






Concept and Formation of

STEAM

From Water to Wet, Dry & Superheated Steam — Engineering Fundamentals

 Course: Engineering Thermodynamics

 Duration: 1 Hour |  B.Tech – Year 1

Lecture Roadmap

Design Thinking applied to Steam Thermodynamics — a structured 1-hour journey

01

Empathize

Why steam? Industrial need & historical context

02

Define

Water states, properties & key definitions

03

Ideate

Steam formation — the heating process

04

Prototype

Steam tables, dryness fraction & calculations

05

Test

Applications, case studies & mind map

 *Outcome: Understand how steam forms, classify its states, read steam tables, and calculate dryness fraction*

Concept and Formation of steam

EMPATHIZE — Why Steam Is Central to Engineering

From Watt's engine to ISRO's test stands — steam is everywhere in engineering

80%

of global electricity
generated using steam
turbines

**₹12 Lakh
Cr**

India's thermal power
capacity (coal + gas)
steam-based

170 °C+

Steam temperature in
autoclave sterilisation
(medical/food sectors)

- Steam is the working fluid in the Rankine cycle — the thermodynamic cycle powering every conventional and nuclear thermal power plant
- Industrial process steam: Paper mills, textile dyeing, chemical reactors, food processing, oil refining — all depend on steam at controlled pressures and temperatures
- Steam propulsion: Marine steam turbines power naval vessels; ISRO uses steam catapults and steam-heated test stands for rocket engine testing
- Historical foundation: James Watt's steam engine (1769) launched the Industrial Revolution — steam engineering created the modern industrial world
- India context: NTPC, BHEL, Thermax, and L&T Boilers are major employers of ME graduates who specialise in steam systems

Steam Engineering – A Brief History

From ancient observations to modern supercritical power plants

- Hero of Alexandria's Aeolipile — first steam-powered device (reaction turbine principle)
- Thomas Savery's 'Miner's Friend' — first practical steam pump for mine drainage
- James Watt improves Newcomen engine — separate condenser; launches Industrial Revolution
- Charles Parsons invents steam turbine — 100 kW prototype; modern power generation begins
- First supercritical boiler (USA) — steam above critical point (374°C, 220.6 bar)
- Ultra-supercritical plants at 600°C / 300 bar — 45%+ efficiency; BHEL's Sipat Plant (India)

DEFINE — Pure Water: States and Key Properties

Before understanding steam, we must understand water as a pure substance

- Pure substance: Homogeneous, fixed chemical composition (H_2O) — properties depend only on two independent state variables (e.g., P and T)
- Three phases: Solid (ice), Liquid (water), Vapour (steam) — all exist simultaneously at the Triple Point (0.006 bar, 0.01°C)
- Critical Point: 374.14°C and 220.9 bar — above this, liquid and vapour phases are indistinguishable; supercritical fluid
- Specific volume (v): Volume per unit mass (m^3/kg) — liquid water $\approx 0.001 \text{ m}^3/\text{kg}$; steam significantly higher
- Specific enthalpy (h): Total energy content per unit mass (kJ/kg) — most useful property for steam cycle analysis
- Specific entropy (s): Degree of disorder per unit mass ($\text{kJ}/\text{kg}\cdot\text{K}$) — critical for Rankine cycle efficiency analysis



Key Definitions – Steam Terminology

Precise vocabulary is the foundation of thermodynamic analysis

Saturation Temperature (T_{sat})

Temperature at which water boils at a given pressure. At 1 atm: $T_{sat} = 100^{\circ}\text{C}$. At 10 bar: $T_{sat} = 179.9^{\circ}\text{C}$. Higher pressure \rightarrow higher boiling point.

Sensible Heat (h_f)

Heat required to raise water from 0°C to saturation temperature at constant pressure. Also called enthalpy of saturated liquid (kJ/kg).

Enthalpy of Saturated Vapour (h_g)

Total enthalpy of dry saturated steam: $h_g = h_f + h_{fg}$ (kJ/kg). This is the maximum enthalpy before superheating at that pressure.

Saturation Pressure (P_{sat})

Pressure at which water boils at a given temperature. The steam tables give P_{sat} for every temperature. At 100°C : $P_{sat} = 1.013$ bar.

Latent Heat of Vaporisation (h_{fg})

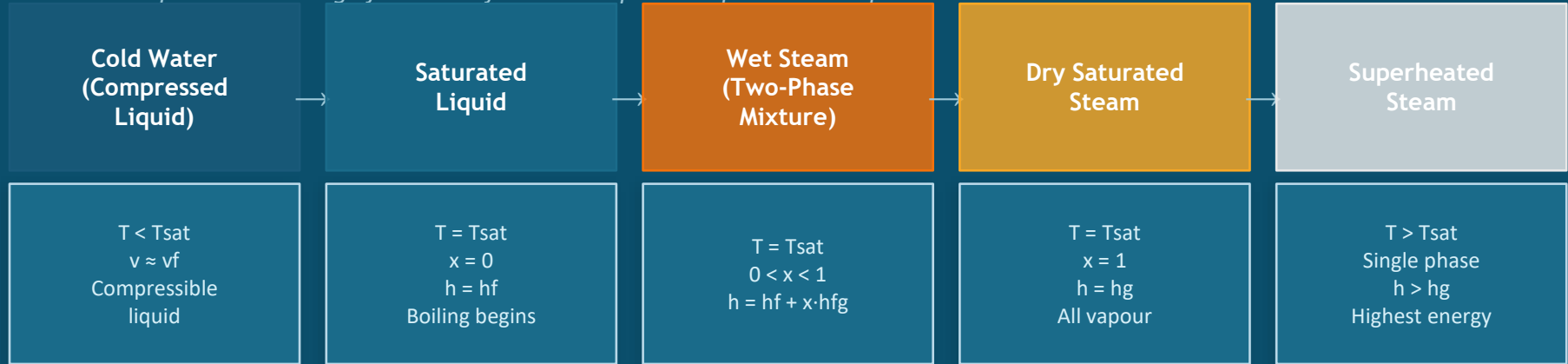
Heat required to completely vaporise saturated liquid at constant pressure and temperature. At 100°C : $h_{fg} = 2257$ kJ/kg. Decreases with increasing pressure.

Dryness Fraction (x)

Ratio of dry steam mass to total wet mixture mass: $x = m_g / (m_g + m_f)$. $x = 0 \rightarrow$ saturated liquid; $x = 1 \rightarrow$ dry saturated steam. Critical quality parameter.

IDEATE – The Steam Formation Process

Constant pressure heating of water — from cold liquid to superheated vapour



← SENSIBLE HEAT ADDITION (h_f) →

← LATENT HEAT (h_{fg}) →

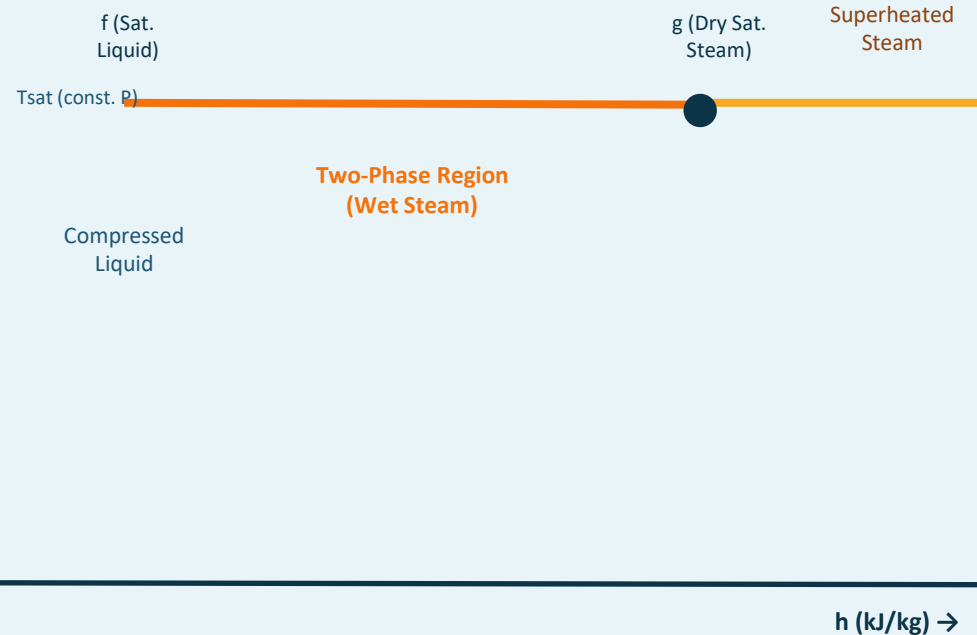
→ SUPERHEAT

- Stage 1 → 2: Sensible heating — temperature rises from ambient to T_{sat} ; volume increases slightly; no phase change occurs
- Stage 2 → 3: Latent heat absorption at constant temperature and pressure — liquid converts to vapour; dryness fraction x rises from 0 to 1
- Stage 3 → 4: Continued heating raises temperature above T_{sat} ; steam becomes superheated; pressure remains constant; volume increases significantly
- At higher pressures, T_{sat} is higher and h_{fg} is lower — at critical point (220.9 bar), $h_{fg} \rightarrow 0$ and there is no phase change

Temperature-Enthalpy (T-H) Diagram for Water

The most important diagram for understanding steam formation — every power engineer must read it fluently

$T (^{\circ}\text{C}) \uparrow$



Reading the T-H Diagram

- Point f : h_f = enthalpy of saturated liquid. All water just at boiling point, $x = 0$
- Point g : $h_g = h_f + h_{fg}$. Enthalpy of dry saturated steam, $x = 1$
- Between f and g : Wet steam. $h = h_f + x \cdot h_{fg}$; temperature constant at T_{sat}
- Beyond g : Superheated steam. Temperature $> T_{\text{sat}}$, higher h , single phase
- Higher pressure curves: Shifted up (higher T_{sat}) and narrower (smaller h_{fg})
- Critical point: Curves merge — liquid and vapour become identical

Three Types of Steam – Detailed Classification

Wet, dry saturated, and superheated steam – each with distinct properties and applications

WET STEAM

- Dryness fraction: $0 < x < 1$
- Contains water droplets + vapour
- $T = T_{sat}$ (pressure-dependent)
- $h = h_f + x \cdot h_{fg}$

Application:

Steam traps remove water; used in some industrial heating; avoided in turbines due to blade erosion



DRY SATURATED STEAM

- Dryness fraction: $x = 1$ (exactly)
- All vapour, no liquid droplets
- $T = T_{sat}$, $P =$ saturation pressure
- $h = h_g = h_f + h_{fg}$

Application:

Hospital autoclaves, food sterilisation, some process industry heating; the boundary between wet and superheated



SUPERHEATED STEAM

- Dryness fraction: not defined ($x > 1$ conceptually)
- Temperature $> T_{sat}$ at given pressure
- Single-phase gas; behaves like ideal gas at high superheat
- $h > h_g$; higher energy content

Application:

Steam turbines in all power plants; avoids blade erosion; NTPC plants superheat to 535–600°C for maximum efficiency

Dryness Fraction (Quality) – x

The most important quality parameter for wet steam in engineering practice

- Definition: $x = \text{mass of dry vapour} / \text{total mass of wet steam} = m_g / (m_g + m_f)$
- Range: $x = 0$ (saturated liquid, all water) to $x = 1$ (dry saturated steam, all vapour)
- Enthalpy of wet steam: $h = h_f + x \cdot h_{fg}$ (kJ/kg)
- Specific volume of wet steam: $v = v_f + x \cdot v_{fg}$ (m^3/kg), where $v_{fg} = v_g - v_f$
- Specific entropy of wet steam: $s = s_f + x \cdot s_{fg}$ (kJ/kg·K)
- Practical significance: $x < 0.85$ is dangerously wet for turbines — causes rapid blade erosion and mechanical failure

Quality Scale (x)

$x = 0.0$: Saturated liquid (all water)

$x = 0.5$: 50% vapour, 50% liquid by mass

$x = 0.8$: 80% vapour — minimum acceptable

$x = 0.9$: 90% vapour — typical boiler output

$x = 0.95$: 95% vapour — good quality steam

$x = 1.0$: Dry saturated steam

 **Example: Find h of wet steam at 10 bar with $x = 0.9$**

From steam tables: $h_f = 762.8$ kJ/kg, $h_{fg} = 2013.6$ kJ/kg $\rightarrow h = 762.8 + 0.9 \times 2013.6 = 2575.0$ kJ/kg

Concept and Formation of steam

Steam Tables – Engineering Data for Practice

Steam tables provide thermodynamic property data compiled from experimental measurements

- Two standard table formats: (1) Saturation table indexed by Temperature — gives P_{sat} , h_f , h_{fg} , h_g , v_f , v_g , s_f , s_{fg} , s_g at each temperature
- (2) Saturation table indexed by Pressure — gives T_{sat} and same properties at each pressure
- Superheated steam tables: h , v , s at specified (P, T) pairs above saturation conditions
- Compressed liquid tables: Properties of subcooled water below saturation temperature (rarely needed; approximated by saturated liquid values)
- Interpolation: When exact table values not available, linear interpolation between adjacent table entries; error $< 0.1\%$ for normal engineering use

Excerpt: Saturation Table (Indexed by Pressure)

P (bar)	T_{sat} (°C)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)	v_g (m ³ /kg)	s_g (kJ/kg·K)
1.013	100.0	419.1	2256.9	2676.0	1.673	7.355
5.0	151.8	640.1	2107.4	2747.5	0.375	6.921
10.0	179.9	762.8	2013.6	2776.4	0.194	6.585
20.0	212.4	908.8	1888.7	2797.5	0.0996	6.340
50.0	264.0	1154.2	1639.7	2793.9	0.0394	6.973

PROTOTYPE – Steam Generation in Boilers

The boiler converts chemical or nuclear energy into high-pressure, high-temperature steam

- Boiler (Steam Generator): Pressure vessel that heats water using combustion of fuel (coal, gas, oil, biomass) or nuclear fission, producing steam at required pressure and temperature
- Key boiler components: Furnace (combustion chamber), evaporator tubes (water→steam), superheater (steam→superheated steam), economiser (preheats feedwater using exhaust gas), air preheater
- Fire-tube boilers (low pressure < 20 bar): Hot combustion gases flow inside tubes surrounded by water — Cochran boiler, Lancashire boiler; used in small industrial plants
- Water-tube boilers (high pressure, > 20 bar): Water flows inside tubes, hot gases outside — La-Mont, Benson, Babcock & Wilcox; used in all power stations
- Once-through / Supercritical boilers: No drum — water converts directly to steam in one pass through tubes; operates above critical pressure (220.9 bar); BHEL supercritical boilers for India's new 660 MW units
- Boiler efficiency: Ratio of heat in steam to heat in fuel; modern supercritical boilers: 88–92% efficiency (HHV basis); improves overall plant efficiency by 2–4 percentage points

Boiler Types at a Glance

Cochran (Fire-tube)

P: < 15 bar | Cap: < 4 TPH | Small factories, hospitals

Lancashire (F-tube)

P: < 20 bar | Cap: < 9 TPH | Textile mills, laundries

Babcock & Wilcox

P: < 40 bar | Cap: < 40 TPH | Medium power plants

La-Mont (W-tube)

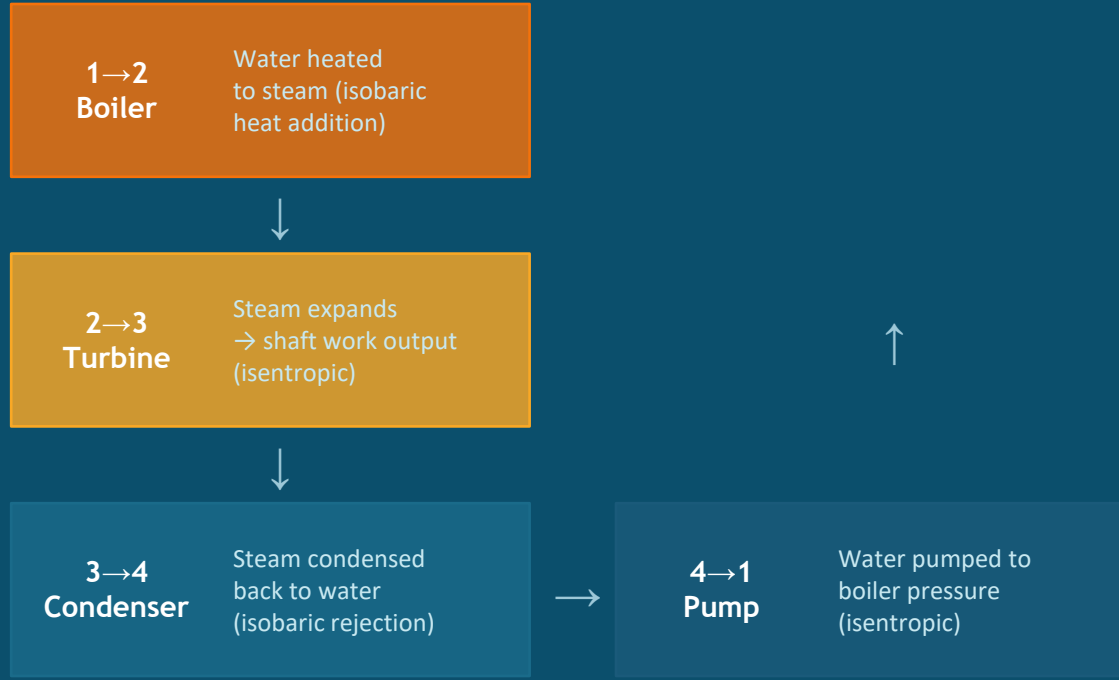
P: < 170 bar | Cap: < 450 TPH | Large power stations

Benson (Once-thru)

P: 250+ bar | Cap: > 1000 TPH | Supercritical plants, BHEL

Steam in the Rankine Cycle — Power Generation

Steam formation is the energy input stage of the most widely used power cycle in the world



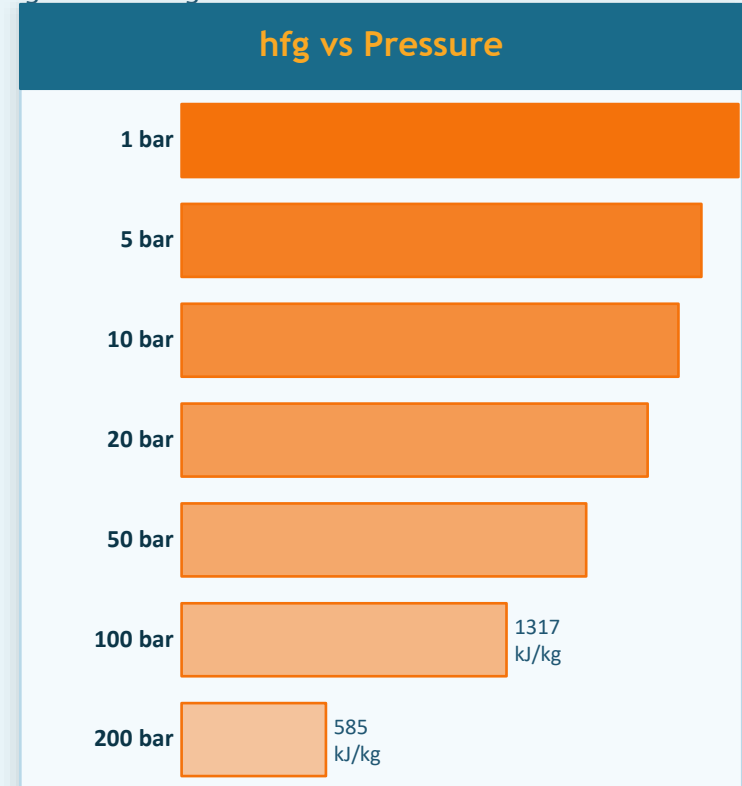
- Thermal efficiency (η_{Rankine}): $\eta = (h_2 - h_3) - (h_1 - h_4) / (h_2 - h_1)$ — all values from steam tables
- Effect of superheat: Higher turbine inlet temperature → larger $(h_2 - h_3)$ → more work → higher efficiency
- Effect of pressure: Higher boiler pressure → higher T_{sat} → more heat added at higher temperature → higher Carnot-equivalent efficiency
- Reheat cycle: Steam partially expanded in HP turbine → reheated in boiler → expanded in LP turbine; avoids excessive wetness; NTPC uses 2-stage reheat
- Regenerative cycle: Bled steam from turbine preheats feedwater in feed heaters — India's 500 MW units have 7

Steam properties (h , s from tables) directly enter the Rankine cycle efficiency equation — this is why steam tables are engineering fundamentals

Effect of Pressure on Steam Formation

How boiler operating pressure fundamentally changes steam properties — the engineer's design variable

- Increasing pressure → T_{sat} increases: At 1 bar: 100°C; at 10 bar: 179.9°C; at 50 bar: 264.0°C; at 200 bar: 365.8°C — enables higher-temperature heat addition
- Increasing pressure → hfg decreases: At 1 bar: 2257 kJ/kg; at 10 bar: 2014 kJ/kg; at 100 bar: 1317 kJ/kg; at critical: 0 kJ/kg — less latent heat needed
- Increasing pressure → v_g decreases sharply: At 1 bar: 1.673 m³/kg; at 10 bar: 0.194 m³/kg; at 100 bar: 0.018 m³/kg — steam becomes much denser
- Engineering implication (1): Higher pressure → more compact steam lines and vessels; but stronger (thicker, heavier) pipe and boiler wall required
- Engineering implication (2): Higher pressure → higher efficiency Rankine cycle; but greater material cost and more rigorous safety requirements
- Sub-critical vs Super-critical: Below 220.9 bar, water boils with distinct phase change; above 220.9 bar, no phase change — direct conversion from liquid-like to gas-like fluid



Measurement of Dryness Fraction

Three experimental methods to determine steam quality in industrial and laboratory settings

Barrel (Throttling) Calorimeter

How it works:

Wet steam throttled through an orifice to atmospheric pressure — measures temperature of throttled steam (should be superheated after throttle)

Formula:

$$h_{\text{wet}} = h_{\text{throttled}} \text{ (constant enthalpy throttling)}$$
$$x = (h_{\text{throttled}} - h_f) / h_{fg}$$

⚠ Cannot measure $x > 0.95$ or very high pressure steam



Separating Calorimeter

How it works:

Mechanically separates liquid from vapour by centrifugal action; measures separated liquid mass (m_f) and vapour mass (m_g) directly

Formula:

$$x = m_g / (m_g + m_f)$$

⚠ Low accuracy for high quality steam ($x > 0.95$)



Separating & Throttling Combined

How it works:

Separator removes most moisture first, then throttle calorimeter measures remaining wetness of the drier sample — multiplied for total x

Formula:

$$x_{\text{total}} = x_{\text{sep}} \times x_{\text{cal}}$$

Combines advantages of both

⚠ More complex setup; used for high-accuracy industrial measurement

TEST – Steam Applications: India Industry Context

Every major Indian industry uses steam — understanding its formation makes you indispensable

NTPC – National Thermal Power Corporation

72,000 MW thermal capacity; Vindhyachal STPP (4,760 MW) — India's largest; supercritical boilers at 250 bar / 540°C superheat; steam tables used daily by 50,000+ engineers



BHEL – Supercritical Boiler Manufacturing

Manufactures 660 MW and 800 MW supercritical boilers at Trichy; BHEL-designed once-through boilers for NTPC Sipat; exports boilers to Bangladesh, Malaysia, UAE

Thermax – Industrial Process Steam

Pune-based; boilers for pharma, textile, food, paper industries; heat recovery steam generators (HRSG) for cogeneration; installed capacity > 100,000 TPH across India



Sugar Industry – Bagasse-Fired Steam

India has 700+ sugar mills; use bagasse (sugarcane residue) as fuel; generate steam at 45–60 bar; cogenerate electricity; Maharashtra, UP mills supply power to state grids

ISRO / DRDO – Steam for Testing

Steam catapults and high-pressure steam jets used for rocket engine test stand facilities; steam-heated chambers for vibration testing of satellites at ISAC Bengaluru



Pharmaceutical – Autoclave Steam

Every pharmaceutical plant and hospital in India uses pure steam at 2.1–2.8 bar, 121–134°C for sterilisation; steam purity (no additives) critical for validation by CDSCO

Global Steam Technology — Advanced Applications

Steam thermodynamics continues to drive the world's most powerful energy systems

Ultra-Supercritical Plants (Germany/Japan/Korea)

600°C / 300 bar steam conditions; 47–48% thermal efficiency; Germany's Niederaussem plant achieved 45.2%; reduces CO₂ per kWh by 30% vs sub-critical

Nuclear Steam Generators (France/USA)

PWR reactors produce steam at 60–70 bar, 280°C (slightly wet) — secondary loop steam; EDF's 56-unit nuclear fleet provides 70% of France's electricity entirely through steam turbines

Geothermal Steam (Iceland/New Zealand/Italy)

Natural underground steam at 150–350°C used directly in turbines; Iceland's Hellisheidi plant generates 303 MW electric + 400 MW thermal from geothermal steam with zero CO₂ emissions

Steam in Rocketry (NASA / ISRO)

Water deluge systems protect launch pads — 300,000 litres/minute of water flashed to steam absorbs acoustic energy; steam

Solved Numerical Examples

Practising steam table reading and property calculations — the core exam skill

Q1: Find the specific enthalpy of wet steam at 5 bar with dryness fraction $x = 0.85$


From steam tables at 5 bar: $h_f = 640.1 \text{ kJ/kg}$, $h_{fg} = 2107.4 \text{ kJ/kg}$
 $h = h_f + x \cdot h_{fg} = 640.1 + 0.85 \times 2107.4 = 640.1 + 1791.3 = 2431.4 \text{ kJ/kg}$

Q2: Find the dryness fraction if wet steam at 10 bar has specific enthalpy of 2500 kJ/kg

From steam tables at 10 bar: $h_f = 762.8 \text{ kJ/kg}$, $h_{fg} = 2013.6 \text{ kJ/kg}$
 $x = (h - h_f) / h_{fg} = (2500 - 762.8) / 2013.6 = 1737.2 / 2013.6 = 0.863$

Q3: Steam at 15 bar, 250°C — is it superheated? Find degree of superheat

From tables: T_{sat} at 15 bar = 198.3°C . Since $250^\circ\text{C} > 198.3^\circ\text{C} \rightarrow$ YES, superheated
 Degree of superheat = $250 - 198.3 = 51.7^\circ\text{C}$ (above saturation)

 Practice Questions: (a) Find v of wet steam at 20 bar, $x = 0.78$ (b) Find T_{sat} and h_g at 25 bar (c) If steam at 100 bar is superheated to 450°C , find h using superheated steam tables

Steam, Sustainability & the Energy Transition

Steam technology is evolving — not disappearing — in a net-zero world

Green Steam Generation

Biomass, solar-thermal concentrating (CSP), geothermal, and waste heat recovery (HRSG) produce steam without fossil fuel combustion; Rajasthan Solar Park uses parabolic troughs to generate 400°C steam



Solar Concentrating Power

Parabolic trough and heliostat systems focus sunlight to heat heat transfer fluid → generate steam → turbine; India's MNRE has 10 GW solar thermal target; Godawari Solar Project (50 MW, Rajasthan) operational

Waste Heat Recovery

Cogeneration (CHP): same fuel generates both electricity (steam turbine) and useful heat (process steam); Thermax installs HRSGs at cement, steel, and glass plants recovering exhaust gas heat into steam



Steam vs Heat Pumps

For low-temperature process heat (< 120°C), industrial heat pumps increasingly compete with steam boilers at higher efficiency; steam remains essential for high-temperature processes (> 200°C)

Hydrogen as Boiler Fuel

H₂-ready boilers can switch from natural gas to green hydrogen without structural changes; Mitsubishi Power's H-25 gas turbine burns 100% hydrogen; NTPC trialling H₂ co-firing at Simhadri plant



Steam Storage

Ruths steam accumulators store thermal energy as pressurised hot water; charge during low demand, discharge as steam during peak demand — smooths renewable energy intermittency for industrial users

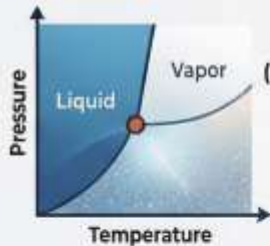
Steam Thermodynamics: The Engine of the Modern World

Sensible vs. Latent Heat



Sensible Heat
Raises water temperature to boiling

Latent Heat
Converts liquid to vapor at constant temperature



The Critical Point
(374.14°C / 220.9 bar)

Above this pressure and temperature, liquid and vapor phases become indistinguishable, forming a supercritical fluid.

THE PHYSICS OF FORMATION



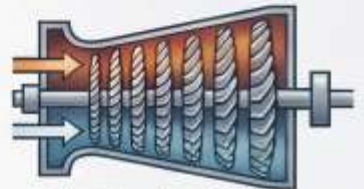
INDUSTRIAL POWER & APPLICATION



80%

OF GLOBAL ELECTRICITY

Most of the world's power is generated using steam turbines via the Rankine cycle.



The Superheat Advantage

Heating steam above its saturation temperature increases energy content and prevents mechanical failure in turbines.

Dryness Fraction (x)



Pressure & Latent Heat Relationship

Pressure (bar)	Saturation Temp (°C)	Latent Heat (h_{fg} in kJ/kg)
1.013 (Atmospheric)	100.0	2256.9
10.0	179.9	2013.6
100.0	311.0	1317.1

