Integrated Study Guide – Applied Thermodynamics and Boiler Operations

Based on official syllabus (Units 1–6)

For continuous learning, class exercises, and exam revision

How to Use This Guide

- Read each unit in sequence.
- After each section, attempt the **Self-Check Questions**.
- Use the **Key Equations & Tables** summary at the end for quick reference.
- Diagrams should be practiced by hand – exam questions often ask for sketches.

Unit 1 – Introduction & Properties of Steam

Essential Definitions

Term	Definition
Thermodynamic property	A measurable characteristic of a system (P, T, v, u, h, s)
Intensive property	Independent of mass (P, T, density)
Extensive property	Depends on mass (V, U, H, S)
State	Condition defined by properties
Phase	Homogeneous region (solid, liquid, vapour)
Change of state	Process from one equilibrium state to another
Specific internal energy (u)	Energy per unit mass due to molecular motion + bonding
Specific enthalpy (h)	h = u + Pv – useful for flow systems
Specific volume (v)	Volume per unit mass (inverse of density)

Two-Phase Mixtures (Wet Steam)

- **Dryness fraction (x)** = mass of vapour / total mass
  $0 \le x \le 1$
- **Property equations** for any intensive property Y (v, h, u, s):
  $Y = Y_f + x \cdot Y_{fg}$ where $Y_{fg} = Y_g – Y_f$
- **Saturated liquid** (x=0), **Saturated vapour** (x=1)
- **Superheated steam** – above saturation temperature at given P

Steam Tables (How to use them)

- **Saturation tables** (Temperature or Pressure) give Tsat, P, v_f, v_g, h_f, h_fg, h_g, s_f, s_g, etc.
- **Superheat tables** – at a given pressure and superheat temperature.
- **Interpolation** – when your P or T is not listed, do linear interpolation between nearest values.

Calorimeters (Dryness fraction measurement)

Type	Principle	Limitation
Separating	Mechanically separates moisture	Underestimates dryness if water droplets are carried
Throttling	Throttles to superheated region, uses superheat temp	Only works if final state is superheated
Combined	Separator + throttling	Accurate for very wet steam

Formula for throttling calorimeter:

h_1 (wet) = h_2 (superheated) → $h\_f1 + x_1\, h\_fg1 = h_2$ at P_2, T_2 → solve for x_1

Phase Diagrams (You must be able to sketch)

- **P-T diagram** (triple point, critical point, fusion/sublimation/vapourization curves)
- **P-v diagram** (saturation dome, constant temperature lines)
- **T-h and P-h diagrams** (useful for refrigeration)

Self-Check Questions (Unit 1)

1. Differentiate between specific internal energy and specific enthalpy.
2. Steam at 1.5 MPa has dryness fraction 0.9. Calculate h, v, and u using steam tables.
3. Why is superheated steam preferred for electricity generation?
4. Sketch the P-v diagram for water and label: saturated liquid line, saturated vapour line, critical point, wet region, superheat region.

Unit 2 – Thermodynamic Systems & Processes

Systems & Energy Conservation

- **Closed system** (control mass) – no mass transfer. First law: $\Delta U = Q - W$
- **Open system** (control volume) – mass flows. Steady Flow Energy Equation (SFEE):
  $Q - W = \dot{m} [(h_2 - h_1) + ½(V_2^2 - V_1^2) + g(z_2 - z_1)]$

- **Simplifications for common devices**:
  - Turbine/compressor: $W = \dot{m} (h_1 - h_2)$ (adiabatic, negligible KE/PE)
  - Nozzle/diffuser: $½(V_2^2 - V_1^2) = h_1 - h_2$
  - Boiler/condenser: $Q = \dot{m} (h_2 - h_1)$ (no work, negligible KE/PE)

Polytropic Process

- Law: PV^n = constant
- Work for closed system: $W = (P_2V_2 - P_1V_1)/(1 - n)$ ($n \neq 1$)
- Special cases:
  - n=0: isobaric (constant P)
  - n=1: isothermal (constant T, ideal gas only)
  - n=γ: isentropic (reversible adiabatic)
  - n=∞: isochoric (constant V)

Adiabatic vs Isothermal

- **Adiabatic** – no heat transfer (Q=0). Real processes are often nearly adiabatic (insulated).
- **Isothermal** – constant temperature. Requires perfect heat transfer.
- On a P-V graph, the adiabatic curve is steeper than the isothermal for an ideal gas.

Self-Check Questions (Unit 2)

1. Derive the SFEE for a steam turbine. Start from the general form and state your assumptions.
2. 0.2 kg of air (ideal gas) expands polytropically with n=1.3 from 500 kPa, 150°C to 100 kPa. Find final temperature and work done. (R=0.287 kJ/kgK)
3. Sketch P-V curves for isothermal and adiabatic compression of an ideal gas. Explain which requires more work.

Unit 3 – Second Law of Thermodynamics & Vapour Cycles

Second Law Statements

- **Kelvin-Planck**: It is impossible to construct a heat engine that converts all heat from a reservoir into work (some heat must be rejected).
- **Clausius**: Heat cannot spontaneously flow from a cold body to a hot body without external work.
- **Carnot efficiency** (maximum possible): $\eta = 1 - T_L/T_H$ (temperatures in Kelvin)

Entropy (s)

- For a reversible process: $\Delta S = \int dQ/T$
- For any process: $\Delta S_{total} \geq 0$ (increase in entropy principle)
- **Reversible adiabatic = isentropic** ($s_1 = s_2$)
- Use steam tables: for wet steam $s = s_f + x\, s_{fg}$
- T-s diagram for water – constant pressure lines slope upward, saturation dome.

Vapour Cycles (Examination focus – Rankine cycle especially)

Rankine cycle (ideal steam power plant):
1→2 Pump (isentropic compression)
2→3 Boiler (constant pressure heat addition)
3→4 Turbine (isentropic expansion)
4→1 Condenser (constant pressure heat rejection)

- $\eta_{Rankine} = (h_3 - h_4) / (h_3 - h_2)$ (pump work often neglected in simple calculations)
- Pump work: $W_{pump} = v_1 (P_2 - P_1)$ in kJ/kg (v_1 = specific volume of saturated liquid at condenser pressure)

Other cycles you must know (compare to Rankine):

- **Carnot** – same two reservoirs, but impractical for steam.
- **Otto** (spark ignition) – constant volume heat addition.
- **Diesel** – constant pressure heat addition.
- **Brayton** (gas turbine) – compressor, combustor, turbine.
- **Stirling** – external heat, regenerator.

Efficiency ratio = (actual cycle efficiency) / (Carnot efficiency at same T limits)

Self-Check Questions (Unit 3)

1. State the Kelvin-Planck and Clausius statements of the second law. Show they are equivalent.
2. A Rankine cycle uses boiler at 4 MPa, 400°C and condenser at 10 kPa. Find cycle efficiency (neglect pump work). Use steam table values.
3. Explain why the Carnot cycle is not practical for steam power plants.
4. Steam at 2 MPa, 300°C expands isentropically in a turbine to 0.1 MPa. Determine the final dryness fraction (if wet) or temperature (if superheated).

Unit 4 – Boiler Types & Mountings

Fire-Tube (Smoke Tube) Boilers

- **Lancashire**: Two internal flues, low pressure (≤10 bar). Large water volume.
- **Economic two-pass dry back**: Reversal chamber not water-cooled → higher metal temps. ≤17 bar.
- **Economic three-pass wet back**: Reversal chamber submerged in water → longer life. ≤20 bar.
- **Packaged boiler**: Factory assembled, compact, quick installation. ≤30 bar.
- **Exhaust gas boiler**: Uses engine/GT exhaust heat. Often supplementary fired.

Water-Tube Boilers (sketch required)

- **General**: Water inside tubes, hot gas outside. Faster response, higher pressure.
- **Key parts**: Steam drum, mud drum, headers, risers, downcomers.
- **Common layouts**: D-type, A-type, O-type.
- **Economizer**: Uses flue gas to preheat feedwater (improves efficiency ~1% per 6°C reduction in flue gas temp).
- **Superheater**: Located in hottest flue gas zone to raise steam temperature above saturation.

Boiler Mountings (must name, locate, and state purpose)

Mounting	Purpose	Test / Maintenance
Safety valves	Prevent overpressure (lift at MAWP)	Daily hand-lift test; annual pop test
Main steam stop valve	Isolate boiler from steam line	Check for leaks
Feed check valve (non-return)	Allow water in, prevent backflow	Ensure disc seats properly
TDS blowdown valve	Remove dissolved solids	Continuous or periodic
Bottom blowdown valves	Remove sludge from mud drum	Open daily (quickly)
Pressure gauge	Display steam pressure	Blowdown siphon periodically
Gauge glass & water level controls	Indicate and maintain water level	Daily blowdown glass; test low-water cutoff
Air vent	Release air during startup	Open until steam appears
Vacuum breaker	Prevent vacuum on shutdown	Check after shutdown

Self-Check Questions (Unit 4)

1. Draw a cross-section of a three-pass wet-back fire-tube boiler. Label furnace, tubes, reversal chamber, and flue gas outlet.
2. Compare fire-tube and water-tube boilers for: (a) pressure capability, (b) steam generation rate, (c) risk of explosion.
3. Explain why a boiler must have at least two safety valves.
4. Describe the daily test for a low water cutoff.

Unit 5 – Boiler Efficiency & Combustion

Combustion Basics

- **Complete combustion**: C → CO_2, H_2 → H_2O (all chemical energy released)
- **Excess air**: Air supplied above theoretical. Typical:
  - Natural gas: 15–20% excess
  - Oil: 10–15% excess
  - Coal: 20–50% excess
- **Too little air** → CO, smoke, unburned fuel (inefficient, dangerous)
- **Too much air** → heat lost up stack (lower efficiency)

Boiler Efficiency Methods

Direct method: η = (steam energy output) / (fuel energy input)
$\eta = [\dot{m}_{steam} (h_{steam} - h_{feed})] / (\dot{m}_{fuel} \times CV)$

Indirect (loss) method (more accurate for exams):

$\eta = 100 - (L1+L2+L3+L4+L5+L6)\%$

- L1 = Dry flue gas loss (largest)
- L2 = Loss due to H_2 in fuel (forms water vapour)
- L3 = Loss from moisture in fuel/air
- L4 = Unburned carbon in ash
- L5 = Radiation & convection loss (1–2%)
- L6 = Blowdown loss

Burner Types (must describe operation)

Burner	Fuel	Working principle
Pressure jet	Oil	Oil at 10–30 bar through small nozzle, atomises
Rotary cup	Heavy oil	Rotating cup flings oil into primary air
Low pressure gas	Gas	Gas at <50 mbar, air injected by venturi
High pressure gas	Gas	Gas at >50 mbar, nozzle mixing

Fuel Oil System (block diagram sequence)

Settling tank → Sludge valve → Strainer → Transfer pump → Heater → Fine filter → Burner pump → Burner nozzle

- **Settling tank**: Water & heavy solids settle. Drained via sludge valve.
- **Safety devices**: Flame scanner, safety shutoff valves, pressure switches.

Self-Check Questions (Unit 5)

1. A boiler burns natural gas with 20% excess air. Will the CO_2 percentage in flue gas be higher or lower than at stoichiometric? Why?
2. List the main heat losses in a boiler. Which is usually the largest?
3. Describe the operating sequence for an automatic oil burner from startup to full load.
4. What is the purpose of a settling tank in an oil fuel system? How often should sludge valves be opened?

Unit 6 – Water Treatment & Operation

Water Treatment Objectives

1. Prevent scale (hardness removal)
2. Prevent corrosion (control pH, remove oxygen)
3. Prevent carryover (control TDS, alkalinity)

External Treatment (before boiler)

Process	Removes
Ion exchange (softening)	Ca^{2+}, Mg^{2+} (replaces with Na^{+})
Dealkalisation	Bicarbonate alkalinity
Demineralisation	All dissolved minerals (pure water)

Internal Treatment (inside boiler)

- **Phosphate** – precipitates Ca as sludge (blowdown removes)
- **Oxygen scavenger** (sodium sulfite) – removes dissolved O_2
-
- **pH control** – add alkali to maintain 8.5–11

Steam Quality & Carryover

- **Good steam**: dry (x close to 1), clean, no air/incondensable gases.
- **Carryover causes**: high TDS, foaming (oil contamination), sudden load increase.
- **Prevention**: proper blowdown, avoid oil, install steam separator.

Steam Circuit (Sketch required)

Boiler → Stop valve → Steam main → Process/equipment → Condensate return → Condensate tank → Feed pump → Economizer → Boiler

Pressure Distribution

- **Upper limit**: Boiler MAWP
- **Lower limit**: Minimum pressure required at farthest consumer
- **Pressure drop causes**: Pipe friction, condensation (reduces volume)

Critical Operating Procedures (Exam favourite)

Procedure	Key Steps
Raising steam (cold)	1. Check water level 2. Open vent 3. Purge furnace 4. Ignite low fire 5. Warm slowly 6. Close vent at 1-2 bar 7. Blowdown gauge glass 8. Test safety valves at 75% MAWP
Low water emergency	**SHUT OFF FUEL IMMEDIATELY** Close main steam valve. Do NOT add water. Let cool naturally.
High water level	Reduce feed, blowdown to lower level.
Parallel operation	Equalise pressure, open stop valve slowly, share load by adjusting firing rate.
Blowdown (bottom)	Open quickly for 5–10 seconds, close fully. Repeat. Only at <15 psi after shutdown.

Safety Device Testing

- **Low water cutoff** – Test daily by blowing down float chamber (burner should trip).
- **Gauge glass** – Blow down daily: steam side, water side, then both.
- **Safety valve** – Hand-lift weekly (under pressure). Annual pop test.

Self-Check Questions (Unit 6)

1. What immediate action must an operator take upon discovering a low water condition?
2. Why is oil contamination in feedwater dangerous?
3. Sketch and label a basic steam circuit (closed loop) including all major components.
4. Describe the correct sequence for placing a newly repaired boiler into service and coupling it to a running steam header.
5. A boiler water sample shows pH = 12.2 and high conductivity. Is this acceptable? What corrective action?

Key Equations Summary

Topic	Equation
Dryness fraction properties	Y = Y_f + x Y_fg
Ideal gas	$PV = mRT$
Steady flow energy	$Q - W = \dot{m}[\Delta h + \Delta KE + \Delta PE]$
Polytropic work (closed)	$W = (P_2V_2 - P_1V_1)/(1-n)$
Carnot efficiency	$\eta = 1 - T\_L/T\_H$
Rankine efficiency (simple)	$(h_3 - h_4)/(h_3 - h_2)$
Rankine pump work	$W\_pump = v_1(P_2 - P_1)$
Boiler efficiency direct	$\eta = \dot{m}\_s(h\_s - h\_fw) / (\dot{m}\_f \times CV)$
Boiler blowdown %	(Cl_feed / Cl_boiler) × 100
Entropy change (rev)	$\Delta S = \int dQ/T$
Isentropic turbine work	$W\_t = \dot{m} (h_3 - h_4s)$

Steam Table Extract (for practice)

Use actual steam tables from your course. Example values for learning:

P (MPa)	Tsat (°C)	h_f (kJ/kg)	h_fg (kJ/kg)	h_g (kJ/kg)	s_f (kJ/kgK)	s_g (kJ/kgK)
0.1	99.63	417.5	2257.5	2675.0	1.3026	7.3589
1.0	179.88	762.8	2015.3	2778.1	2.1387	6.5865
4.0	250.40	1087.3	1712.9	2800.2	2.7964	6.0701

Additional Support

For assistance with research or accessing resources such as past papers, visit the CMU Library or contact:

📩 **Email:** library@cmu.edu.jm/cmulibrary123@gmail.com

WhatsApp: (876) 564-4274

📞 **Phone:** University Librarian – (876) 809-3103

📖 **Librarians:** (876) 833-2187; (876) 781-1178; (876) 564-4274

Prepared by: CMU Library, Information Resources and Digital Services

Prepared: April 2026