PROPERTIES OF STEAM

AND THEIR SIGNIFICANCE

A Visual Engineering Guide for Undergraduate Students

Thermodynamics | Engineering Design | Industrial Applications | Sustainability

Introduction — What Are Steam Properties?

Steam properties are quantifiable physical & thermodynamic characteristics of water in its vapor state that determine its behavior, energy content, and suitability for engineering applications.

Pressure

Force per unit area exerted by steam on surfaces

Temperature

Measure of thermal energy state of steam molecules

Enthalpy

Total heat content = internal energy + flow work

Entropy

Measure of disorder / heat irreversibility in cycle

Specific Vol.

Volume occupied per unit mass of steam (m^3/kg)

Dryness Frac.

Ratio of steam mass to total mixture mass (0–1)

Why Steam Properties Matter — Global Significance

80%
Global electricity via steam turbines

2260 kJ/kg
Latent heat of vaporization

374°C
Critical temperature of water/steam

$280B
Steam equipment market 2024 (USD)

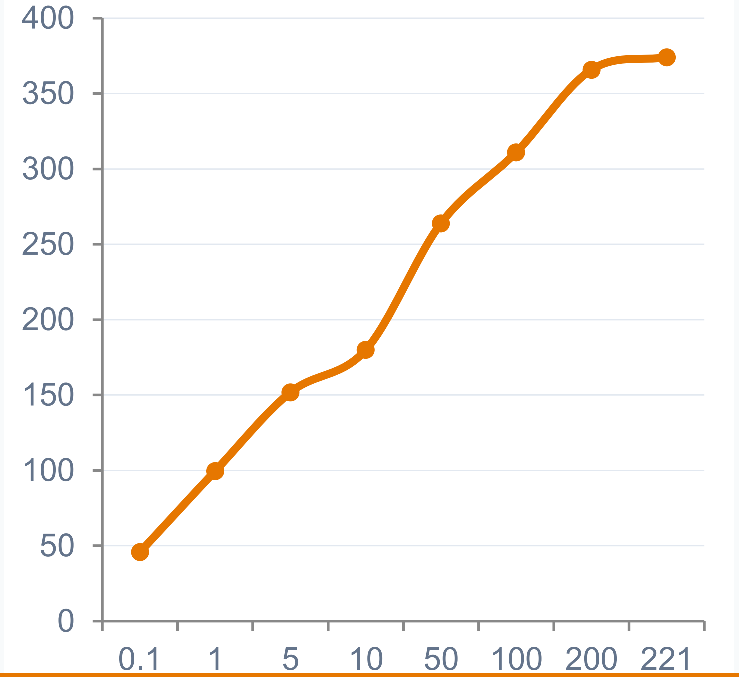
WHY PROPERTIES MUST BE PRECISELY KNOWN

1. **Accurate Steam Properties** — *From tables / equations of state* →
2. **Correct Equipment Sizing** — *Boilers, turbines, condensers* →
3. **Optimal Cycle Efficiency** — *Rankine / combined cycle design* →
4. **Safe Plant Operation** — *Pressure limits, relief valves* →
5. **Energy & Cost Savings** — *Reduced fuel & maintenance costs*

Core Property 1 — Pressure

Pressure is the normal force exerted by steam per unit area (Pa or bar). It directly determines saturation temperature and steam quality.

Low Pressure	Medium Pressure	High Pressure	Supercritical
< 2 bar	**2–40 bar**	**40–160 bar**	**> 221 bar**
Comfort heating *District heat*	*Industrial process* *Food industry*	*Power generation* *Subcritical boiler*	*Ultra-SC plants* *>45% efficiency*



Key Insight: Increasing pressure raises saturation temperature — higher pressure steam carries more energy per unit mass.

Core Property 2 — Temperature

Superheated
> 600°C (USC)

Superheated
300–600°C

Saturation
100–374°C

Sub-cooled
< 100°C

T Category	Significance	Example
< 100°C	Sub-cooled liquid, no steam	Feed water
100°C @ 1 atm	Boiling point — phase change begins	Domestic boiler
100–374°C (Sat.)	T-P linked via saturation curve	Process steam
T > T_sat (same P)	Superheated — behaves as ideal gas	Turbine inlet
> 374.14°C (>221 bar)	Supercritical — no phase boundary	USC power plants

📐 Superheat Degree: $\Delta T = T_{actual} - T_{sat}(P)$ | Critical Point: 374.14°C at 220.9 bar | Rankine scale: $T(R) = T(K) \times 1.8$

Core Property 3 — Specific Enthalpy (h)

$$h = u + Pv$$

Internal Energy + Pressure–Volume Work (kJ/kg)

hf — Sensible Heat

Enthalpy of saturated liquid (water) at saturation temperature

hfg — Latent Heat

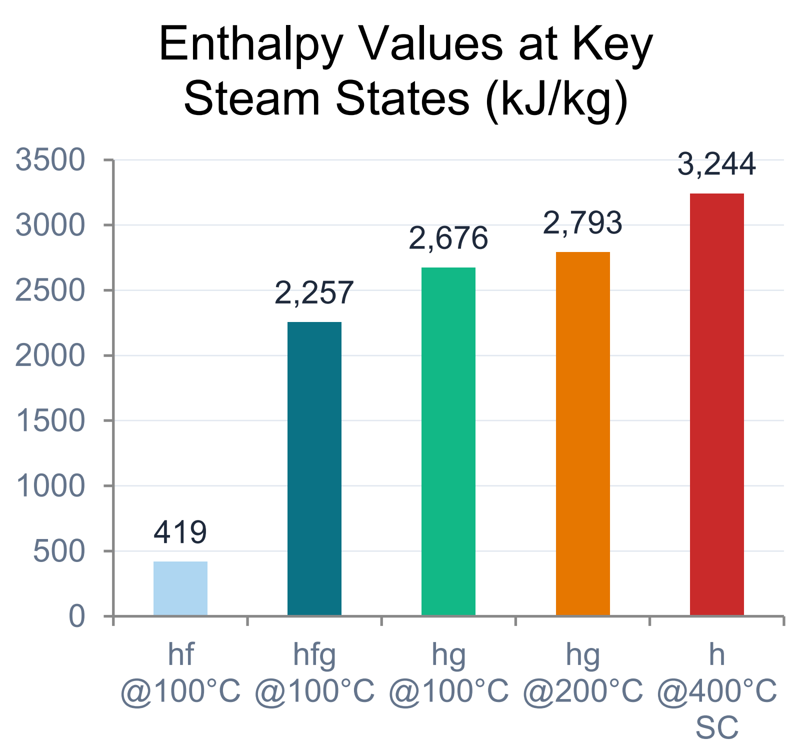
Heat required to vaporise liquid at constant T & P (≈ 2260 kJ/kg)

hg = hf + hfg

Enthalpy of dry saturated steam at saturation conditions

h_superheat

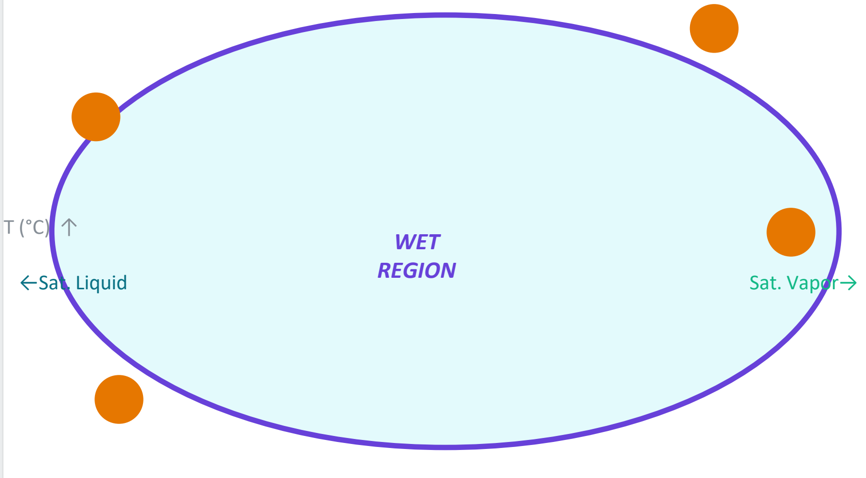
hg + Cp·ΔT above saturation
Higher h → more turbine work



💡 Turbine work output = h_in − h_out. Maximising inlet enthalpy (via superheating) directly maximises power output.

Core Property 4 — Specific Entropy (s)

$ds = \delta Q_{rev} / T \rightarrow s = s_f + x \cdot s_{fg}$ (kJ/kg·K)



Isentropic Process

Ideal turbine expansion: $s_{in} = s_{out}$ — sets max efficiency

Isentropic Efficiency

$\eta_s = (h_1 - h_{2,actual})/(h_1 - h_{2,ideal})$ — real vs ideal turbine

Entropy Generation

$s_{gen} > 0$ always (2nd Law) — measures process irreversibility

Mollier Diagram

h–s chart is essential for all steam turbine cycle calculations

💡 The area enclosed by the T-s cycle diagram equals the net work output of the cycle — larger area = more work.

Core Property 5 — Specific Volume (v)

SPECIFIC VOLUME COMPARISON ACROSS STATES

Pipeline & Duct Sizing

v determines velocity; oversized ducts waste material, undersized cause high ΔP losses

Turbine Blade Design

Low-pressure turbine blades are huge because v is large — must accommodate volume flow

Boiler Drum Design

Specific volume ratio vg/vf determines steam separation and drum sizing requirements

Compressibility Factor

At supercritical pressures, v changes continuously — no sudden phase-change jump

0.001003 m³/kg

Water @25°C

1.674 m³/kg

Sat. Steam @100°C

0.1274 m³/kg

Sat. Steam @200°C

3.103 m³/kg

Superheated @400°C, 1 bar

Steam occupies ~1600× more volume than water at same T, P. This drives the huge size of low-pressure turbine stages.

Core Property 6 — Dryness Fraction (Quality, x)

$$x = m\_steam / (m\_steam + m\_water) \quad \text{where } 0 \le x \le 1$$

x=0 Pure Water	x=0.1	x=0.25	x=0.5 Mix	x=0.75	x=0.9	x=1 Dry Sat.

Enthalpy

$h = hf + x \cdot hfg$

Higher x → higher energy content

Entropy

$s = sf + x \cdot sfg$

Used in T-s diagram moisture tracking

Specific Volume

$v = vf + x \cdot vfg$

Determines two-phase pipe flow

Internal Energy

$u = uf + x \cdot ufg$

Closed system energy balance

⚙️ Turbine Design

$x < 0.88$ → blade erosion

📐 Steam Quality

Measured by calorimeter

🔧 Heat Exchangers

x determines flow regime

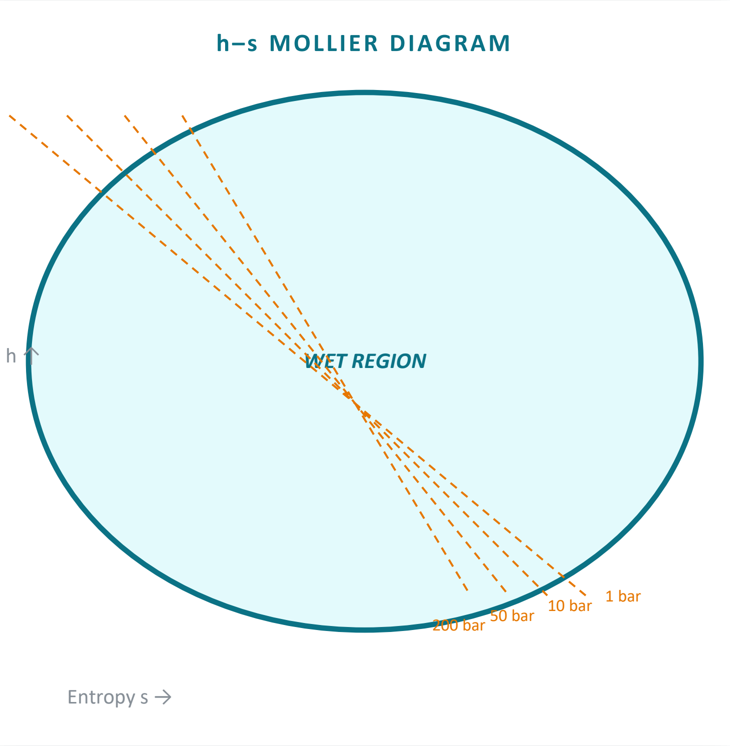
⚡ Energy Recovery

Higher x = more work

Engineering Tools — Steam Tables & Mollier Diagram

T (°C)	P (bar)	hf	hfg	hg	sf	sg	vg
100	1.013	419	2257	2676	1.307	7.355	1.674
150	4.758	633	2114	2747	1.841	6.837	0.393
200	15.54	852	1941	2793	2.331	6.430	0.127
250	39.78	1085	1716	2801	2.793	6.073	0.050
300	85.81	1345	1406	2751	3.255	5.705	0.022

(kJ/kg) (kJ/kg·K) (m^3/kg)



Steam tables → precise values at given T or P. Mollier chart → visualise cycle paths and read isentropic expansion graphically.

Process — How Steam Properties Evolve During Generation

Feed Water Pumping

Pump raises P from ~0.06→160 bar

→

Pre-heating (Economizer)

T rises from ~40→300°C (still liquid)

→

Evaporation (Steam Drum)

Boiling at const T & P
hf → hg (latent heat)

→

Superheating (Superheater)

T rises above T_sat
h increases by Cp·ΔT

→

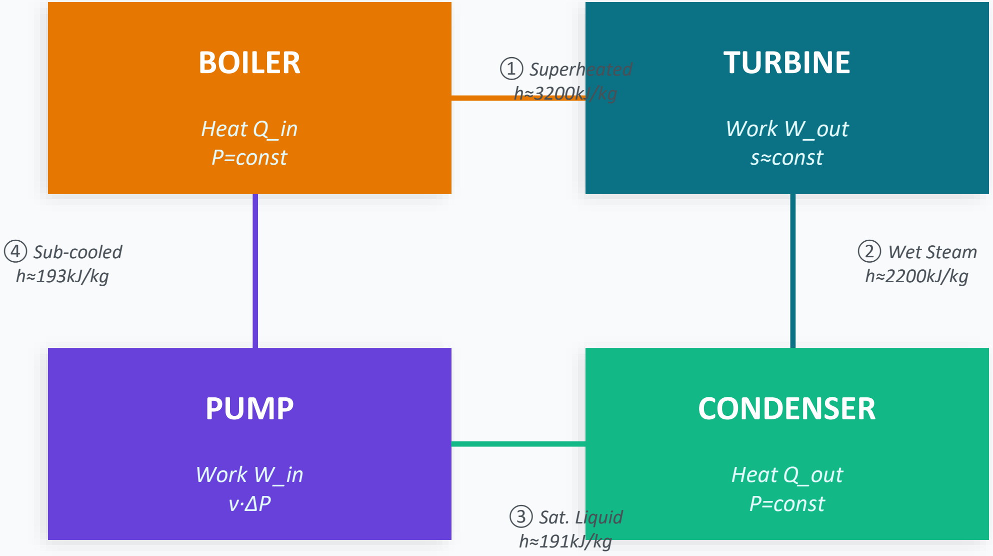
Turbine Expansion

h drops, work out
s ≈ const (ideal)

PROPERTY CHANGES THROUGH EACH STAGE

Stage	Pressure	Temperature	Enthalpy h	Phase
Pump	↑ +160 bar	≈ constant	+2 kJ/kg	Subcooled liq.
Econ.	≈ constant	↑ +200°C	+850 kJ/kg	Subcooled liq.
Evap.	≈ constant	constant (T_sat)	↑ +2257 kJ/kg	Wet → dry sat.
S.Htr	≈ constant	↑ +150°C	+450 kJ/kg	Superheated
Turb.	↓ to 0.1 bar	↓ to ~45°C	−1000 kJ/kg	Wet steam exit

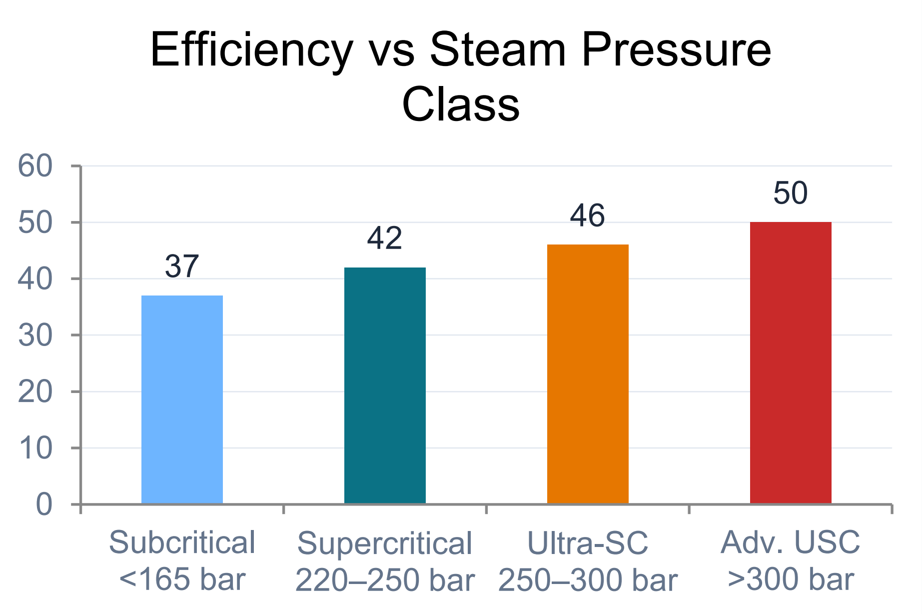
Rankine Cycle — Properties at Every State Point



RANKINE CYCLE PERFORMANCE EQUATIONS	
Turbine Work:	$w\_t = h_1 - h_2$
Pump Work:	$w\_p = h_4 - h_3 \approx v_3 \cdot (P_1 - P_3)$
Boiler Heat:	$q\_in = h_1 - h_4$
Condenser Heat:	$q\_out = h_2 - h_3$
Net Work:	$w\_net = w\_t - w\_p$
Efficiency:	$\eta = w\_net / q\_in = 1 - (q\_out/q\_in)$

📊 Typical η_Rankine = 35–45% (subcritical), 45–49% (USC) | Modern plants: $P_1 \approx 160–300$ bar, $T_1 \approx 540–620$°C

Applications — Power Generation (Property-Driven Design)



Subcritical Plant

Steam: < 165 bar, 540°C

Standard coal plant — steam properties well within wet region on exit

Supercritical Plant

Steam: 220–250 bar, 566°C

No distinct phase change — h and s change continuously with T

Ultra-Supercritical

Steam: 250–300 bar, 600°C

Nickel alloy steam pipes; 46% efficiency reduces CO_2 by 15%/MWh

15%	**850g**	**700g**	**30%+**
CO_2 reduction USC vs subcritical	CO_2/kWh subcritical coal plant	CO_2/kWh USC coal plant	Efficiency gain USC vs 1970s plants

Applications — Industrial Processes & HVAC

🍽️ Food Sterilisation

Saturated steam at 121°C / 2 bar (autoclave) kills all pathogens — WHO standard

📄 Paper & Pulp

Steam-heated cylinders at ~170°C dry paper webs; need precise T for quality

⚗️ Chemical Processes

Superheated steam as process fluid & carrier gas in steam reforming (H_2 prod.)

🏘️ District Heating

Saturated steam or hot water distributed to homes/offices at 2–8 bar

🧵 Textile Industry

Steam pressing at ~200°C removes wrinkles; dyeing at controlled T & P

💊 Pharmaceutical

Clean steam (pure water) for GMP sterilisation — no additives allowed

💡 Each application demands specific property combinations: sterilisation needs saturated steam's constant T; turbines need high h; heating needs latent heat.

Advantages — Why Steam Properties Make It Ideal

STEAM ADVANTAGES HIERARCHY

- Safe & Eco-Friendly Medium
- Versatile T-P Range
- High Latent Heat (2260 kJ/kg)
- Precise T Control via P
- Enormous Energy Density

✓ Energy Density

2260 kJ/kg latent heat — steam transports 5× more energy than equivalent hot water flow

✓ T-P Controllability

Saturation curve gives predictable temperature at any set pressure — ideal for process control

✓ Scalability

From 1 kW domestic boilers to 1,300 MW ultrasupercritical turbines — same thermodynamics

✓ Clean & Non-Toxic

Pure water/steam — no contamination risk; used in food, pharma, and medical applications

✓ Heat Recovery

Flash steam and condensate return recover 80–85% of invested energy in good systems

Challenges — Engineering Problems from Steam Properties

STEAM CHALLENGES

⚠ Corrosion

O_2 & CO_2 dissolved in feed water attack metal surfaces

⚠ Scale Deposits

$CaCO_3$ & $MgSO_4$ build-up reduces heat transfer 20%

⚠ Water Hammer

Condensate slugs create destructive pressure transients

⚠ Wet Steam Erosion

$x < 0.88$ causes droplet erosion of turbine blades

⚠ Heat Loss

Pipe insulation failure wastes 15–30% of transported heat

⚠ Safety Risk

High P/T steam explosions can be catastrophic

🔧 Solutions: chemical feed-water treatment, regular trap inspection, blade moisture extraction, pressure relief valves, insulation audits.

Future Trends — Advanced Steam Technology & Innovation

STEAM TECHNOLOGY TIMELINE

1800s — *Saturated steam engines (Watt)*

1920s — *Superheated steam turbines (Parsons)*

1960s — *Subcritical power plants 37% eff.*

2010s — *Ultra-supercritical 600°C / 300 bar*

2030+ — *700°C A-USC & sCO_2 hybrid*

🏭 700°C A-USC Steam

Nickel alloy components target >50% efficiency; EU COMTES700

🔬 Supercritical CO_2

sCO_2 Brayton cycle: smaller turbines, higher density fluid

☀️ Solar Steam

CSP plants: parabolic troughs generate 550°C superheated steam

🤖 AI Property Prediction

ML models predict steam properties beyond table ranges

💧 Hydrogen Economy

Steam methane reforming (SMR) & electrolysis use steam heavily

📱 Digital Twin Boilers

Real-time property simulation optimises combustion & steam flow

PROPERTIES OF STEAM — MASTER SUMMARY

PRESSURE	TEMPERATURE	ENTHALPY	ENTROPY	SPEC. VOL.	DRYNESS
P	**T**	**h**	**s**	**v**	**x**
Unit: bar/Pa	*Unit: °C/K*	*Unit: kJ/kg*	*Unit: kJ/kg·K*	*Unit: m^3/kg*	*Unit: –*
P = F/A	T_sat = f(P)	h=u+Pv hg=hf+hfg	ds=δQ/T s=sf+x·sfg	v=1/ρ v=vf+x·vfg	x=mg/(mg+mf)
Drives T_sat & energy content	*Governs phase & superheat degree*	*Turbine work $w=h_1-h_2$*	*Cycle efficiency η = 1−T_L/T_H*	*Pipe & turbine blade sizing*	*Steam quality & turbine safety*

KEY RELATIONS: η = w_net/q_in | h=u+Pv | ds=δQ/T | v=vf+x·vfg | T-s area = net work | x=m_steam/m_total

KEY TAKEAWAYS

01

Six Core Properties Define Steam Behaviour

Pressure, temperature, enthalpy, entropy, specific volume, and dryness fraction together fully describe any steam state.

02

Properties Directly Drive Engineering Decisions

Equipment sizing, efficiency calculations, safety limits, and operating procedures are all founded on steam property data.

03

Steam Tables & Mollier Diagram Are Essential Tools

These encode all property relationships — mastering their use is a fundamental engineering skill in thermodynamics.

04

Higher P & T → Higher Efficiency & More Work Output

Ultra-supercritical plants achieve 46–49% efficiency vs 37% for subcritical, cutting CO_2 by ~20% per kWh generated.

05

Properties Underpin Both Advantages & Challenges

The same properties that make steam powerful (high h, large v) create engineering challenges (erosion, water hammer, corrosion).

"Understanding steam properties is understanding the language of thermal engineering."