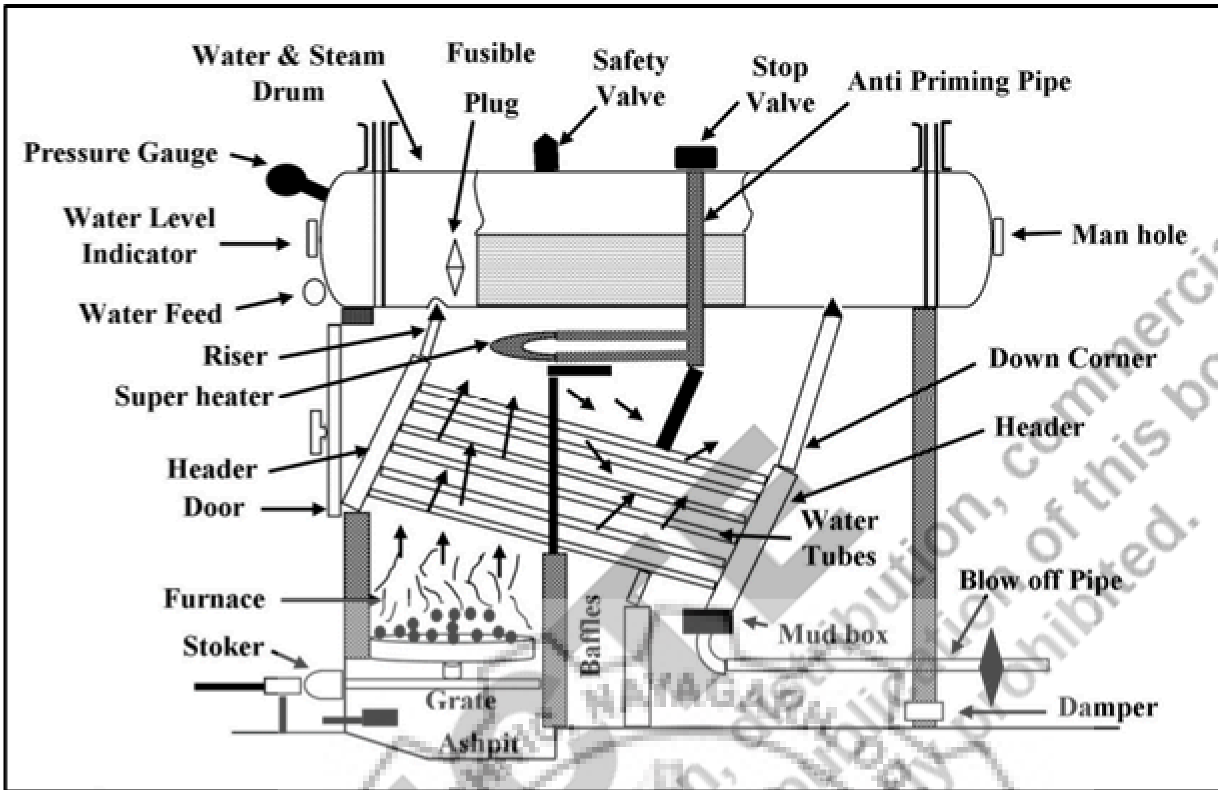


Fig. 3.4 Babcock and Wilcox Boiler

> ***Refer to Fig. 3.4:*** *Babcock and Wilcox Boiler*

3.7.1 Construction and Main Parts

1. **Drum:** Horizontal cylinder holding water and steam
2. **Down Take Header:** Connects drum to water tubes at back
3. **Up Take Header:** Connects water tubes to drum at front
4. **Water Tubes:** Inclined 10-15°, water inside, hot gases outside
5. **Baffle Plates:** Create zigzag gas path for better heat transfer
6. **Mud Collector:** Collects impurities from water
7. **Superheater:** Increases steam temperature
8. **Safety Valve, Pressure Gauge, Water Level Indicator:** Mountings

3.7.2 Working Principle

1. Water from drum → down take header → water tubes

2. Hot flue gases heat water tubes in zigzag path (baffle plates)
3. Steam forms, rises to drum via uptake header
4. Steam dried (anti-priming pipe) → superheater → turbine
5. Superheated steam drives turbine for power generation

Key Point: Water tubes are inclined to ensure natural circulation and easy separation of steam and water.

3.8 COMPARISON: WATER TUBE vs FIRE TUBE BOILERS

FIRE TUBE BOILER	WATER TUBE BOILER
Hot flue gases circulate within the tubes, while water flows outside.	Water circulates within the tubes, while hot flue gas flows outside.
These boilers are often fired from inside.	These boilers are fired from outside.
The maximum boiler pressure is 20 bar.	The maximum boiler pressure is 100 bar.
The fire-tube boiler produces less steam at a slower rate.	The water tube boiler produces steam at a higher rate.
Insufficient for larger power plants.	Sufficient for larger power plants.

FIRE TUBE BOILER	WATER TUBE BOILER
Because of the low pressure, there is less chance of an explosion.	Because of the high pressure, there is more chances of an explosion.
It takes up a lot of floor space for a given amount of power.	It takes up a less floor space for a given amount of power.
Construction is difficult.	Construction is simple.
Transportation is challenging.	Transportation is simple.
They require less skill to operate than a water tube boiler.	They require high skill to operate than a water tube boiler
They are tough to repair and clean due to the fact that they are internally fired.	They are easy to repair and clean as they are externally fired.
Because the fire tube is located inside the shell, they require a high shell diameter.	They require a small shell diameter.
The fire tube boiler has a lower efficiency than the water tube boiler.	The efficiency of the water tube boiler is more.
This boiler's servicing is expensive. It must be inspected on a regular basis.	They are easy to maintain as they are externally fired.
Example: Cornish Boiler, Lancashire Boiler	Example: Babcock and Wilcox Boiler

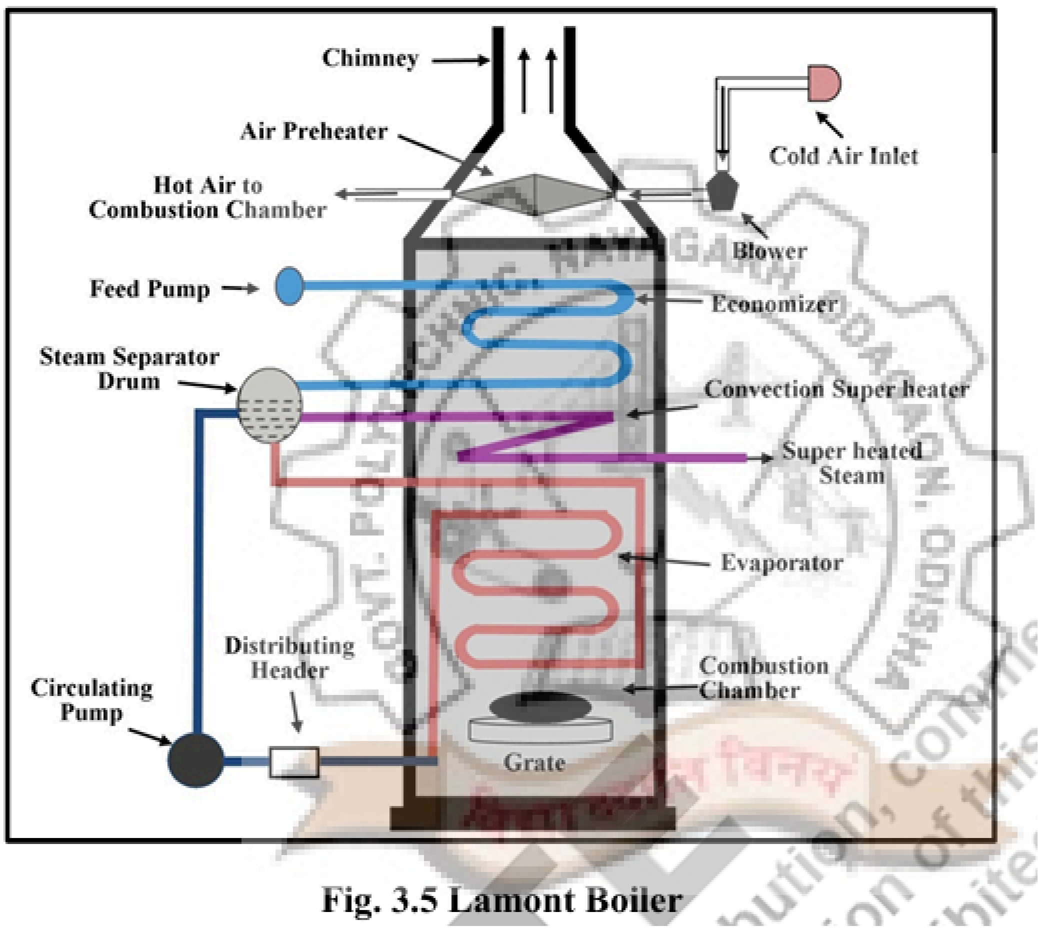
Parameter	Fire Tube Boiler	Water Tube Boiler

Flow Configuration	Hot gases inside tubes, water outside	Water inside tubes, hot gases outside
Firing Method	Internally fired	Externally fired
Pressure Capacity	Up to 20 bar	Up to 100 bar
Steam Production Rate	Lower	Higher
Suitability for Power Plants	Insufficient for large plants	Sufficient for large plants
Explosion Risk	Lower (low pressure)	Higher (high pressure)
Floor Space	More for given power	Less for given power
Construction	Difficult	Simple
Transportation	Challenging	Simple
Operating Skill Required	Less	More
Maintenance & Repair	Difficult (internally fired)	Easy (externally fired)
Shell Diameter	Large	Small
Efficiency	Lower	Higher
Examples	Cochran, Lancashire	Babcock & Wilcox

3.9 HIGH PRESSURE BOILERS

Definition: High-pressure boilers operate at pressures above 80 bar, producing steam typically between 1 bar to 55 bar. Used in thermal power plants for efficient power generation.

3.9.1 Lamont Boiler



Lamont Boiler

Inventor: Thomas C. Lamont (early 20th century)

Type: Forced circulation water tube boiler

Construction and Main Parts:

1. **Economizer:** Preheats feed water using waste heat
2. **Centrifugal Pump:** Forces water circulation (driven by steam turbine)
3. **Evaporator Tubes:** Convert water to steam

4. **Furnace & Grate:** For fuel combustion
5. **Superheater:** Increases steam temperature
6. **Water-Steam Separator Drum:** Separates steam from water
7. **Air Preheater:** Heats combustion air

Working Principle:

1. Feed water → economizer (preheated) → centrifugal pump
2. Water forced through evaporator tubes → steam-water mixture
3. Mixture → separator drum (steam separated)
4. Steam → superheater → turbine
5. Water returned to economizer

Operating Parameters:

```
Working pressure > 170 bar
```

```
Steam production ≈ 50,000 kg/hour
```

```
Steam temperature ≈ 773 K (500°C)
```


Advantages and Disadvantages:

Advantages	Disadvantages
• High steam production rate • Quick start-up	• Bubble formation reduces heat transfer • Expensive maintenance

• Simple construction concept	• High construction cost
• High heat transfer rate	• Reduced efficiency at part load
• Customizable design	• Requires skilled operators
	• Limited to large-scale applications

3.9.2 Benson Boiler

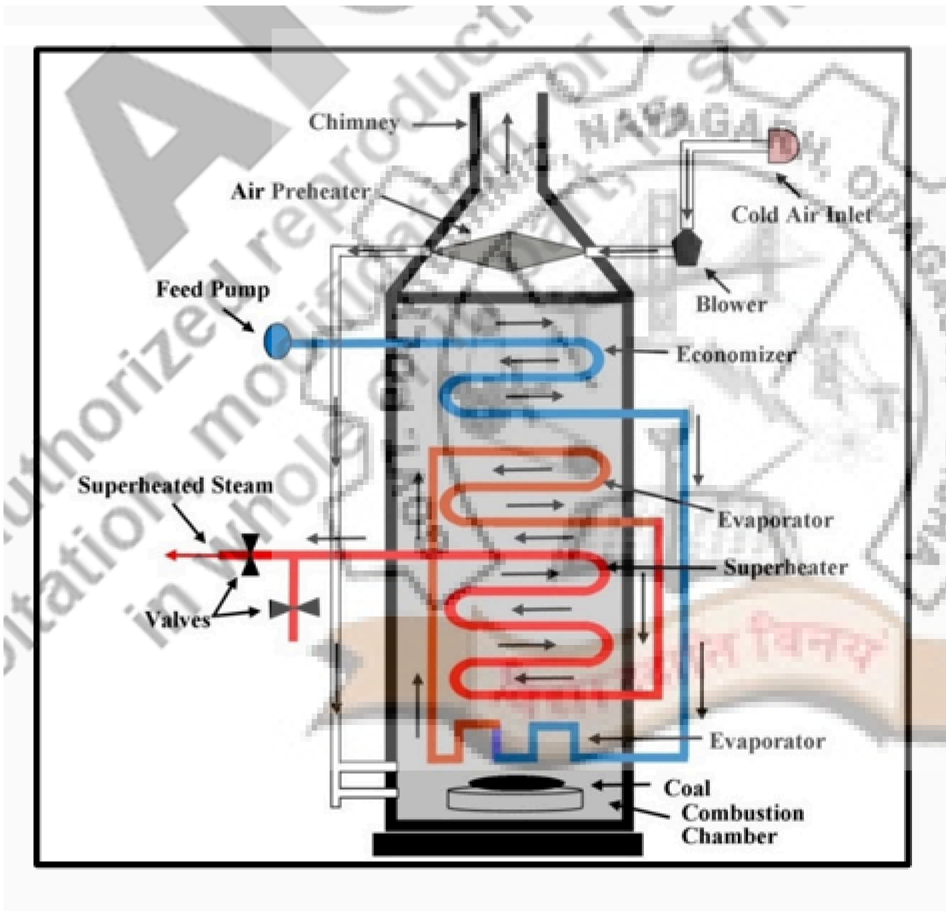


Fig. 3.6 Benson Boiler

***Refer to Fig. 3.6:** Benson Boiler*

Type: Supercritical pressure, once-through boiler (no drum)

Key Concept:

At supercritical pressure (>225 bar for water), latent heat of vaporization becomes zero. Water directly converts to steam without boiling, preventing bubble formation.

Construction and Main Parts:

1. **Economizer:** Preheats feed water
2. **Radiant Evaporator:** Converts most water to steam via radiation
3. **Convection Evaporator:** Completes evaporation via convection
4. **Convection Superheater:** Superheats steam to 650°C
5. **Steam Outlet:** Supplies superheated steam to turbine

Working Principle:

1. Feed water pressurized to supercritical pressure (>225 bar)
2. Water → economizer → radiant evaporator (partial steam)
3. → convection evaporator (complete steam)
4. → superheater (650°C) → turbine

Advantages and Disadvantages:

Advantages	Disadvantages

• No drum, lighter weight • Faster start-up than conventional boilers • High thermal efficiency (up to 90%) • No bubble formation issues	• Requires constant monitoring to prevent explosions • Difficult to control under varying loads • High initial cost • Complex control systems

3.10 BOILER MOUNTINGS

Definition: Boiler mountings are essential fittings attached to boilers for safe and efficient operation. They are mandatory safety devices.

3.10.1 Types of Mountings

Mounting	Function	Key Features
Water Level Indicator	Shows water level in boiler	Transparent glass tube, steam valve, water valve, drain valve
Pressure Gauge	Indicates steam pressure	Bourdon tube mechanism, calibrated dial
Safety Valve	Releases excess pressure to prevent explosion	Types: Deadweight, lever, spring-loaded
Steam Stop Valve	Controls steam flow from boiler	Also called junction valve

Blow-Off Valve	Removes sediments and drains boiler	Located at bottom of boiler
Feed Check Valve	Controls feed water entry, prevents backflow	Located at feed pump delivery end
Fusible Plug	Melts if water level is low, extinguishes fire	Made of low melting point alloy (tin/lead)

3.11 BOILER ACCESSORIES

Definition: Boiler accessories are components that improve efficiency and performance but are not essential for basic operation.

3.11.1 Types of Accessories

Accessory	Function	Benefits
Economizer	Preheats feed water using waste heat from flue gases	Increases efficiency by 5-10%, reduces fuel consumption
Air Pre-heater	Preheats combustion air using waste heat	Improves combustion, allows use of low-grade fuels
Superheater	Increases steam temperature above saturation point	Increases turbine efficiency, reduces condensation

Feed Pump	Supplies high-pressure feed water to boiler	Types: Reciprocating (steam-driven), Rotary (electric/turbine)

3.12 STEAM SEPARATORS

Definition: Steam separators (moisture separators) remove water droplets from steam to improve quality and prevent equipment damage.

3.12.1 Need for Steam Separation

- Wet steam reduces thermal efficiency of engines
- Water droplets cause erosion of turbine blades
- Can lead to hydraulic lock in piston engines
- Causes steam hammer in pipes

3.12.2 Types of Steam Separators

Type	Working Principle	Efficiency
Baffle Separator	Changes steam direction, droplets separate by inertia	Moderate
Centrifugal Separator	Uses centrifugal force to separate droplets	High

Mechanical Coalescing Separator	Two-stage: coalescence + centrifugal separation	Very high (≈99.9%)

3.13 STEAM TRAPS

Definition: Steam traps remove condensate and non-condensable gases from steam systems without losing steam.

3.13.1 Types of Steam Traps

Type	Working Principle	Applications
Balanced Pressure Trap	Uses liquid medium that boils/condenses with temperature	General purpose
Thermostatic Trap	Temperature-activated purge cycle	Non-sensitive sub-cooling environments
Thermodynamic Trap	Uses flash steam to open/close valve	High pressure applications
Bimetallic Trap	Bimetallic element responds to temperature	Durable but permeable at low pressure
Float Trap	Float mechanism opens valve at set condensate level	Continuous drainage applications

Inverted Bucket Trap	Bucket rises with steam, opens valve	Heavy duty applications

3.14 DIFFERENCE: STEAM SEPARATOR vs STEAM TRAP

Steam Separator	**Steam trap**
The steam separator is a mechanical apparatus designed to effectively separate water particles from steam.	Steam traps are devices that effectively separate condensate and non-condensate gases, such as air and CO_2, from steam without any steam leakage.
The purpose of this device is to enhance the dryness fraction, or quality, of steam prior to its introduction into a turbine or engine.	Their primary purpose is to prevent the buildup of condensate in steam ducts and pipes.
Typically, a chamber is utilised for the purpose of collecting condensate, accompanied by an automated drain valve that is triggered based on the predetermined water level within the chamber.	These valves operate using distinct mechanisms and are purely automated in nature.
Large surface areas that are exposed to an environment that results in significant heat loss. Certain individuals require an insulating jacket in order to mitigate thermal energy dissipation.	The magnitude of heat loss is significantly lower in comparison to steam separators.
The primary categorizations are the baffle separator, centrifugal separator, and mechanical coalescing separator.	These traps may be categorised into three types: thermostatic trap, mechanical trap (also known as density trap), and thermodynamic trap.

Aspect	Steam Separator	Steam Trap
Primary Function	Removes water droplets from steam	Removes condensate and non-condensable gases

Purpose	Improves steam dryness/quality	Prevents condensate accumulation in pipes
Working Principle	Mechanical separation (baffle, centrifugal)	Automatic valve operation
Heat Loss	Large surface area, significant heat loss	Smaller, less heat loss
Types	Baffle, centrifugal, mechanical coalescing	Thermostatic, mechanical, thermodynamic

3.15 EQUIVALENT EVAPORATION AND BOILER PERFORMANCE

Definition: Equivalent evaporation is the amount of water evaporated at 100°C to dry saturated steam at 100°C using the same heat as in actual conditions. Used to compare boiler performance.

3.15.1 Key Formulas

Equivalent Evaporation (W_e):

$$W_e = \frac{W_a(H - H_w)}{2257}$$

Where:

- W_e = Equivalent evaporation (kg/kg of fuel)
- W_a = Actual steam produced (kg/h)
- H = Enthalpy of steam at working pressure (kJ/kg)
- H_w = Enthalpy of feed water (kJ/kg)
- 2257 = Latent heat of steam at atmospheric pressure (kJ/kg)

Factor of Evaporation (F):

$$F = \frac{H - H_w}{2257}$$

$$W_e = F \times W_a$$

Boiler Efficiency (η_b):

$$\eta_b = \frac{W_a(H - H_w)}{W_f \times C}$$

Where:

- W_f = Fuel consumed (kg/h)
- C = Calorific value of fuel (kJ/kg)

Boiler Horsepower (BHP):

```
1 BHP = Evaporation of 15.653 kg/h from and at 100°C
```

3.15.2 Sample Numerical Problems

Example 3.1: Equivalent Evaporation Calculation

Problem: A boiler evaporates 3.6 kg of water per kg of coal into dry saturated steam at 10 bar. Feed water temperature is 32°C. Find equivalent evaporation and factor of evaporation.

Step 1: From steam tables at 10 bar: h_g = 2776.2 kJ/kg

Step 2: Enthalpy of feed water: H_w = 4.187 × 32 = 134.0 kJ/kg

Step 3: Heat supplied per kg steam: 2776.2 - 134.0 = 2642.2 kJ/kg

Step 4: Total heat for 3.6 kg steam: 3.6 × 2642.2 = 9511.9 kJ

Step 5: Equivalent evaporation: W_e = 9511.9 / 2257 = 4.21 kg/kg coal

Step 6: Factor of evaporation: F = 4.21 / 3.6 = 1.17

Answer: W_e = 4.21 kg/kg coal, F = 1.17

Example 3.2: Boiler Efficiency Calculation

Problem: Steam pressure = 12 bar, dryness = 0.85, feed water at 30°C, coal CV = 33400 kJ/kg. Steam generated = 40000 kg in 6 hours, coal used = 4000 kg. Find boiler efficiency.

Step 1: Steam per kg coal: W_a = 40000/4000 = 10 kg/kg coal

Step 2: From steam tables at 12 bar: h_f = 798.4 kJ/kg, h_{fg} = 1984.3 kJ/kg

Step 3: h = 798.4 + 0.85×1984.3 = 2485.1 kJ/kg

Step 4: H_w = 4.187×30 = 125.6 kJ/kg

Step 5: η_b = [10×(2485.1-125.6)] / 33400 = 0.706 = 70.6%

Answer: Boiler efficiency = 70.6%

3.16 DRAUGHT SYSTEMS

Definition: Draught is the pressure difference between outside air and gases inside furnace/chimney at grate level, causing airflow through boiler for combustion and flue gas removal.

3.16.1 Types of Draught

1. Natural Draught

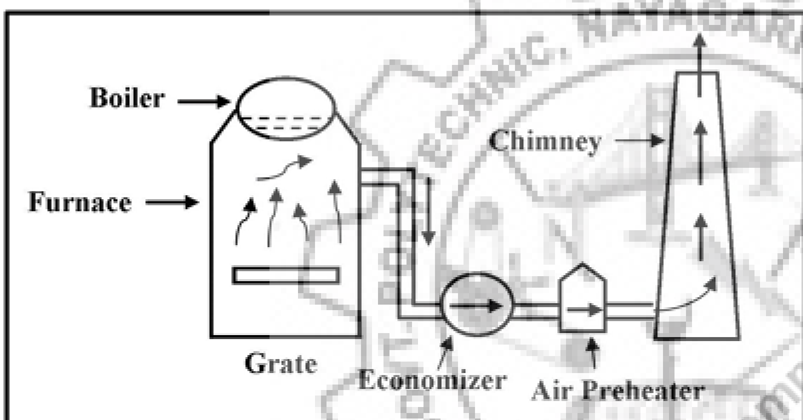


Fig. 3.7 Natural Draught

Fig. 3.7: Natural Draught

- **Principle:** Created by chimney due to temperature difference between hot gases and outside air
- **Components:** Tall chimney (masonry or reinforced concrete)
- **Advantages:** Simple, no external power required
- **Disadvantages:** Limited pressure difference, depends on weather conditions

2. Artificial Draught

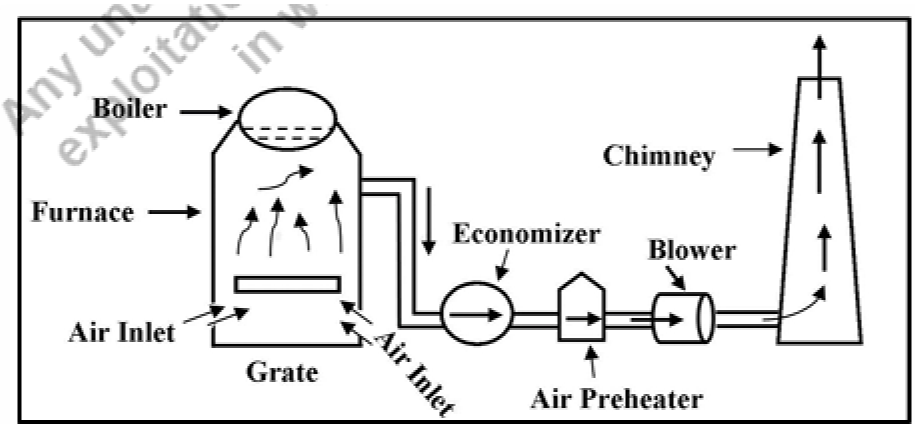


Fig. 3.8 Induced Draught

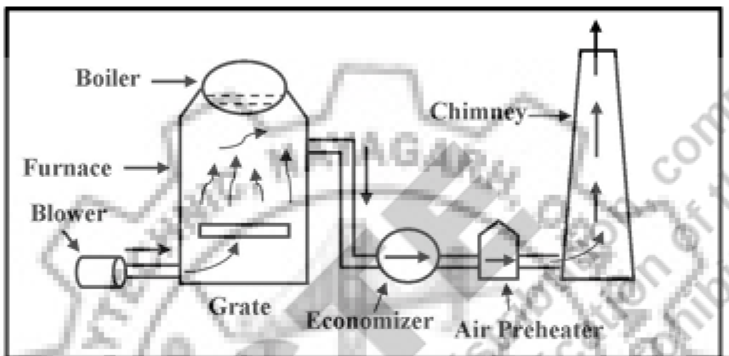


Fig. 3.9 Forced Draught

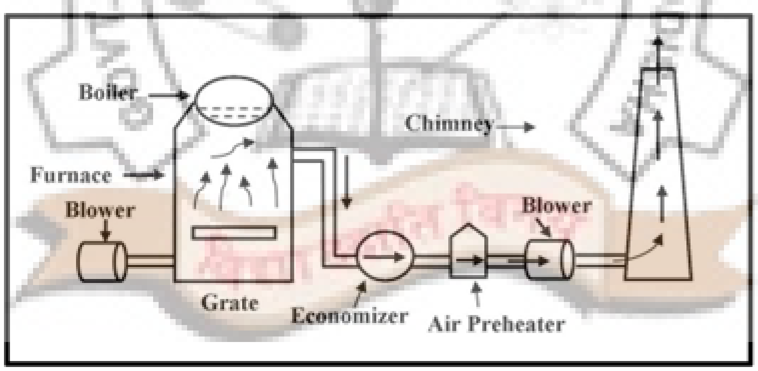


Fig. 3.10 Balanced Draught

Created using mechanical fans/blowers. Three types:

Type	Fan Position	Pressure Condition	Diagram Reference

Induced Draught (ID)	**Near chimney base**	**Negative pressure in boiler**	**Fig. 3.8**
Forced Draught (FD)	**Before grate**	**Positive pressure in boiler**	**Fig. 3.9**
Balanced Draught	**Both FD and ID fans**	**Near atmospheric pressure in furnace**	**Fig. 3.10**

3.16.2 Comparison: Forced vs Induced Draught

Aspect	Forced Draught	Induced Draught
Fan Position	**Before grate or in burner assembly**	**Near chimney (downstream of grate)**
Pressure in Flue	**Slightly above atmospheric**	**Slightly below atmospheric**
Fire Risk	**Higher (leakage causes flames)**	**Lower (safer)**
Air/Gas Handled	**Cold, dense air**	**Hot flue gases**
Power Consumption	**Lower**	**Higher**
Flow Uniformity	**More uniform**	**Less uniform**

3.17 UNIT SUMMARY – KEY POINTS

1. **Boiler Definition: Closed vessel producing steam from water via fuel combustion**
2. **Fire Tube vs Water Tube:**
   - **Fire tube: Hot gases in tubes, water outside (Cochran)**
   - **Water tube: Water in tubes, hot gases outside (Babcock & Wilcox)**
3. **High-Pressure Boilers: Operate >80 bar (LaMont, Benson)**
4. **Boiler Mountings: Essential safety fittings (safety valve, pressure gauge, etc.)**
5. **Boiler Accessories: Improve efficiency (economizer, superheater, etc.)**
6. **Performance Parameters:**
   - **Equivalent evaporation: Standardized comparison metric**
   - **Boiler efficiency: $\eta_b = [W_a(H-H_w)]/(W_f \times C)$**
   - **Boiler horsepower: 1 BHP = 15.653 kg/h evaporation at 100°C**
7. **Draught Systems:**
   - **Natural: Chimney-based**
   - **Artificial: Forced, induced, balanced**
8. **Steam Separators vs Traps: Separators remove water droplets; traps remove condensate and gases**

3.18 EXAM PREPARATION GUIDE

Important Topics for Exams:

- **Classification of boilers with examples**

- **Construction and working of Cochran, Babcock & Wilcox boilers**
- **Comparison of fire tube and water tube boilers**
- **High-pressure boilers: LaMont and Benson**
- **Boiler mountings and accessories (functions)**
- **Equivalent evaporation and efficiency calculations**
- **Draught systems: Types and comparisons**
- **Steam separators and traps**

3.18.1 Expected Question Types

- **Short Answer (2-3 marks): Definitions, comparisons, component functions**
- **Long Answer (5-10 marks): Working of boilers with diagrams, draught systems**
- **Numerical Problems (3-5 marks): Equivalent evaporation, boiler efficiency**
- **Diagram Drawing (3-4 marks): Boiler diagrams, draught systems**

3.18.2 Common Exam Questions

1. **Classify boilers with examples**
2. **Explain working of Cochran boiler with neat sketch**
3. **Compare fire tube and water tube boilers**
4. **Describe construction and working of Babcock & Wilcox boiler**
5. **Explain high-pressure boilers: LaMont and Benson**
6. **List and explain boiler mountings and accessories**
7. **Derive formula for equivalent evaporation**
8. **Calculate boiler efficiency from given data**
9. **Explain draught systems with diagrams**
10. **Differentiate between steam separator and steam trap**

3.19 ADDITIONAL RESOURCES

3.19.1 Recommended Textbooks

- **Thermal Engineering by B.R. Sarkar (McGraw-Hill)**
- **Thermal Engineering by R.K. Rajput (Laxmi Publications)**
- **A Textbook of Thermal Engineering by R.S. Khurmi & J.K. Gupta (S. Chand)**
- **Thermal Engineering by Mahesh M. Rathore (McGraw-Hill)**

3.19.2 Online Resources (via QR codes in textbook)

- **NPTEL Course on "Types of Boiler" - IIT Guwahati**
- **Lectures on Cochran Boiler Operation - IIT Guwahati**
- **Lectures on Boiler Mountings and Accessories - IIT Roorkee**
- **Lectures on Draught - RKB EduHub**

3.19.3 Important Values to Remember

- **1 Boiler Horsepower = 15.653 kg/h evaporation at 100°C**
- **Latent heat at atmospheric pressure = 2257 kJ/kg**
- **Typical boiler efficiency: 70-90%**
- **High-pressure boilers: >80 bar operating pressure**
- **Supercritical pressure for water: >225 bar**

Final Study Tips:

- **Practice drawing and labeling boiler diagrams**
- **Memorize classification criteria for boilers**
- **Understand working principles of different draught systems**
- **Solve numerical problems on equivalent evaporation and efficiency**
- **Compare and contrast different boiler types**
- **Review the functions of each mounting and accessory**

- **Focus on applications of each concept in real engineering systems**

These comprehensive notes cover Chapter 3: Steam Generators as per AICTE Diploma curriculum.

Best of luck for your exams! Practice diagrams and numerical problems regularly.

 # Thermal Engineering II – Chapter 4: Steam Nozzles

Thermal Engineering II – Chapter 4: Steam Nozzles

Course: Diploma in Mechanical/Engineering • Semester: 4th • Author: Dr. Parvesh Antil • Based on AICTE Model Curriculum

📘 **Chapter Overview: This chapter covers steam nozzles, their classification, flow of steam through nozzles, velocity and discharge calculations, critical pressure ratio, effect of friction, supersaturated flow, and steam injectors. Essential for understanding steam turbines and jet propulsion systems.**

4.0 UNIT SPECIFICS

This unit provides comprehensive understanding of steam nozzles, which are crucial components in steam turbines, jet engines, and various flow systems where conversion of pressure energy to kinetic energy is required.

Topics Covered:

- **Classification of nozzles: convergent, divergent, convergent-divergent**
- **Flow of steam through nozzles and velocity calculations**
- **Mass discharge of steam through nozzles**
- **Critical pressure ratio and its importance**
- **Calculation of cross-sectional areas at throat and exit for maximum discharge**
- **Effect of friction in nozzles and nozzle efficiency**
- **Supersaturated flow in nozzles and its effects**
- **Working principle of steam injectors**

> 📐 ***Key Diagrams to Study: Fig. 4.1(a-c) – Nozzle types; Fig. 4.2 – Flow through nozzle; Fig. 4.3 – Discharge-pressure curve; Fig. 4.4-4.5 – Enthalpy-entropy charts; Fig. 4.6 – Supersaturated flow; Fig. 4.7 – Steam injector.***

4.1 RATIONALE – IMPORTANCE OF STEAM NOZZLES

Steam nozzles are critical components in thermal engineering systems for several reasons:

- **Energy Conversion: Convert pressure energy of steam into kinetic energy**
- **Steam Turbine Operation: Essential for efficient operation of steam turbines**
- **Jet Propulsion: Used in jet engines and rocket nozzles**
- **Flow Measurement: Employed in flow measuring devices**
- **Industrial Applications: Used in fuel injection systems, spray painting, and various industrial processes**
- **Efficiency Optimization: Understanding nozzle behavior helps in designing efficient thermal systems**

4.2 PRE-REQUISITES

Before studying this unit, students should review:

- **Chapter 2: Properties of Steam: Enthalpy, entropy, dryness fraction**
- **Basic Thermodynamics: First law, steady flow energy equation**
- **Fluid Mechanics: Continuity equation, Bernoulli's principle**
- **Mathematics: Differentiation, integration, logarithmic functions**

4.3 UNIT OUTCOMES

After completing this unit, students will be able to:

- **U4-O1: Understand the flow of steam through nozzles**
- **U4-O2: Learn about velocity of steam at nozzle exit in terms of heat drop**
- **U4-O3: Calculate discharge of steam through nozzles and critical pressure ratio**
- **U4-O4: Learn methods of calculating cross-sectional areas at throat and exit for maximum discharge**
- **U4-O5: Understand effect of friction in nozzles, supersaturated flow, and working of steam injector**

4.4 NOZZLE - BASIC CONCEPTS

Definition: A nozzle is a device with varying cross-sectional area that converts the pressure energy of a fluid into kinetic energy. For steam nozzles, this conversion results in increased steam velocity while decreasing pressure.

4.4.1 Key Characteristics of Nozzles

- **Mass flow rate remains constant at any cross-section**
- **Velocity increases as fluid flows through the nozzle**
- **Pressure decreases along the flow direction**

- **The process is approximately adiabatic (no heat addition or rejection)**
- **Work is done by increasing the kinetic energy of steam**

4.4.2 Applications of Nozzles

- **Steam Turbines: To direct high-velocity steam onto turbine blades**
- **Jet Engines: For propulsion in aircraft**
- **Flow Measurement: In venturimeters and ***** meters**
- **Fuel Injection: In internal combustion engines**
- **Spray Systems: In paint sprayers, agricultural sprayers**
- **Rocket Nozzles: For space propulsion**

4.5 CLASSIFICATION OF NOZZLES

Classification: Nozzles are classified based on their shape and the variation of cross-sectional area along the flow direction.

Fig. 4.1(a) Convergent Nozzle

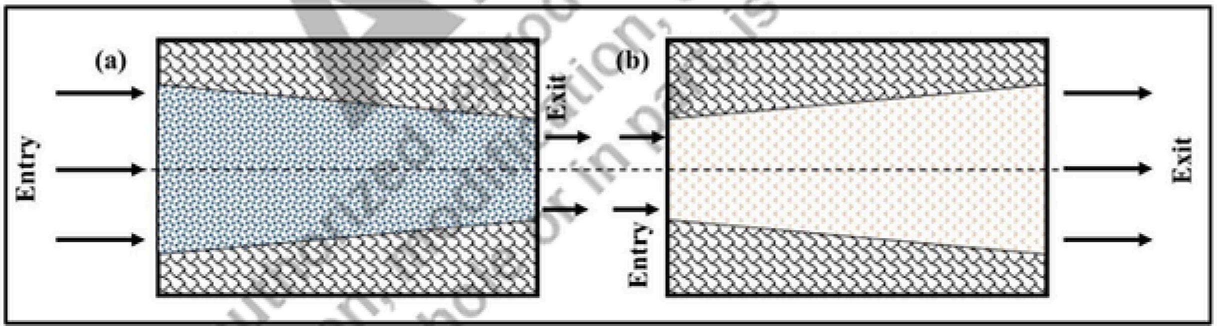


Fig. 4.1 (a) Convergent nozzle (b) Divergent nozzle

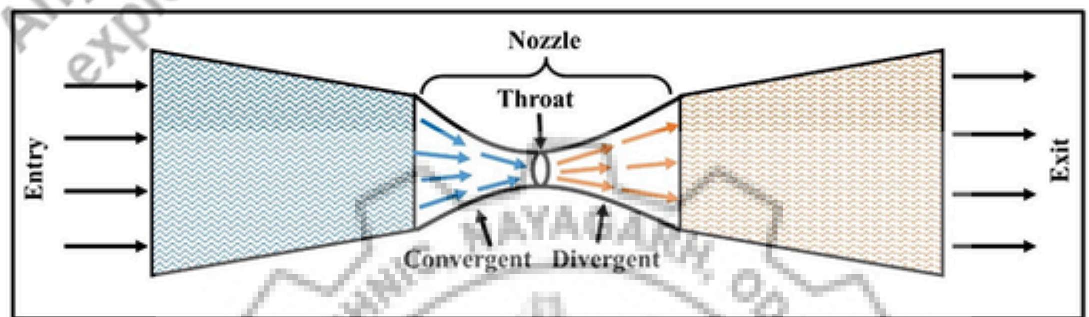


Fig. 4.1 (c) Convergent-Divergent nozzle

Cross-sectional area decreases from entrance to exit

Fig. 4.1(b) Divergent Nozzle

Cross-sectional area increases from entrance to exit

Fig. 4.1(c) Convergent-Divergent Nozzle

Area decreases then increases, with a throat section

4.5.1 Types of Nozzles

Type	Cross-Sectional Area Variation	Application Condition	Typical Use
Convergent Nozzle	**Decreases uniformly from entrance to exit**	**When back pressure ≥ critical pressure ratio**	**Non-compressible fluids, low-pressure applications**
Divergent Nozzle	**Increases uniformly from entrance to exit**	**When back pressure < critical pressure ratio**	**To further increase velocity after throat**
Convergent-Divergent Nozzle (De Laval Nozzle)	**Decreases to a minimum (throat) then increases**	**When back pressure < critical pressure ratio**	**Steam turbines, rocket nozzles, supersonic flow**

4.6 FLOW OF STEAM THROUGH NOZZLE

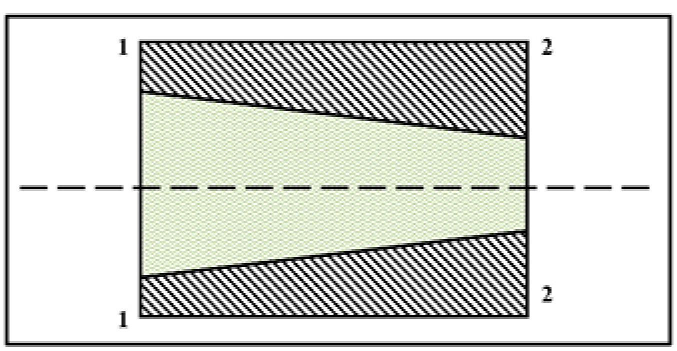


Fig. 4.2 Flow of steam through nozzle

Refer to Fig. 4.2: Flow of steam

through nozzle

4.6.1 Fundamental Principles

- **The flow through a nozzle is approximately adiabatic (no heat transfer)**
- **No external work is done except for increasing kinetic energy**
- **The process follows the steady flow energy equation**
- **For isentropic flow: $Pv^n = C$ (where n = 1.135 for saturated steam, 1.3 for superheated steam)**

4.6.2 Velocity Calculation

Steady Flow Energy Equation:

$$\frac{V_2^2 - V_1^2}{2 \times 1000} = h_1 - h_2$$

Where:

- **V_1, V_2 = Velocities at sections 1 and 2 (m/s)**
- **h_1, h_2 = Enthalpies at sections 1 and 2 (kJ/kg)**
- **Factor 1000 converts kJ to J**

Simplified Velocity Formula (when $V_1 \approx 0$):

$$V_2 = \sqrt{2000(h_1 - h_2)}$$

$$V_2 = 44.72\sqrt{h_1 - h_2}$$

For Air/Perfect Gas:

$$V_2 = 44.72\sqrt{C_p(T_1 - T_2) \times \eta_n}$$

Where:

- C_p = **Specific heat at constant pressure (kJ/kg·K)**
- η_n = **Nozzle efficiency (accounts for friction losses)**

4.7 MASS OF DISCHARGED STEAM

4.7.1 Fundamental Equation

Continuity Equation:

$$m = \frac{A \times V}{v}$$

Where:

- m = **Mass flow rate (kg/s)**
- A = **Cross-sectional area (m²)**

- V = Velocity (m/s)
- v = Specific volume (m³/kg)

For Isentropic Flow (Pv^n = constant):

$$v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{1/n}$$

Complete Mass Flow Equation:

$$m = \frac{A}{v_2} \times \sqrt{2000(h_1 - h_2)}$$

$$m = A \times \frac{\sqrt{2000 \times \frac{n}{n-1} \times P_1 v_1 \left[\left(\frac{P_2}{P_1}\right)^{2/n} - \left(\frac{P_2}{P_1}\right)^{(n+1)/n}\right]}}{v_1 \times \left(\frac{P_2}{P_1}\right)^{-1/n}}$$

Key Point: The value of 'n' depends on steam condition: n = 1.135 for saturated steam, n = 1.3 for superheated steam.

4.8 DISCHARGE OF STEAM THROUGH NOZZLES

4.8.1 Flow Behavior in Convergent-Divergent Nozzle

1. **Convergent Section (Inlet to Throat):**
   - **Pressure decreases**
   - **Velocity increases**
   - **Enthalpy decreases (converted to kinetic energy)**
2. **Throat Section (Minimum Area):**
   - **Minimum cross-sectional area**
   - **Velocity reaches sonic speed (Mach 1) under design conditions**
   - **Critical pressure occurs here**
3. **Divergent Section (Throat to Exit):**
   - **Pressure decreases further**
   - **Velocity increases to supersonic values**
   - **Further enthalpy conversion to kinetic energy**

4.8.2 Important Terms

- **Back Pressure: Pressure at nozzle exit**
- **Isentropic Flow: Ideal flow with constant entropy**
- **Isentropic Expansion: Expansion without heat transfer**
- **Design Pressure Ratio: Ratio of exit pressure to inlet pressure for optimum performance**

4.9 MAXIMUM DISCHARGE OF STEAM THROUGH NOZZLE

4.9.1 Condition for Maximum Discharge

Maximum discharge occurs when the pressure at the throat reaches a specific value called the critical pressure. This is determined by differentiating the mass flow equation with respect to pressure ratio and setting it to zero.

Derivation of Critical Pressure Ratio:

$$\frac{d}{d(P_2/P_1)}\left[\left(\frac{P_2}{P_1}\right)^{2/n} - \left(\frac{P_2}{P_1}\right)^{(n+1)/n}\right] = 0$$

$$\frac{2}{n}\left(\frac{P_2}{P_1}\right)^{(2-n)/n} - \frac{n+1}{n}\left(\frac{P_2}{P_1}\right)^{(1)/n} = 0$$

$$\frac{P_2}{P_1} = \left(\frac{2}{n+1}\right)^{n/(n-1)}$$

This is the critical pressure ratio for maximum discharge.

4.9.2 Maximum Mass Flow Rate

Formula for Maximum Discharge:

$$m_{max} = A \times \sqrt{1000 \times n \times \frac{P_1}{v_1}\left(\frac{2}{n+1}\right)^{(n+1)/(n-1)}}$$

Where:

- m_{max} **= Maximum mass flow rate (kg/s)**
- A **= Throat area (m²)**
- P_1 **= Inlet pressure (N/m²)**
- v_1 **= Inlet specific volume (m³/kg)**
- n **= Isentropic index**

4.10 VELOCITY OF STEAM AT NOZZLE EXIT IN TERMS OF HEAT DROP

4.10.1 Fundamental Relationship

Velocity from Heat Drop:

$$V_2 = \sqrt{2\left(\frac{n}{n-1}\right)P_1 v_1 \left[1 - \left(\frac{P_2}{P_1}\right)^{(n-1)/n}\right]}$$

Maximum Velocity at Throat (for maximum discharge):

$$V_{max} = \sqrt{2\left(\frac{n}{n+1}\right)P_1v_1}$$

Practical Formula (using enthalpy drop):

$$V_2 = 44.72\sqrt{h_1 - h_2}$$

Where:

- V_2 = **Exit velocity (m/s)**
- $h_1 - h_2$ = **Enthalpy drop (kJ/kg)**
- **Factor 44.72 comes from** $\sqrt{2000}$

4.11 CRITICAL PRESSURE RATIO

Definition: Critical pressure ratio is the ratio of pressure at the throat (where area is minimum) to the inlet pressure, at which the mass flow rate is maximum. At this condition, the velocity at throat equals the speed of sound (Mach 1).

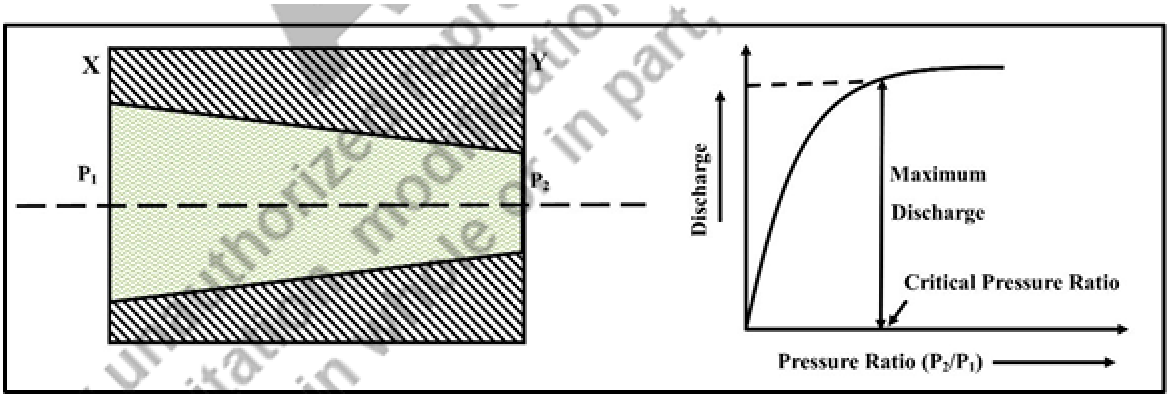


Fig. 4.3 Nozzle section and Discharge-Pressure curve

Refer to Fig. 4.3: Nozzle section and Discharge-Pressure curve

4.11.1 Critical Pressure Ratio Formula

$$\frac{P_c}{P_1} = \left(\frac{2}{n+1}\right)^{n/(n-1)}$$

Where:

- P_c **= Critical pressure at throat (N/m²)**
- P_1 **= Inlet pressure (N/m²)**
- n **= Isentropic index**

4.11.2 Critical Pressure Ratios for Different Fluids

Fluid	Isentropic Index (n)	Critical Pressure Ratio (P_c/P_1)	Critical Pressure (P_c)

Air	**1.4**	**0.528**	$P_c = 0.528P_1$
Saturated Steam	**1.135**	**0.577**	$P_c = 0.577P_1$
Superheated Steam	**1.3**	**0.546**	$P_c = 0.546P_1$
Wet Steam (approximate)	**1.113**	**0.582**	$P_c = 0.582P_1$

4.11.3 Importance of Critical Pressure Ratio

1. **Maximum Discharge:** At critical pressure ratio, mass flow rate is maximum
2. **Choking Condition:** Further decrease in back pressure doesn't increase flow rate
3. **Sonic Velocity:** At throat, fluid velocity equals speed of sound (Mach 1)
4. **Design Basis:** Essential for designing convergent-divergent nozzles
5. **Supersonic Flow:** To achieve supersonic velocities, flow must expand below critical pressure in divergent section

4.12 CALCULATION OF CROSS-SECTIONAL AREAS AT THROAT AND EXIT

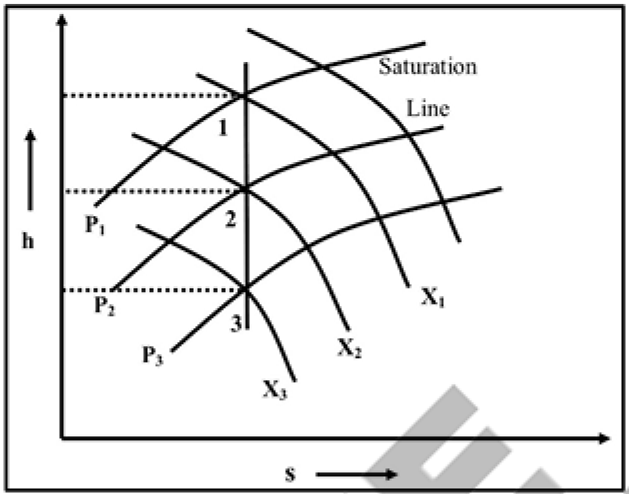


Fig. 4.4 Enthalpy (h) – Entropy (s) chart

Refer to Fig. 4.4: Enthalpy (h) - Entropy (s) chart for nozzle flow

4.12.1 For Convergent Nozzle (Exit at Throat)

Area Calculation:

$$A_2 = \frac{m \times x_2 \times v_{s2}}{V_2}$$

Where:

- A_2 **= Throat area (m²)**
- m **= Mass flow rate (kg/s)**
- x_2 **= Dryness fraction at throat**
- v_{s2} **= Specific volume of dry steam at throat pressure (m³/kg)**
- V_2 **= Velocity at throat (m/s)**

Velocity Calculation:

$$V_2 = 44.72\sqrt{h_1 - h_2}$$

Enthalpy Drop:

$$\Delta h = h_1 - h_2 \quad (\text{kJ/kg})$$

4.12.2 For Convergent-Divergent Nozzle

Exit Area Calculation:

$$A_3 = \frac{m \times x_3 \times v_{s3}}{V_3}$$

Where:

- A_3 = **Exit area (m²)**
- m = **Mass flow rate (kg/s)**
- x_3 = **Dryness fraction at exit**
- v_{s3} = **Specific volume of dry steam at exit pressure (m³/kg)**
- V_3 = **Velocity at exit (m/s)**

4.13 EFFECT OF FRICTION IN NOZZLES

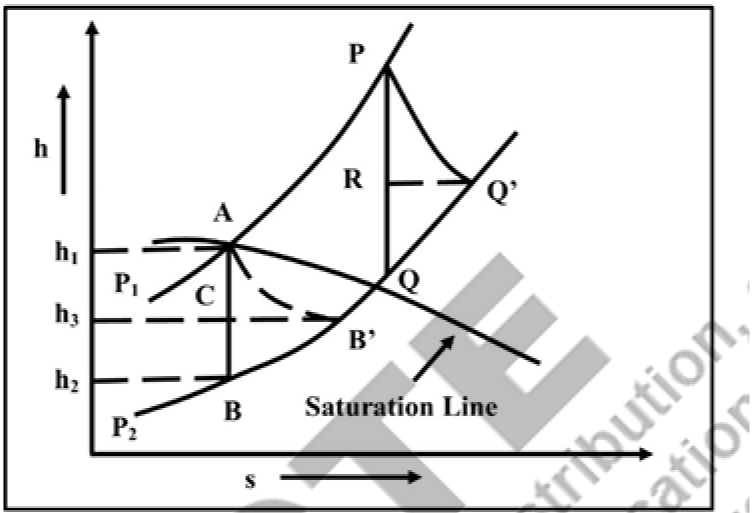


Fig. 4.5 Enthalpy (h) – Entropy (s) chart

shake phone to roll dice

Refer to Fig. 4.5: Enthalpy-entropy chart showing effect of friction

4.13.1 How Friction Affects Nozzle Flow

- **Friction between steam and nozzle walls causes energy loss**
- **Actual enthalpy drop is less than isentropic enthalpy drop**
- **Velocity at exit is reduced**
- **Entropy increases (process is irreversible)**
- **Dryness fraction may change**

4.13.2 Analysis Using h-s Diagram

1. **Point A: Initial condition (pressure P_1, dryness x_1 or temperature T_1)**
2. **Line AB: Isentropic expansion to pressure P_2 (ideal, no friction)**
3. **Line AC: Actual expansion with friction**
4. **Point C: Actual state at pressure P_2**
5. **Line CB': Constant pressure line to final state B'**

4.13.3 Nozzle Efficiency (Coefficient of Nozzle)

$$\eta_n = \frac{\text{Actual heat drop}}{\text{Isentropic heat drop}} = \frac{h_1 - h_2'}{h_1 - h_2}$$

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

Where:

- η_n **= Nozzle efficiency (typically 0.85 to 0.95)**
- $h_1 - h_2'$ **= Actual enthalpy drop (kJ/kg)**
- $h_1 - h_2$ **= Isentropic enthalpy drop (kJ/kg)**

Velocity with Friction:

$$V_{2(\text{actual})} = 44.72\sqrt{\eta_n(h_1 - h_2)}$$

4.14 SUPER SATURATED FLOW IN NOZZLES

Definition: Supersaturated flow (also called metastable flow) occurs when steam expands rapidly in a nozzle, and condensation is delayed beyond the

saturation line. The steam exists in the vapor phase at conditions where it should normally condense.

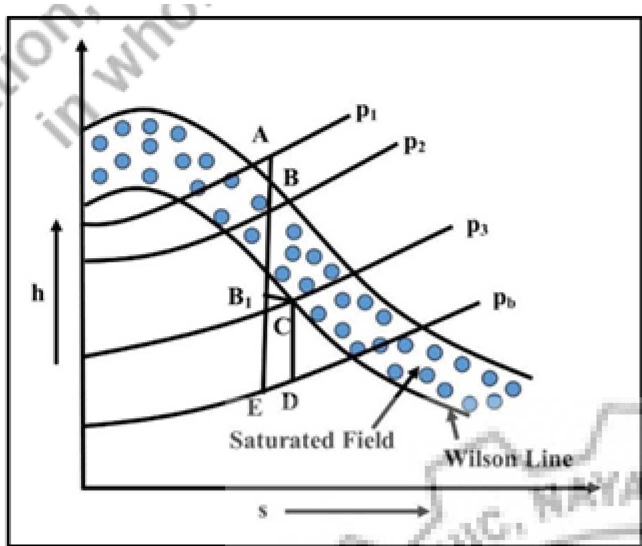


Fig. 4.6 Supersaturated flow of steam

Refer to Fig. 4.6: Supersaturated flow of steam on h-s diagram

4.14.1 Explanation of Supersaturated Flow

1. **Normal Expansion (Line AE): Isentropic expansion of superheated steam**
2. **Saturation Point (B): Where expansion line meets saturation curve**
3. **Supersaturated Expansion (BB_1): Due to high velocity, condensation is delayed**
4. **Wilson Line (B_1): Limit of supersaturation where condensation suddenly occurs**
5. **Condensation (B_1C): Constant pressure, constant enthalpy condensation**
6. **Further Expansion (CD): Isentropic expansion of wet steam**

4.14.2 Key Terms

- **Degree of Undercooling: Difference between saturation temperature and actual temperature at given pressure**
- **Degree of Supersaturation: Ratio of saturation pressures at temperatures B and B_1**

- **Wilson Line: Practical limit of supersaturation on h-s diagram**

4.14.3 Effects of Supersaturation

1. **Increased Mass Flow: Density of supersaturated steam is higher than equilibrium steam**
2. **Reduced Heat Drop: Actual heat drop is less than isentropic heat drop**
3. **Lower Temperature: Temperature is below saturation temperature**
4. **Increased Entropy: Process is irreversible, entropy increases**
5. **Increased Dryness Fraction: Delayed condensation increases dryness fraction**

4.15 STEAM INJECTOR

Definition: **A steam injector is a device that uses the kinetic energy of a steam jet to increase the pressure and velocity of water. It's commonly used to feed water into steam boilers against high pressure.**

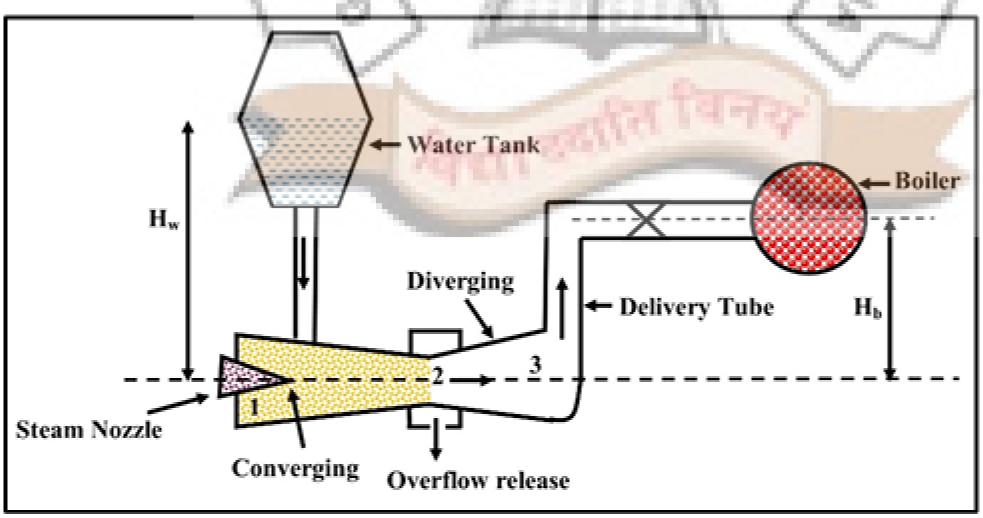


Fig. 4.7 Schematic diagram of Steam Injector

Refer to Fig. 4.7: Schematic diagram of Steam Injector

4.15.1 Working Principle

1. **Steam Expansion (Section 1): Steam expands through convergent nozzle, gaining velocity**
2. **Mixing (Section 2): High-velocity steam mixes with cold water in mixing cone**
3. **Condensation: Steam condenses, transferring momentum to water**
4. **Diffuser (Section 3): Mixture passes through diverging cone, converting kinetic energy to pressure energy**
5. **Delivery: Pressurized water delivered to boiler against pressure**

4.15.2 Key Formulas for Steam Injector

Mass of Injected Water:

$$M_w = \frac{V_s - V_m}{V_m - V_w}$$

Where:

- M_w **= Mass of water per kg of steam (kg/kg)**
- V_s **= Steam velocity at nozzle exit (m/s)**
- V_m **= Mixture velocity at section 2 (m/s)**
- V_w **= Water velocity at entry (m/s)**

Steam Velocity at Nozzle Exit:

$$V_s = 44.72\sqrt{h_1 - h_2}$$

Mixture Velocity at Section 2:

$$V_m = \sqrt{2000\left[\frac{P - P_m}{w} + \frac{gh_b}{1000} + \frac{V^2}{2000}\right]}$$

Where:

- P = **Boiler pressure (kPa)**
- P_m = **Mixture pressure at section 2 (kPa)**
- w = **Density of mixture (kg/m³)**
- h_b = **Lift height (m)**
- V = **Velocity in delivery tube (m/s)**
- g = **Acceleration due to gravity (9.81 m/s²)**

Area of Steam Nozzle:

$$A_1 = \frac{V_1}{V_s} \times \frac{m}{M_w}$$

Area of Mixing Cone:

$$A_2 = \frac{m_s + m}{1000V_m}$$

4.16 SOLVED EXAMPLES

Example 4.1: Velocity Calculation with Friction

Problem: Dry saturated steam at 15 bar expands in a nozzle to 1.5 bar. If friction causes 10% heat drop loss, find final velocity and percentage reduction.

Step 1: From steam tables at 15 bar: $h_1 = 2789.9$ **kJ/kg**

Step 2: At 1.5 bar: $h_2 = 2693.4$ **kJ/kg (for isentropic expansion)**

Step 3: Isentropic enthalpy drop: $\Delta h = 2789.9 - 2693.4 = 96.5$ **kJ/kg**

Step 4: Isentropic velocity: $V_s = 44.72\sqrt{96.5} = 439.3$ **m/s**

Step 5: Nozzle efficiency: $\eta_n = 1 - 0.1 = 0.9$

Step 6: Actual velocity: $V_{\text{actual}} = 44.72\sqrt{0.9 \times 96.5} = 416.8$ **m/s**

Step 7: Percentage reduction: $\frac{439.3-416.8}{439.3} \times 100 = 5.1\%$

Answer: Final velocity = 416.8 m/s, Reduction = 5.1%

Example 4.2: Using Mollier Diagram

Problem: Dry saturated steam at 10 bar expands in nozzle to 0.7 bar. Find exit velocity and dryness fraction using Mollier diagram.

Step 1: Locate point A on saturation line at 10 bar

Step 2: Draw vertical line (isentropic) to 0.7 bar line (point B)

Step 3: Read $h_1 = 2772$ **kJ/kg,** $h_2 = 2310$ **kJ/kg**

Step 4: Enthalpy drop: $\Delta h = 2772 - 2310 = 462$ **kJ/kg**

Step 5: Velocity: $V = 44.72\sqrt{462} = 961$ **m/s**

Step 6: Dryness fraction from chart: $x = 0.848$

Answer: Velocity = 961 m/s, Dryness fraction = 0.848

Example 4.3: Critical Pressure and Discharge

Problem: Convergent-divergent nozzle receives steam at 10 bar, 210°C. Throat area = 15 cm². Exit at critical pressure. Actual flow = 7200 kg/h. Find discharge coefficient.

Step 1: For superheated steam: $n = 1.3$

Step 2: From steam tables: $v_1 = 0.2113$ **m³/kg (at 10 bar, 210°C)**

Step 3: Maximum theoretical discharge:

$m_{\text{max}} = A \times \sqrt{1000 \times n \times \frac{P_1}{v_1} \times \left(\frac{2}{n+1}\right)^{\frac{n+1}{n-1}}}$

$= 15 \times 10^{-4} \times \sqrt{1000 \times 1.3 \times \frac{10 \times 10^5}{0.2113} \times \left(\frac{2}{2.3}\right)^{\frac{2.3}{0.3}}} = 2.177$ **kg/s** $= 7837.2$ **kg/h**

Step 4: Discharge coefficient = Actual/Theoretical $= 7200/7837.2 = 0.92$

Answer: Discharge coefficient = 0.92

Example 4.4: Air Nozzle Calculation

Problem: Air at 20 bar, 18°C enters convergent-divergent nozzle. Throat diameter = 1.25 cm. Discharges to atmosphere. n = 1.4, R = 287 J/kg·K. Find mass discharged per minute.

Step 1: Critical pressure ratio for air: $\frac{P_2}{P_1} = 0.528$

Step 2: Throat pressure: $P_2 = 0.528 \times 20 = 10.56$ **bar** $= 10.56 \times 10^5$ **Pa**

Step 3: Throat temperature: $T_2 = T_1 \times \left(\frac{2}{n+1}\right) = 291 \times \left(\frac{2}{2.4}\right) = 242.5$ **K**

Step 4: Specific volume at throat: $v_2 = \frac{RT_2}{P_2} = \frac{287 \times 242.5}{10.56 \times 10^5} = 0.0659$ **m³/kg**

> **Step 5: Throat velocity:**
> $V_2 = 44.72\sqrt{C_p(T_1 - T_2)} = 44.72\sqrt{1.005(291 - 242.5)} = 312.12$ **m/s**
>
> **Step 6: Throat area:** $A_2 = \frac{\pi}{4} \times (0.0125)^2 = 1.227 \times 10^{-4}$ **m²**
>
> **Step 7: Mass flow rate:** $m = \frac{A_2V_2}{v_2} = \frac{1.227\times10^{-4}\times312.12}{0.0659} = 0.581$ **kg/s**
>
> **Step 8: Per minute:** $0.581 \times 60 = 34.86$ **kg/min**
>
> **Answer: Mass discharged = 34.86 kg/min**

4.17 UNIT SUMMARY – KEY POINTS

1. **Nozzle Function: Converts pressure energy to kinetic energy**
2. **Nozzle Types:**
   - **Convergent: Area decreases, used when** $P_{\text{back}}/P_1 \geq$ **critical ratio**
   - **Divergent: Area increases, used when** $P_{\text{back}}/P_1 <$ **critical ratio**
   - **Convergent-Divergent: For supersonic flow**
3. **Velocity Formula:** $V = 44.72\sqrt{h_1 - h_2}$ **m/s**
4. **Critical Pressure Ratio:**
   - **Air (n=1.4): 0.528**
   - **Saturated steam (n=1.135): 0.577**
   - **Superheated steam (n=1.3): 0.546**
5. **Maximum Discharge: Occurs at critical pressure ratio**
6. **Nozzle Efficiency:** $\eta_n = \frac{\text{Actual heat drop}}{\text{Isentropic heat drop}}$
7. **Supersaturated Flow: Delayed condensation due to rapid expansion**
8. **Steam Injector: Uses steam jet to pump water into boiler**
9. **Area Calculations:**

- **For throat:** $A_2 = \frac{mx_2v_{s2}}{V_2}$
- **For exit:** $A_3 = \frac{mx_3v_{s3}}{V_3}$

4.18 EXAM PREPARATION GUIDE

Important Topics for Exams:

- **Classification of nozzles and their applications**
- **Derivation and application of velocity formulas**
- **Critical pressure ratio for different fluids**
- **Calculation of nozzle areas for given flow conditions**
- **Effect of friction and nozzle efficiency**
- **Supersaturated flow concept and effects**
- **Working principle of steam injector**
- **Numerical problems on velocity, discharge, and area calculations**

4.18.1 Expected Question Types

- **Short Answer (2-3 marks): Definitions, classifications, principles**
- **Long Answer (5-10 marks): Derivations, working principles, comparisons**
- **Numerical Problems (3-5 marks): Velocity, discharge, area, efficiency calculations**
- **Diagram Drawing (3-4 marks): Nozzle types, h-s diagrams for various processes**

4.18.2 Common Exam Questions

1. **Classify nozzles with neat sketches**

2. **Derive expression for velocity of steam at nozzle exit**
3. **Explain critical pressure ratio and its significance**
4. **Derive condition for maximum discharge through nozzle**
5. **Explain effect of friction in nozzles using h-s diagram**
6. **What is supersaturated flow? Explain with h-s diagram**
7. **Explain working of steam injector with sketch**
8. **Calculate velocity, discharge, or areas for given nozzle conditions**
9. **Compare convergent, divergent, and convergent-divergent nozzles**
10. **Explain how to determine throat and exit areas for maximum discharge**

4.19 ADDITIONAL RESOURCES

4.19.1 Recommended Textbooks

- **Thermal Engineering by B.R. Sarkar (McGraw-Hill)**
- **Thermal Engineering by R.K. Rajput (Laxmi Publications)**
- **A Textbook of Thermal Engineering by R.S. Khurmi & J.K. Gupta (S. Chand)**

4.19.2 Important Values to Remember

- **Velocity conversion factor: 44.72 =** $\sqrt{2000}$
- **Isentropic index: n = 1.135 (saturated steam), 1.3 (superheated steam), 1.4 (air)**
- **Critical pressure ratios:**
  - **Air: 0.528**
  - **Saturated steam: 0.577**
  - **Superheated steam: 0.546**
- **Typical nozzle efficiency: 0.85 to 0.95**
- **Speed of sound in steam at 100°C: ≈ 405 m/s**

Final Study Tips:

- **Memorize the velocity formula:** $V = 44.72\sqrt{\Delta h}$
- **Practice using steam tables and Mollier charts**
- **Understand the physical meaning of critical pressure ratio**
- **Practice drawing and interpreting h-s diagrams for nozzle flow**
- **Solve numerical problems from textbook exercises**
- **Review the derivations of key formulas**
- **Focus on applications of nozzles in real engineering systems**
- **Understand the difference between isentropic and actual processes**

These comprehensive notes cover Chapter 4: Steam Nozzles as per AICTE Diploma curriculum.

Best of luck for your exams! Practice numerical problems regularly.

Unit 5: Steam Turbines

Unit Specifics

This unit provides comprehensive coverage of steam turbines, which are prime movers that convert the thermal energy of steam into mechanical

energy. The unit is structured to cover:

- Classification and fundamental principles of steam turbines
- Detailed analysis of impulse and reaction turbines with velocity diagrams
- Construction and working of specific turbine types: Simple De-Laval and Parson's turbines
- Methods for controlling rotor speed including velocity compounding, pressure compounding, and combined compounding
- Advanced concepts: bleeding, reheating, reheat factor, and thermodynamic charts
- Governing systems for steam turbines: throttle governing and nozzle control governing

The unit includes detailed derivations of velocity diagrams, efficiency calculations, and practical numerical problems. Each section is supplemented with schematic diagrams and h-s charts for visual understanding.

Rationale

Steam turbines are the workhorses of modern power generation, accounting for approximately 80% of the world's electricity production. Their ability to efficiently convert thermal energy at high temperatures and pressures into mechanical work makes them indispensable in thermal power plants, nuclear power stations, and large industrial applications. Understanding steam turbine operation is fundamental for engineers involved in power plant design, operation, and maintenance. This unit bridges theoretical thermodynamics with practical engineering applications, enabling students to analyze turbine performance, optimize efficiency, and understand the principles behind modern power generation systems.

Pre-requisites

Before studying this unit, students should have a solid understanding of:

- **Basic Mechanical Engineering (MEPC102): Fundamental concepts of energy conversion and machine elements**
- **Thermodynamics (Class XII): Laws of thermodynamics, energy balance, and thermodynamic cycles**
- **Properties of Steam (Unit 2): Steam formation, enthalpy, entropy, and Mollier chart interpretation**
- **Steam Nozzles (Unit 4): Flow through nozzles, critical pressure ratio, and velocity calculations**
- **Steam Generators (Unit 3): Boiler operation and steam generation principles**

Unit Outcomes

After completing this unit, students will be able to:

- **U5-O1: Classify steam turbines based on various criteria and explain their fundamental operating principles**
- **U5-O2: Differentiate between impulse and reaction turbines through constructional features and working principles**
- **U5-O3: Analyze and construct velocity diagrams for impulse and reaction turbines to determine work output and efficiency**
- **U5-O4: Explain methods for reducing rotor speed including compounding techniques and their applications**
- **U5-O5: Describe advanced operational concepts including bleeding, reheating, and governing systems for steam turbines**

Mapping with Course Outcomes

Unit Outcomes	CO-1	CO-2	CO-3	CO-4	CO-5
U5-O1: Classification & Principles	3	-	-	-	3
U5-O2: Impulse vs Reaction	3	2	-	-	3
U5-O3: Velocity Diagrams	3	3	-	-	3
U5-O4: Compounding Methods	2	3	-	-	2
U5-O5: Advanced Concepts	3	3	-	-	2

Legend: 1 = Weak Correlation, 2 = Medium Correlation, 3 = Strong Correlation

5.0 Steam Turbines

Steam Turbine: A steam turbine is a rotary mechanical device that extracts thermal energy from pressurized steam and converts it into mechanical work through the dynamic action of steam flowing over a series of blades mounted on a rotating shaft. The steam expands through stationary nozzles (in impulse turbines) or through both fixed and moving blades (in reaction turbines), causing the rotor to rotate and produce shaft power.

Steam turbines operate on the principle of converting the heat energy of steam into kinetic energy and then into mechanical energy. They are classified as prime movers and find extensive applications in:

- Electric power generation (thermal, nuclear, and geothermal power plants)
- Marine propulsion (ships and submarines)

- **Industrial drives (compressors, pumps, and blowers)**
- **Mechanical drives in refineries and chemical plants**

5.1 Classification of Steam Turbines with Examples

Steam turbines can be classified based on various criteria as shown in Figure 5.1:

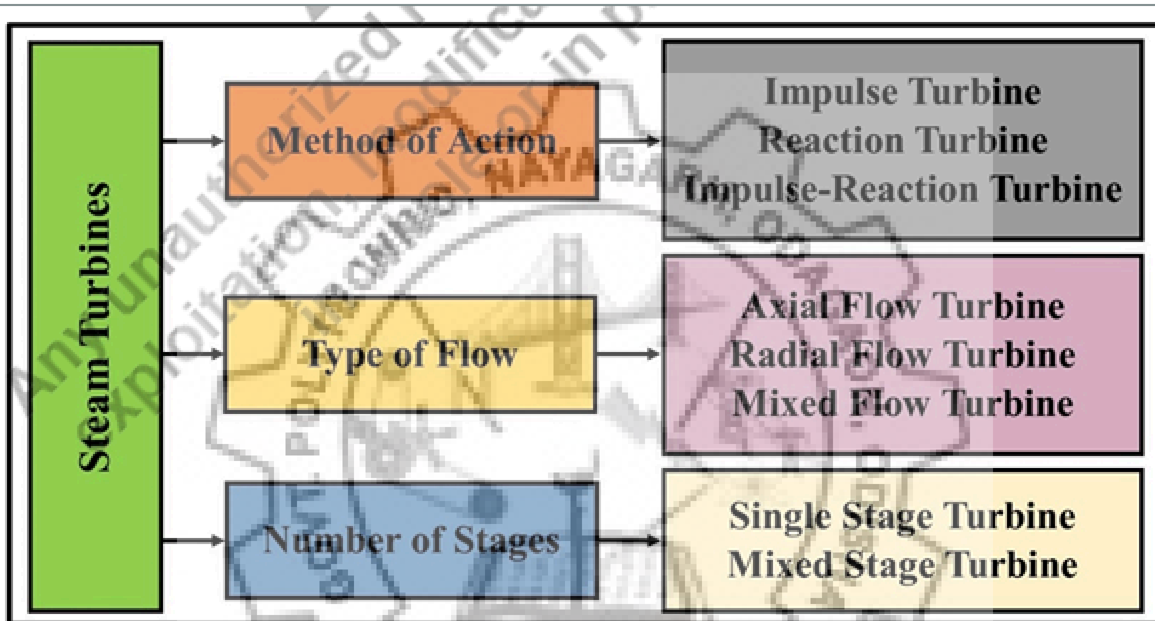


Fig. 5.1 Classification of steam turbines

[Refer to Figure 5.1: Classification of steam turbines on page 113]

Figure 5.1: Classification of Steam Turbines

Classification Based on Principle of Operation:

1. **Impulse Turbine: Steam expands completely in stationary nozzles, and the high-velocity jet impinges on moving blades. Pressure remains constant across moving blades.**
    - ***Example:*** **Simple De-Laval Turbine**

2. **Reaction Turbine: Steam expands gradually in both fixed and moving blades. Pressure drops occur in both stationary and moving blades.**
   - ***Example:*** **Parson's Reaction Turbine**

Classification Based on Direction of Steam Flow:

- **Axial Flow Turbines: Steam flows parallel to the turbine axis (most common type)**
- **Radial Flow Turbines: Steam flows perpendicular to the turbine axis (used in special applications)**

Classification Based on Number of Pressure Stages:

- **Single-Stage Turbines: One set of nozzles and blades (for small power requirements)**
- **Multi-Stage Turbines: Multiple sets of nozzles and blades arranged in series (for large power generation)**

Classification Based on Steam Conditions:

- **High-Pressure Turbines: Operate at inlet pressures above 100 bar**
- **Medium-Pressure Turbines: Operate at inlet pressures between 20-100 bar**
- **Low-Pressure Turbines: Operate at inlet pressures below 20 bar**

5.2 Difference between Impulse & Reaction Turbines

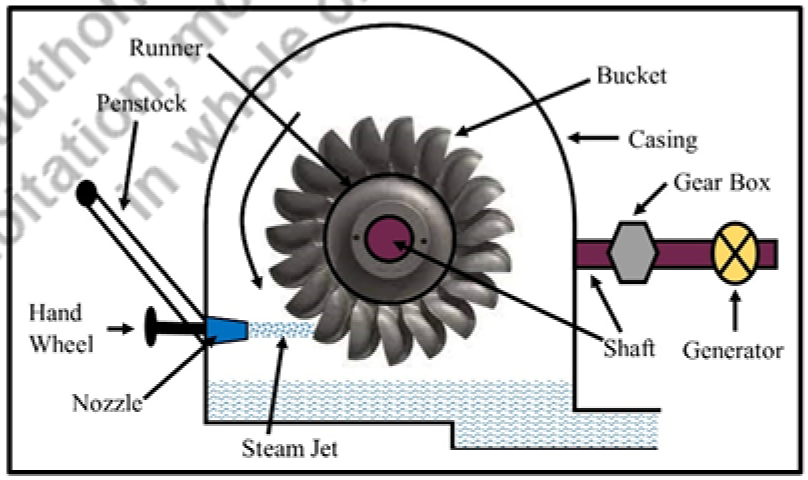


Fig. 5.2 Impulse Turbine

[Refer to Figure 5.2: Impulse Turbine on page 114]

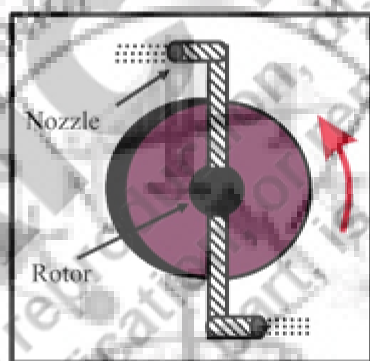


Fig 5.3 Reaction Turbine

[Refer to Figure 5.3: Reaction Turbine on page 116]

Figure 5.2 & 5.3: Comparison of Impulse and Reaction Turbines

Parameter	Impulse Turbine	Reaction Turbine
Principle of Operation	**Works on Newton's second law of motion (impulse principle). The steam jet impinges on moving blades with high velocity, transferring momentum.**	**Works on Newton's third law of motion (reaction principle). Steam expands through both fixed and moving blades, creating reaction forces.**

Pressure Drop	**Pressure drop occurs only in stationary nozzles. No pressure change across moving blades.**	**Pressure drop occurs in both stationary guide blades and moving blades. Approximately 50% in each.**
Blade Profile	**Moving blades are symmetrical with constant cross-section. Blade passages have constant area.**	**Moving blades are aerofoil-shaped with convergent passages. Blade passages have varying area.**
Blade Fixation	**Moving blades are mounted on rotor disc. Only moving blades experience mechanical stress.**	**Both fixed blades (stator) and moving blades (rotor) are subjected to pressure differences and mechanical stress.**
Degree of Reaction	**Zero reaction (R=0). No pressure drop across moving blades.**	**50% reaction (R=0.5) for Parson's turbine. Equal pressure drop in fixed and moving blades.**
Efficiency Characteristics	**Higher efficiency at design conditions but efficiency drops significantly at part loads.**	**Maintains good efficiency over a wider range of loads. More uniform efficiency curve.**
Space Requirements	**Requires less axial length for same power output.**	**Requires more axial length due to gradual pressure drop.**
Maintenance	**Simpler construction, easier maintenance.**	**More complex construction, requires careful maintenance.**
Typical Applications	**Small power plants, auxiliary drives, first stages of large turbines.**	**Large power plants, base load operations, later stages of large turbines.**

5.3 Simple De-Laval Turbine

De-Laval Turbine: Named after Swedish engineer Gustaf de Laval, this is the simplest form of impulse turbine consisting of a single rotor stage with convergent-divergent nozzles. It operates at very high speeds (up to 30,000 RPM) and is used for small power applications.

[Refer to Figure 5.4: Schematic of Simple De-Laval turbine on page 118]

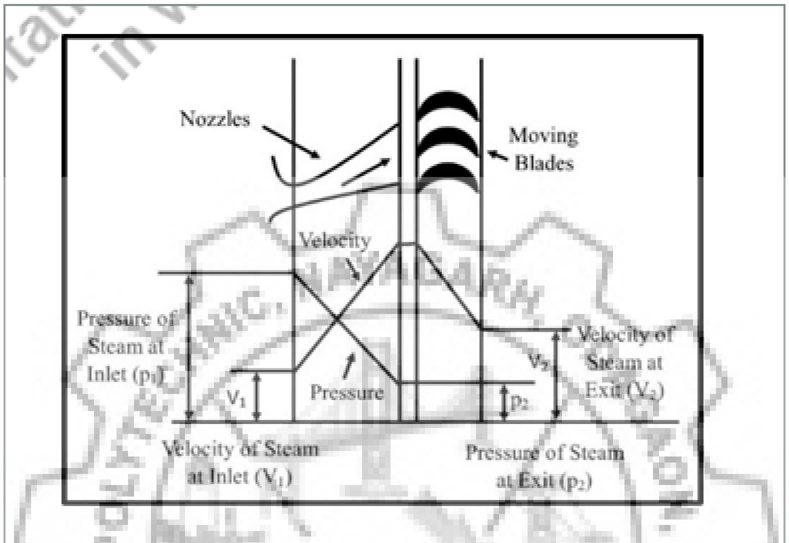


Fig. 5.4 Schematic of Simple De-Laval turbine

Figure 5.4: Schematic Diagram of Simple De-Laval Turbine

Construction Features:

- **Nozzle: Convergent-divergent type to accelerate steam to supersonic velocities**
- **Rotor: Disc-type rotor mounted on a shaft with curved blades around its periphery**
- **Blades: Symmetrical bucket-shaped blades with inlet and outlet angles typically equal**
- **Casing: Encloses the rotor and directs steam flow**
- **Bearings: Support the high-speed rotor**

Working Principle:

1. **High-pressure steam enters the convergent-divergent nozzle where it expands to a very high velocity (supersonic)**

2. The high-velocity steam jet impinges on the curved blades mounted on the rotor
3. The blades change the direction of steam flow, causing a change in momentum
4. This change in momentum creates an impulsive force on the blades, causing the rotor to rotate
5. The steam leaves the blades with reduced velocity and is exhausted to the condenser

[Refer to Figure 5.5: Velocity diagram on page 119]

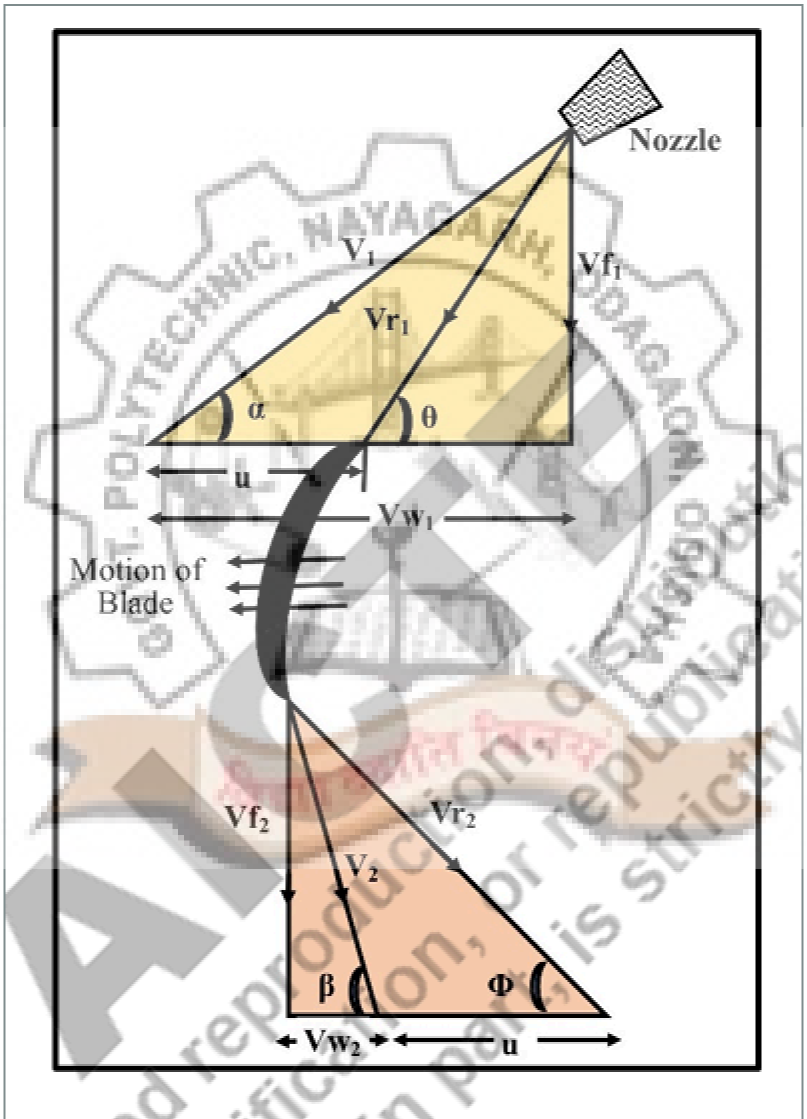


Fig. 5.5 Velocity diagram

Velocity Diagram Analysis:

Let: V_1 = Absolute velocity of steam at nozzle exit

V_β = Blade velocity

V_{r1} = Relative velocity at blade inlet

V_{r2} = Relative velocity at blade outlet

V_2 = Absolute velocity at blade exit

α = Nozzle angle (angle between V_1 and blade motion)

β = Blade inlet angle

θ = Blade outlet angle

Work done per kg of steam: $W = V_\beta (V_{r1} \cos \beta + V_{r2} \cos \theta)$

Blade efficiency: $\eta_\beta = 2V_\beta(V_{r1} \cos \beta + V_{r2} \cos \theta) / V_1^2$

For symmetrical blades ($\beta = \theta$) and frictionless flow: $\eta_\beta(max) = \cos^2\alpha$

5.4 Methods of Reducing Rotor Speed

Simple impulse turbines like De-Laval turbine operate at very high rotational speeds (up to 30,000 RPM), which are impractical for direct coupling to electrical generators (typically 3000 RPM for 50 Hz systems). Three methods are employed to reduce rotor speed:

5.4.1 Velocity Compounding (Curtis Stage)

[Refer to Figure 5.7(a): Velocity Compounding on page 122]

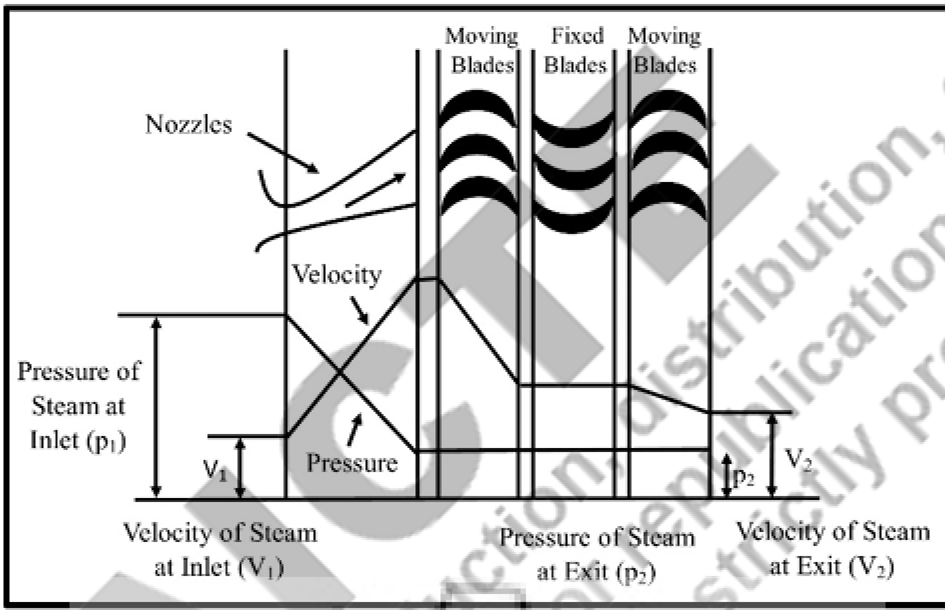


Fig. 5.7 (a) Velocity Compounding

Figure 5.7(a): Velocity Compounding Arrangement

Velocity Compounding: Also known as Curtis staging, this method uses multiple rows of moving blades with fixed guide blades in between. The kinetic energy of steam is absorbed in stages.

Working Principle:

- **Steam expands in nozzles to high velocity**
- **First row of moving blades absorbs part of kinetic energy**
- **Fixed guide blades redirect steam to second row of moving blades without pressure change**
- **Second row absorbs remaining kinetic energy**
- **Typically uses 2-3 rows of moving blades (2-row Curtis, 3-row Curtis)**

[Refer to Figure 5.6: Combined velocity diagram on page 120]

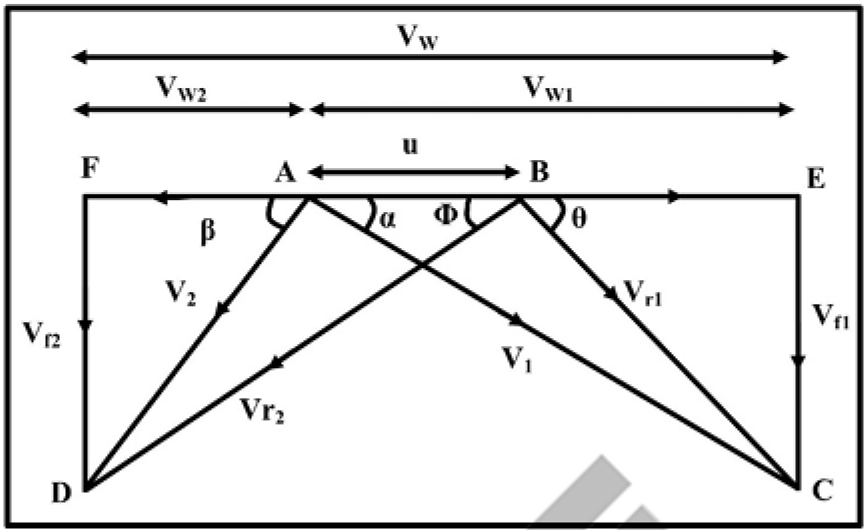


Fig. 5.6 Combined velocity diagram

Figure 5.6: Combined Velocity Diagram for Velocity Compounding

5.4.2 Pressure Compounding (Rateau Stage)

[Refer to Figure 5.7(b): Pressure Compounding on page 123]

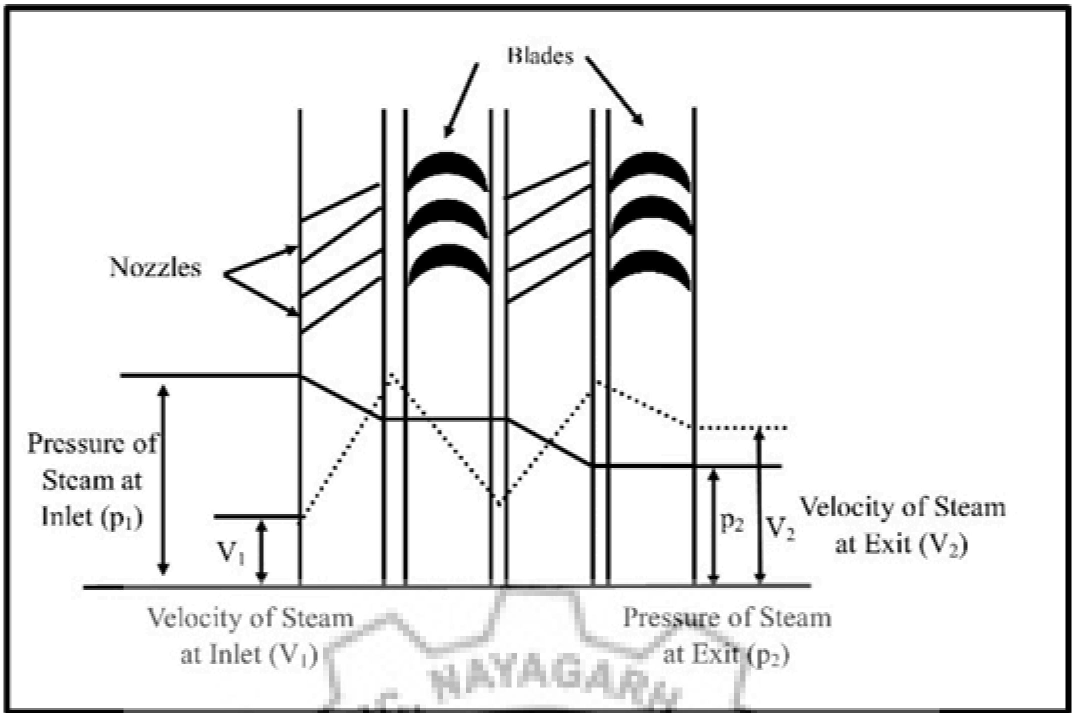


Fig. 5.7 (b) Pressure Compounding

Figure 5.7(b): Pressure Compounding Arrangement

Pressure Compounding: Also known as Rateau staging, this method divides the total pressure drop into several stages. Each stage consists of nozzle ring and moving blade row.

Working Principle:

- **Total pressure drop is divided among multiple stages**
- **Each stage has its own nozzle ring where pressure drop occurs**
- **Steam velocity in each stage is moderate**
- **Moving blades in each stage absorb kinetic energy**
- **Rotor speed is significantly reduced compared to single stage**

5.4.3 Pressure-Velocity Compounding (Combined Staging)

[Refer to Figure 5.7(c): Pressure-Velocity Compounding on page 123]

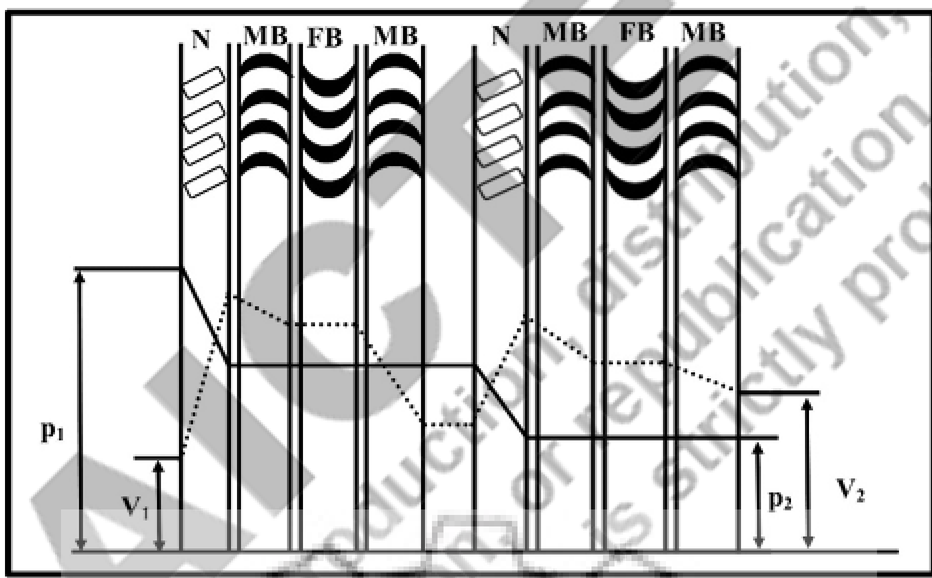


Fig. 5.7 (c) Pressure - Velocity Compounding

Figure 5.7(c): Pressure-Velocity Compounding Arrangement

Pressure-Velocity Compounding: A combination of both pressure and velocity compounding principles. Used in modern large turbines for optimal performance.

Compounding Method	Principle	Number of Stages Required	Efficiency	Applications
Velocity Compounding	**Kinetic energy absorbed in stages**	**Few stages (2-3 moving rows)**	**Lower efficiency per stage**	**First stages of large turbines, small turbines**
Pressure Compounding	**Pressure drop divided into stages**	**Many stages (10-20+)**	**Higher overall efficiency**	**Medium to large power plants**

Pressure-Velocity Compounding	Combination of both methods	Moderate number of stages	Optimal efficiency	Modern large power plants

5.5 Parson's Reaction Turbine

Parson's Reaction Turbine: Developed by Sir Charles Parsons in 1884, this is the most common type of reaction turbine with 50% degree of reaction. It features symmetrical staging where fixed and moving blades have identical shape, and pressure drop occurs equally in both.

[Refer to Figure 5.8: Velocity diagram of Parson's reaction turbine on page 125]

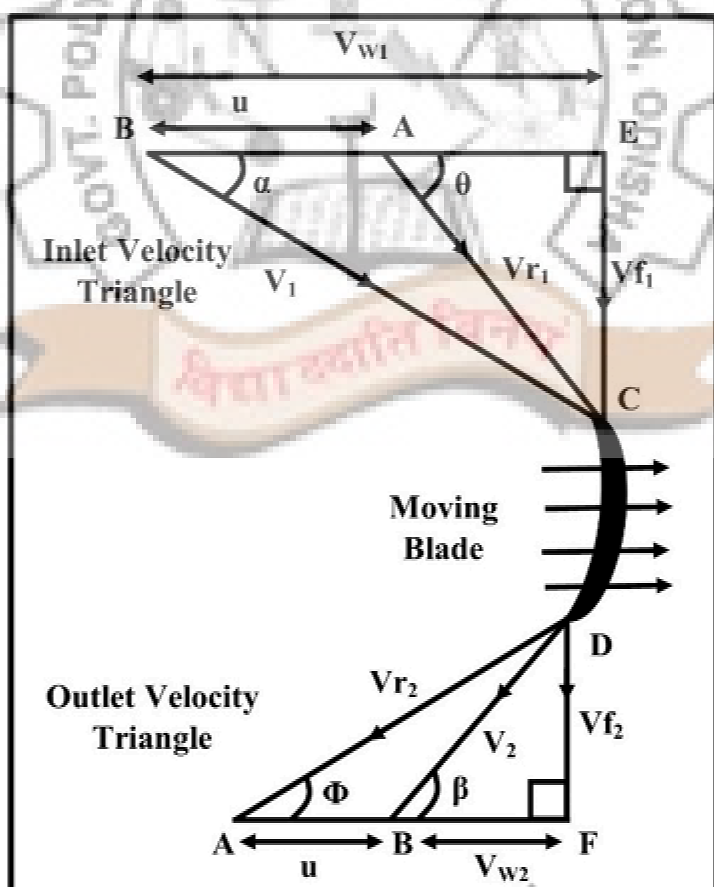


Fig. 5.8 Velocity diagram of Parson's reaction turbine

Figure 5.8: Velocity Diagram for Parson's Reaction Turbine

Construction Features:

- **Symmetrical Blading: Fixed and moving blades have identical aerofoil shape**
- **Drum-type Rotor: Blades are mounted directly on a drum-shaped rotor**
- **Gradual Expansion: Blade passages are convergent to allow gradual steam expansion**
- **Reaction Principle: 50% reaction - equal pressure drop in fixed and moving blades**
- **Axial Flow: Steam flows parallel to turbine axis through alternating fixed and moving blades**

Working Principle:

1. **Steam enters the first stage fixed blades (guide blades) where partial expansion occurs**
2. **Steam then flows through moving blades where further expansion takes place**
3. **The expanding steam creates reaction forces on the moving blades**
4. **This process repeats through multiple stages until steam pressure drops to condenser pressure**
5. **Steam velocity is maintained approximately constant throughout the turbine**

[Refer to Figure 5.9: Combined velocity diagram for Parson's reaction turbine on page 126]

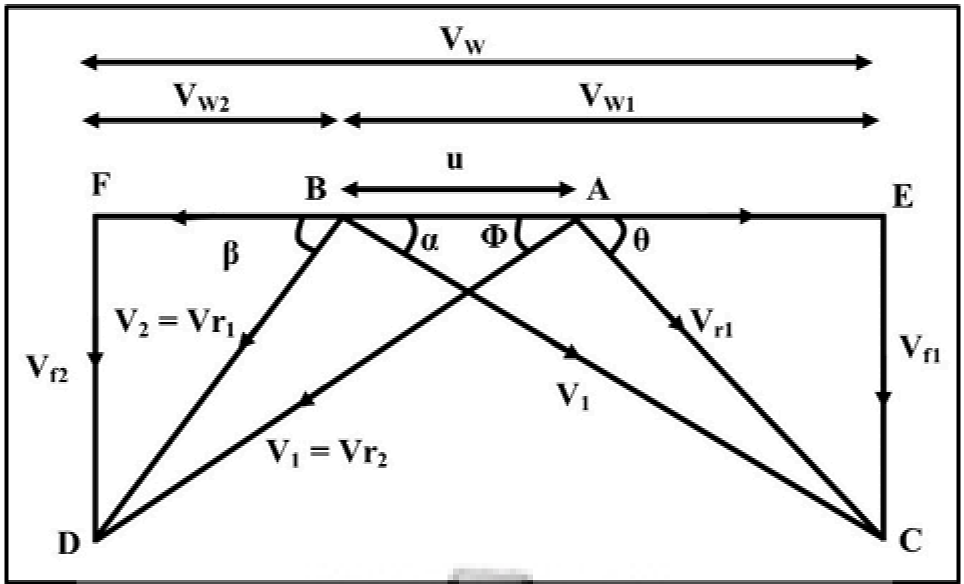


Fig. 5.9 Combined velocity diagram for Parson's reaction turbine

Figure 5.9: Combined Velocity Diagram for Parson's Reaction Turbine

Degree of Reaction (R):

R = (Enthalpy drop in moving blades) / (Total enthalpy drop in stage)

For Parson's turbine: R = 0.5 (50% reaction)

Blade angles: α = β (nozzle angle = blade inlet angle)

θ = α (blade outlet angle = nozzle angle)

Stage Efficiency Calculation:

Stage work: $W = V_\beta (V_{r1} \cos\beta + V_{r2} \cos\theta)$

For Parson's turbine with symmetrical blading: $\beta = \theta$ and $V_{r1} = V_{r2}$

Stage efficiency: $\eta_{stage} = 2V_\beta(V_r \cos\beta + V_r \cos\beta) / (h_1 - h_2)$

Maximum efficiency occurs when $V_\beta/V_1 = \cos\alpha$

5.6 Bleeding

Bleeding (Steam Extraction): The process of extracting partially expanded steam from intermediate stages of a steam turbine for feedwater heating. This improves overall cycle efficiency by reducing the amount of heat added in the boiler.

Purpose and Benefits:

- **Improves Cycle Efficiency:** Raises average temperature of heat addition in the Rankine cycle
- **Reduces Boiler Heat Input:** Feedwater is preheated using extracted steam instead of boiler heat
- **Reduces Thermal Stress:** Lower temperature difference between boiler components
- **Increases Plant Capacity:** More steam can be generated with same boiler size
- **Reduces Condenser Load:** Less steam flows to condenser, reducing cooling requirements

Bleeding Arrangement:

- Steam is extracted from suitable turbine stages (typically 4-8 extraction points)
- Extracted steam is used in feedwater heaters (closed or open type)
- Optimum extraction pressure is determined by thermodynamic analysis
- Modern plants use 6-8 stage feedwater heating for maximum efficiency

[Refer to Figure 5.10: h-s chart on page 126]

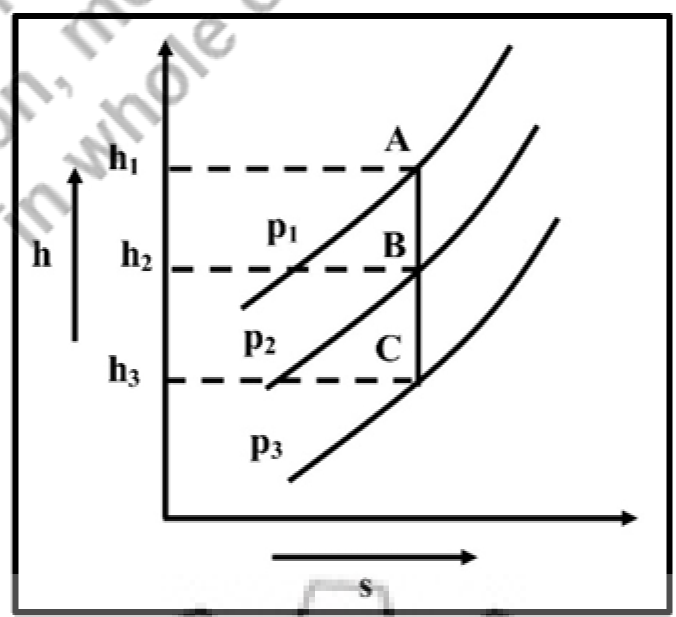


Fig. 5.10 h-s chart

Figure 5.10: h-s Chart Showing Bleeding Process

Efficiency Improvement:

With bleeding: $\eta_{improved} = (W_{turbine} - \Sigma W_{loss}) / (Q_{in} - \Sigma Q_{saved})$

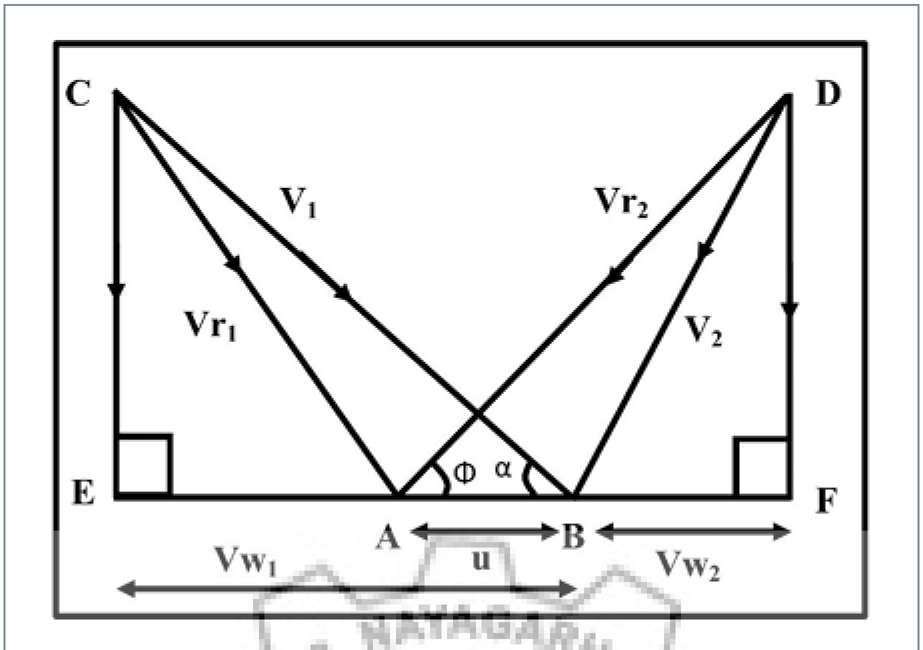
Typical efficiency improvement: 5-15% compared to non-bled cycle

Optimum number of heaters: 6-8 for large power plants

5.7 Re-heating

Re-heating: The process of returning partially expanded steam from an intermediate turbine stage back to the boiler for reheating, then returning it to the next turbine stage for further expansion. This increases the dryness fraction at turbine exhaust and improves cycle efficiency.

[Refer to Figure 5.11: Reheating of steam on page 134]



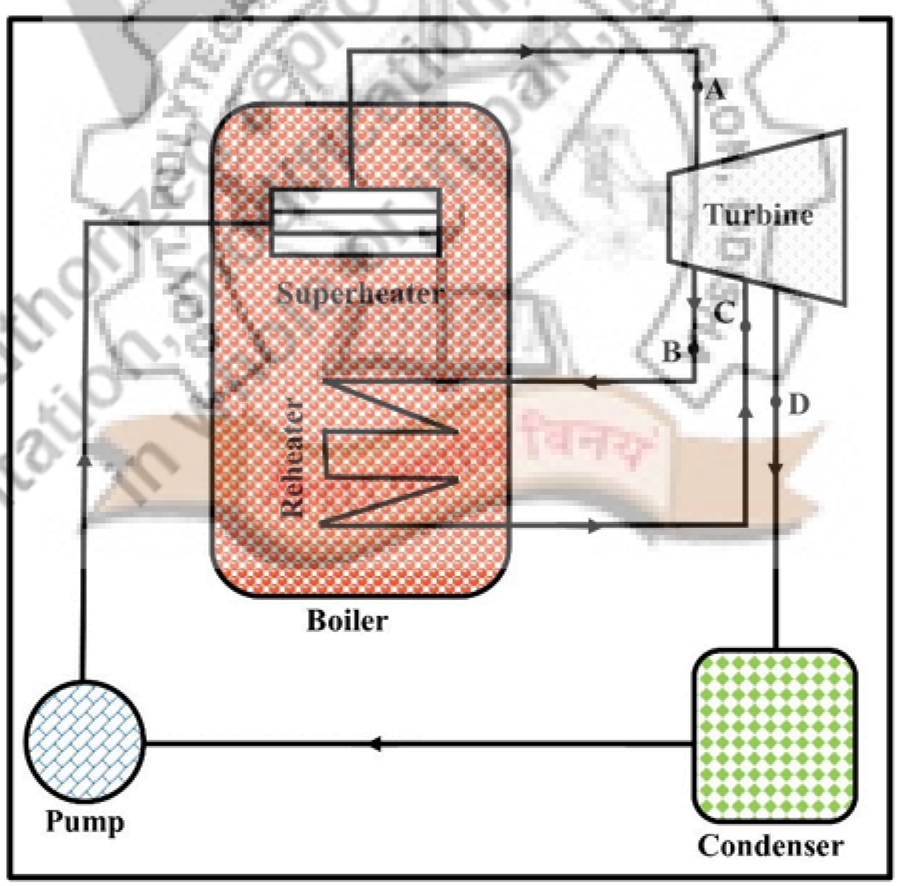


Fig. 5.11 Reheating of steam

Figure 5.11: Schematic of Reheating System

Re-heating Cycle Operation:

1. **High-pressure steam expands in HP turbine to intermediate pressure**
2. **Steam is returned to boiler reheater section (not the main furnace)**
3. **Steam is reheated to original temperature (or slightly lower) at constant pressure**
4. **Reheated steam expands in IP and LP turbines to condenser pressure**
5. **Typical reheat pressure: 20-25% of initial pressure**
6. **Typical reheat temperature: Same as or slightly below initial temperature**

Advantages of Re-heating:

- **Increases Dryness Fraction: Reduces moisture content in later stages (below 10-12%)**
- **Improves Efficiency: 4-5% efficiency improvement over non-reheat cycle**
- **Reduces Erosion: Less moisture reduces blade erosion in LP stages**
- **Increases Work Output: More work per kg of steam due to additional expansion**
- **Reduces Heat Rate: Lower heat input per kWh generated**

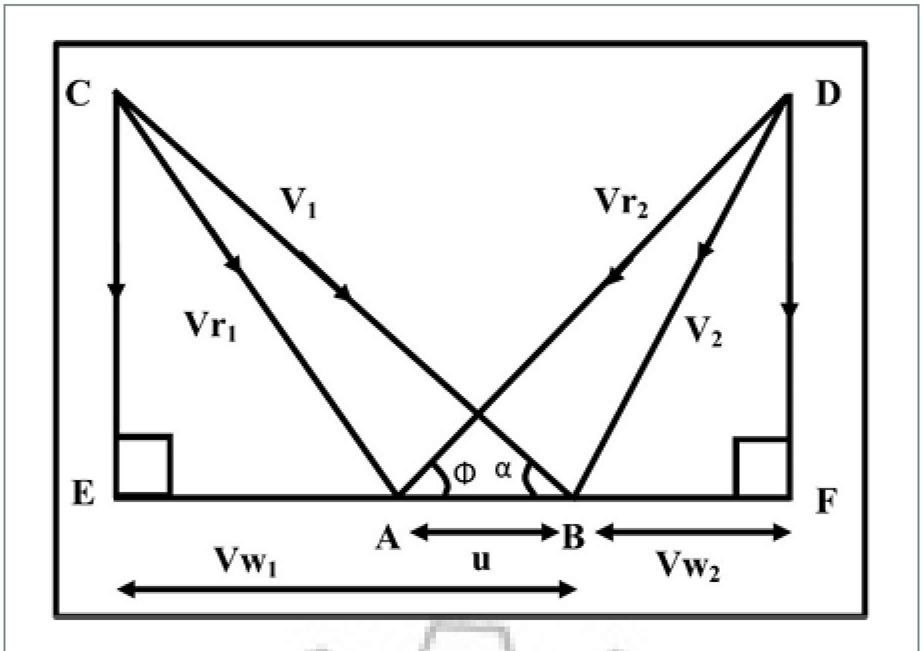
Disadvantages:

- **Increased complexity and cost of boiler and piping**
- **Additional pressure drop in reheat piping**
- **Requires careful control during load changes**
- **Increased maintenance requirements**

5.8 Reheat Factor

Reheat Factor (RF): The ratio of cumulative adiabatic heat drop to the isentropic heat drop in a multi-stage turbine. It accounts for the regain of enthalpy due to the inefficiency of preceding stages and is always greater than 1.

[Refer to Figure 5.12: Enthalpy-Entropy chart (Mollier Chart) on page 135]



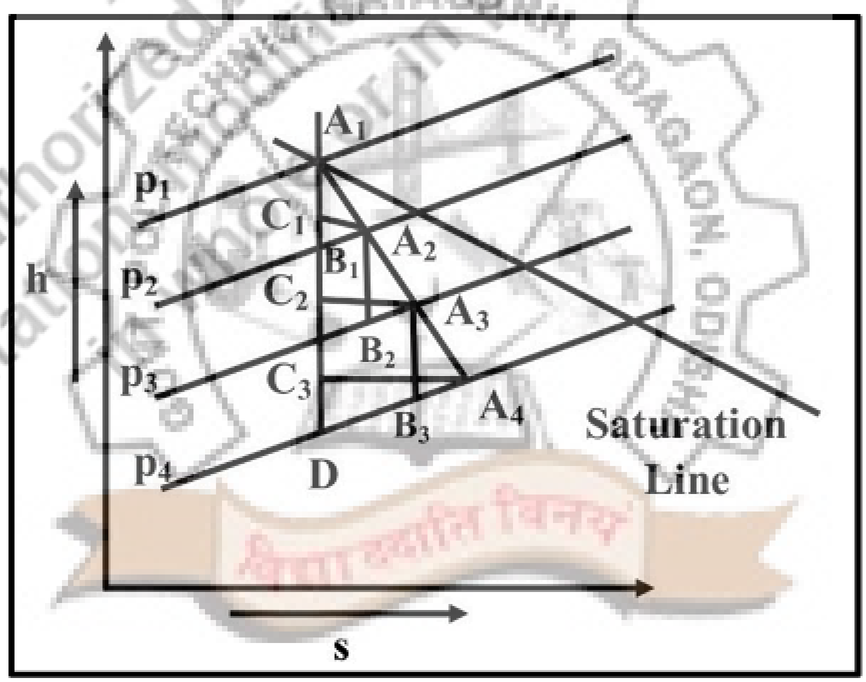


Fig. 5.12 Enthalpy-Entropy chart (Mollier Chart)

Figure 5.12: h-s Chart Showing Reheat Factor

Reheat Factor (RF) = Cumulative adiabatic heat drop / Isentropic heat drop

$$RF = (\Sigma \Delta h_i) / (h_1 - h_2')$$

```
Where: Δhᵢ = Actual heat drop in each stage
h₁ = Initial enthalpy
h₂' = Final enthalpy for isentropic expansion

Typical values: RF = 1.03 to 1.08 for well-designed turbines
```

Physical Significance:

- **Represents the "regain" of expansion capability due to stage inefficiencies**
- **Higher stage efficiencies lead to lower reheat factor**
- **More stages generally result in higher reheat factor**
- **Accounts for the divergence of constant pressure lines on h-s diagram**

Stage Efficiency vs Overall Efficiency:

```
Overall efficiency = Stage efficiency × Reheat factor
η_overall = η_stage × RF
Since RF > 1, overall efficiency > stage efficiency
This explains why multi-stage turbines have higher efficiency
than single stage
```

Factors Affecting Reheat Factor:

- **Number of Stages: Increases with more stages**
- **Stage Efficiency: Decreases with higher stage efficiency**
- **Pressure Ratio: Increases with higher overall pressure ratio**
- **Initial Steam Conditions: Higher initial pressure increases RF**

5.9 Governing of Steam Turbines

Governing System: The mechanism that controls the speed and output of a steam turbine to maintain constant speed under varying load conditions. It

> **regulates steam flow to match power demand while maintaining safe operating conditions.**

5.9.1 Throttle Governing

[Refer to Figure 5.13: Throttle Governing on page 137]

Figure 5.13: Throttle Governing System

Principle: A throttle valve (governor valve) placed in the main steam line controls steam flow to the turbine. As load decreases, the valve partially closes, reducing steam flow and pressure before the first stage nozzles.

Components:

- **Throttle Valve: Main control valve operated by governor**
- **Governor: Speed sensing mechanism (mechanical, hydraulic, or electronic)**
- **Linkage: Connects governor to throttle valve**
- **Emergency Trip: Overspeed protection device**

Advantages:

- **Simple construction and reliable operation**
- **Low maintenance requirements**
- **Suitable for small to medium turbines**

Disadvantages:

- **Poor part-load efficiency due to throttling losses**
- **Reduced turbine efficiency at partial loads**
- **Limited turndown ratio**

5.9.2 Nozzle Control Governing

[Refer to Figure 5.14: Nozzle control governing on page 138]

Figure 5.14: Nozzle Control Governing System

Principle: The first stage nozzles are divided into several groups (typically 4-6), each fed by a separate control valve. As load changes, valves open or close in sequence, admitting steam to more or fewer nozzle groups.

Operation:

1. At full load, all nozzle control valves are open
2. As load decreases, valves close in sequence from one side
3. Steam admission becomes partial arc (not full circumference)
4. At minimum load, only one valve (one nozzle group) is open

Advantages:

- Better part-load efficiency than throttle governing
- Reduced throttling losses
- Suitable for large turbines and variable load operation
- Wider turndown ratio

Disadvantages:

- More complex valve gear and control system
- Higher initial cost
- Requires careful maintenance

5.9.3 By-pass Governing

Principle: Used in conjunction with other methods. At high loads, excess steam is bypassed around high-pressure stages directly to intermediate or low-pressure stages.

Applications:

- Peak load operation

- **Quick response to load changes**
- **Large turbines with extraction points**

Governing Method	Principle	Part-Load Efficiency	Complexity	Applications
Throttle Governing	Throttles main steam flow	Poor	Simple	Small to medium turbines, constant load
Nozzle Control	Controls number of active nozzles	Good	Moderate	Large turbines, variable load
By-pass Governing	Bypass steam around stages	Good at high loads	Complex	Large units with extraction

Unit Summary

This unit covered the comprehensive study of steam turbines, including:

Key Concepts Learned:

- **Classification: Steam turbines are classified based on principle (impulse/reaction), steam flow direction, number of stages, and steam conditions.**
- **Impulse vs Reaction: Impulse turbines (De-Laval) use steam jet momentum with pressure drop only in nozzles. Reaction turbines (Parson's) use both impulse and reaction with pressure drop in both fixed and moving blades.**
- **Velocity Diagrams: Essential tools for analyzing turbine performance, calculating work output, blade efficiency, and optimal blade speeds.**
- **Compounding Methods: Velocity compounding (Curtis), pressure compounding (Rateau), and combined compounding reduce rotor speed to practical values for power generation.**

- **Parson's Turbine: 50% reaction turbine with symmetrical blading, drum-type rotor, and gradual expansion through convergent passages.**
- **Bleeding: Extraction of steam for feedwater heating improves cycle efficiency by 5-15% through increased average temperature of heat addition.**
- **Re-heating: Returning steam to boiler for reheating between turbine stages increases dryness fraction and improves efficiency by 4-5%.**
- **Reheat Factor: Ratio of cumulative adiabatic heat drop to isentropic heat drop (typically 1.03-1.08), accounting for enthalpy regain in multi-stage turbines.**
- **Governing Systems: Throttle governing (simple but inefficient at part load), nozzle control governing (better efficiency), and by-pass governing for special applications.**

Important Formulas:

1. Blade efficiency for impulse turbine: $\eta_\beta = 2V_\beta(V_{r1} \cos \beta + V_{r2} \cos \theta) / V_1^2$
2. Maximum impulse turbine efficiency: $\eta_\beta(max) = \cos^2\alpha$ (for symmetrical blades, no friction)
3. Degree of reaction: R = (Enthalpy drop in moving blades) / (Total enthalpy drop in stage)
4. Stage work: $W = V_\beta (V_{r1} \cos \beta + V_{r2} \cos \theta)$
5. Reheat factor: RF = Cumulative adiabatic heat drop / Isentropic heat drop
6. Overall efficiency: $\eta_{overall} = \eta_{stage} \times RF$

Practical Applications:

- **Power generation in thermal, nuclear, and geothermal plants**
- **Marine propulsion for ships and submarines**
- **Industrial drives for compressors, pumps, and blowers**
- **Mechanical drives in refineries and process industries**

Exercises

Multiple Choice Questions

1. In an impulse turbine, where does the pressure drop occur?

- A) Only in moving blades
- B) Only in stationary nozzles
- C) Equally in fixed and moving blades
- D) In the condenser only

2. What is the degree of reaction for Parson's turbine?

- A) 0%
- B) 25%
- C) 50%
- D) 100%

3. Velocity compounding is used primarily to:

- A) Increase turbine efficiency
- B) Reduce rotor speed
- C) Increase steam temperature
- D) Reduce maintenance cost

4. The reheat factor for a multi-stage turbine is typically:

- A) Less than 1
- B) Equal to 1
- C) Between 1.03 and 1.08
- D) Greater than 2

5. Which governing method provides the best part-load efficiency?

- **A) Throttle governing**
- **B) Nozzle control governing**
- **C) By-pass governing**
- **D) All are equal**

Short and Long Answer Questions

1. **Explain with neat sketches the working principle of a simple De-Laval impulse turbine. Derive the expression for its maximum blade efficiency.**
2. **Differentiate between impulse and reaction turbines based on:**
    - **Principle of operation**
    - **Pressure distribution**
    - **Blade construction**
    - **Degree of reaction**
    - **Efficiency characteristics**
3. **Draw and explain the velocity diagrams for:**
    - **Single-stage impulse turbine**
    - **Parson's reaction turbine**

    Derive expressions for work done and efficiency in each case.
4. **What is compounding? Explain with diagrams:**
    - **Velocity compounding (Curtis stage)**
    - **Pressure compounding (Rateau stage)**
    - **Pressure-velocity compounding**

    Compare their advantages and applications.
5. **Explain the concept of bleeding in steam turbines. How does it improve the overall efficiency of a power plant? Illustrate with a schematic diagram and h-s chart.**

6. **Describe the re-heating process in steam turbines with a suitable schematic. What are its advantages and disadvantages? How does it affect the dryness fraction at turbine exhaust?**
7. **Define reheat factor. Derive its expression and explain why it is always greater than 1. How does it relate stage efficiency to overall efficiency in a multi-stage turbine?**
8. **Compare and contrast:**
   - **Throttle governing**
   - **Nozzle control governing**
   - **By-pass governing**

   Include their principles, advantages, disadvantages, and typical applications.
9. **Solve the following numerical problems:**
   a. **A single-stage impulse turbine has nozzle angle of 20°, blade inlet angle of 30°, and blade outlet angle of 25°. Steam leaves the nozzle at 600 m/s. Blade speed is 250 m/s. Calculate: (i) Relative velocity at inlet (ii) Relative velocity at outlet (iii) Work done per kg of steam (iv) Blade efficiency.**
   b. **A Parson's reaction turbine runs at 3000 RPM with mean blade speed of 150 m/s. The blade outlet angle is 20° for both fixed and moving blades. Determine: (i) Inlet angles (ii) Diagram efficiency (iii) Stage work per kg of steam.**
   c. **A steam turbine has isentropic heat drop of 1000 kJ/kg. The cumulative adiabatic heat drop through multiple stages is 1050 kJ/kg. Calculate the reheat factor. If stage efficiency is 85%, what is the overall efficiency?**

References and Suggested Readings

- **Thermal Engineering by B. R. Sarkar (McGraw-Hill Education (India) Pvt Limited)**
- **Thermal Engineering by R.K. Rajput (Laxmi Publications (P) Ltd)**
- **A Textbook of Thermal Engineering by R.S. Khurmi & J.K. Gupta (S. Chand & Company Ltd)**
- **Steam Turbine Theory and Practice by William J. Kearton (Pitman Publishing)**
- **Thermal Engineering by Mahesh M. Rathore (McGraw-Hill Education (India) Pvt Limited)**
- **Power Plant Engineering by P.K. Nag (McGraw-Hill Education)**

Dynamic QR Code for Further Reading

Scan for NPTEL Course on "Steam Turbines" - IIT Roorkee

Note: All figure references (Fig. 5.1 to Fig. 5.14) correspond to the diagrams in the textbook "Thermal Engineering II" by Dr. Parvesh Antil, published by AICTE (2024). Page numbers are provided for each figure reference as per the textbook pagination.