

ME 322: THERMODYNAMICS • UNIT 2 EXAM CHEAT SHEET (PAGE 1 / 2)

CLOSED SYSTEMS, BOUNDARY WORK, FIRST LAW & THERMAL-FLUID PROPERTIES • Reference: ME 322 Equation Sheet

PRESSURE, TEMPERATURE, AND DENSITY (EQUATION SHEET BASE)

Force & Pressure Relationships:

- $F = P \cdot A$
- $P = P_g + P_{atm}$ • $P_{vac} = P_{atm} - P_a$
- $P_a = 101.33 \text{ kPa} = 14.70 \text{ psia}$
- $g = 9.81 \text{ m/s}^2 = 32.2 \text{ ft/s}^2$
- **Units:** 1 bar = 100 kPa = 0.1 MPa = 10^5 Pa = 14,504 psi
- 1 psi = 144 lbf/ft² • 1 kPa = 1 kN/m² = 1000 N/m²
- 1 Btu = 778.17 ft·lbf = 1.055 kJ • 1 kJ = 1 kPa·m³

Temperature Scales, Ideal Gas Law & Constants:

- $T_K = T_C + 273$ • $T_R = T_F + 460$
- $T_R = (9/5) T_K$ • $T_F = (9/5) T_C + 32$ • $T_{std.atm} = 293 \text{ K}$ or 530 R
- $P \cdot V = R \cdot T$ • $P \cdot V = m \cdot R \cdot T$ • $\bar{P} = \rho \cdot R \cdot T$
- $\rho = 1 / v$ • $R = R_u / M$
- $R_u = 8314.4 \text{ J/kmol} \cdot \text{K} = 1.9859 \text{ Btu/lbmol} \cdot \text{R} = 1545.0 \text{ ft} \cdot \text{lbf/lbmol} \cdot \text{R}$

THERMAL-FLUID PROPERTIES (EQUATION SHEET BASE) & PHASE DETERMINATION

Mixture Quality & Property Relations:

- $x = m_{vap} / m_{tot}$ • $x = (f \cdot f_g) / f_{fg}$ • $f = f_f + x \cdot f_{fg}$
- $f_g = f_g^{vap} - f_f$ • $f \in \{v, u, h, s\}$
- $U = m \cdot u$ • $U_{mix} = m_{mix} \cdot u$ • $H = m \cdot h$ • $H_{mix} = m_{mix} \cdot h$
- $W = m \cdot w$ • $W_{mix} = m_{mix} \cdot w = W / \Delta t$ • $Q = m \cdot q$ • $Q_{mix} = m_{mix} \cdot q = Q / \Delta t$
- $V = m \cdot v$ • $h = u + P \cdot v$
- $C = C_v + R$ • $k = C_p / C_v$ • $C = C_v = C_p$ (incompressible)
- $Q_{solid} = m \cdot h_{if}$ • $Q_{evap} = m \cdot h_{fg}$

Specific Heats, Processes & Phase Determination:

- $du = C_v dT$ • $dh = C_p dT$
- $u_2 - u_1 = C_{v@Tavg} (T_2 - T_1)$ • $h_2 - h_1 = C_{p@Tavg} (T_2 - T_1)$
- $P \cdot v^n = \text{const}$ • Isentropic: $n = k$
- Phase Identification Rules:**
- *Given* (P, T): $T < T_{sat}(P) \Rightarrow$ **Compressed Liq** ($v \approx v_f(T)$, $u \approx u_f(T)$, $h \approx h_f(T)$)
- $T = T_{sat}(P) \Rightarrow$ **Saturated Mixture** (find x) • $T > T_{sat}(P) \Rightarrow$ **Superheated**
- *Given* (P, y) or (T, y): $y < y_f \Rightarrow$ Compressed Liq | $y_f \leq y \leq y_g \Rightarrow$ Mixture | $y > y_g \Rightarrow$ Superheated
- **Incompressible Liquid:** $\Delta u = c \cdot \Delta T$ • $\Delta h = c \cdot \Delta T + v \cdot \Delta P$ • Pump: $w = v \cdot \Delta P$

BOUNDARY WORK INTEGRAL & WORK FORMS (ISOMETRIC TERMINOLOGY)

Process Path	Governing Equation / Condition	Boundary Work Expression $W_{out} = \int P dV$
General Definition	$W = \int_1^2 P dx$	$W_{out} = \int_1^2 P dV$ (Area under P-V process curve)
Isometric	$V = \text{const} \Rightarrow dV = 0$	$W_{out} = 0$ (No boundary work in rigid tank / isometric process)
Isobaric	$P = \text{const}$	$W_{out} = P(V_2 - V_1) = m \cdot P(v_2 - v_1)$
Isothermal	$T = \text{const}$ (Ideal Gas)	$W_{out} = P_1 V_1 \ln(V_2 / V_1) = m R T \ln(V_2 / V_1) = P_1 V_1 \ln(P_1 / P_2)$
Polytropic	$P \cdot v^n = \text{const}$ ($n \neq 1$) Exponent: $n = \ln(P_2/P_1) / \ln(V_1/V_2)$	$W_{out} = (P_2 V_2 - P_1 V_1) / (1 - n) = m R (T_2 - T_1) / (1 - n)$ (If $n = k \Rightarrow$ Isentropic; If $n = 0 \Rightarrow$ Isobaric; If $n = 1 \Rightarrow$ Isothermal)
Spring Piston	$P = P_1 + (k / A^2) \Delta V$ (Linear P-V trapezoid)	$W_{out} = [(P_1 + P_2)/2] \cdot (V_2 - V_1) = P_1 \Delta V + \frac{1}{2} k_s x^2$ Spring stored work: $W_{spring} = \frac{1}{2} k_s x^2 = \frac{1}{2} k_s (\Delta V / A)^2 \cdot W_{atm} = P_{atm} \Delta V$
Shaft & Electric	Shaft: $W_{sh} = 2\pi n T = \omega T$ Electric: $W_e = V \cdot I = I^2 R$	Drivetrain balance: $W_{turb} = W_{comp} + W_{gen}$ Electric work over time: $W_e = V \cdot I \cdot \Delta t$ (Watts = J/s)

FIRST LAW FOR CLOSED SYSTEMS & ISOBARIC HEATING RULE

1st Law for Closed Systems (Mass is fixed):

- $E_{in} - E_{out} = \Delta E_{sys}$ • $Q_{in} - W_{out} = m(u_2 - u_1)_{sys}$
- *Rate form:* $\dot{Q}_{in} - \dot{W}_{out} = dE_{sys}/dt = m(du/dt)_{sys}$
- **Sign Convention:** $Q_{in} > 0$, $Q_{out} < 0$ | $W_{out} > 0$ (expansion), $W_{in} < 0$ (compression)
- **Thermodynamic Cycle:** $\Delta U_{cycle} = 0 \Rightarrow \dot{W}_{net,out} = Q_{net,in} = Q_{in} - Q_{out}$

Constant-Pressure Heating (P = const with Boundary Work):

- $Q_{in} - W_{b,out} = \Delta U = (U_2 - U_1) + P(V_2 - V_1)$
 - $Q_{in} = (U_2 + PV_2) - (U_1 + PV_1) = H_2 - H_1$
 - $Q_{in} = \Delta H = m(h_2 - h_1) = m \cdot \bar{C}_p \cdot (T_2 - T_1)$
- CRITICAL RULE:** For closed constant-P process with boundary work only, Heat Added = Change in Enthalpy!

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CONSERVATION OF MASS, FIRST LAW FOR OPEN FLOW (SFEE) & ALL 6 STEADY-FLOW DEVICES • Reference: ME 322 Equation Sheet

CONSERVATION OF MASS & FIRST LAW FOR CONTROL VOLUMES (EQUATION SHEET BASE)

Conservation of Mass (Continuity):

- $m = \rho V A = V A / v \cdot V = V A$
- $\sum m = \sum m + dm/dt$
- $\sum m = \sum m + [m_2 - m_1]_{CV}$
- *Steady-Flow Single Stream:* $m_1 = m_2 \Rightarrow (A_1 V_1)/v_1 = (A_2 V_2)/v_2$
- **Energy Components & Pump Equation:**
- $ke = \frac{1}{2} V^2 \cdot KE = \frac{1}{2} m V^2 \cdot KE = \frac{1}{2} m V^2$ (kJ/kg: $V^2/2000$)
- $pe = g z \cdot PE = m g z \cdot PE = m g z$ (kJ/kg: $gz/1000$)
- $W_{pump} = m v (P_{out} - P_{in}) = m (P_{out} - P_{in}) / \rho$

1st Law for Open Flow Systems (Control Volumes):

- $E_{in} - E_{out} = \Delta E_{sys}$
- $Q_{in} - W_{out} = m(h_{out} - h_{in})_{CV}$ (Single stream steady)
- $Q_{in} - W_{out} + \sum m_i (h_i + ke_i + pe_i) - \sum m_o (h_o + ke_o + pe_o) = [m_2(u_2 + ke_2 + pe_2) - m_1(u_1 + ke_1 + pe_1)]_{sys}$ (Unsteady USUF)
- $Q_{in} - W_{out} + \sum m_i (h_i + ke_i + pe_i) - \sum m_o (h_o + ke_o + pe_o) = (d/dt)[m(u + ke + pe)]_{CV}$ (General rate equation)

MASTER STEADY-FLOW ENGINEERING DEVICES MATRIX (DIAGRAMS, TRENDS & FORMULAS)

Device & Schematic	Key Assumptions	Property Trends	Governing Energy & Sizing Equations
Nozzle & Diffuser [Nozzle: $A \downarrow, V \uparrow$ Diffuser: $A \uparrow, V \downarrow$]	$W = 0$ $Q = 0$ (adiabatic) $\Delta pe = 0$	Nozzle: $V \uparrow \uparrow, P \downarrow, T \downarrow, h \downarrow$ Diffuser: $V \downarrow \downarrow, P \uparrow, T \uparrow, h \uparrow$	$h_1 + V_1^2/2000 = h_2 + V_2^2/2000$ Exit Velocity: $V_2 = \sqrt{V_1^2 + 2000(h_1 - h_2)}$ (If $V_1=0 \Rightarrow V_2 = \sqrt{2000\Delta h}$) Exit Area: $A_2 = (m \cdot v_2) / V_2$ • If heat loss $Q \neq 0$: $Q/m = (h_2 - h_1) + \Delta ke$
Turbine [Expanding casing • Shaft Work OUT]	$W_{out} > 0$ $Q = 0$ (or heat loss) $\Delta ke = 0, \Delta pe = 0$	$P \downarrow \downarrow, T \downarrow \downarrow, h \downarrow \downarrow$ Fluid expands and turns shaft blades.	$W_{turb,out} = m(h_1 - h_2) \cdot \text{Ideal Gas: } W_{turb} = m \cdot c_p \cdot (T_1 - T_2)$ With heat loss: $W_{turb} = m(h_1 - h_2) - Q_{loss}$ Specific power: $w_{out} = h_1 - h_2$ [kJ/kg]
Compressor (Gas) Pump (Liquid) [Shaft Work IN]	$W_{in} > 0$ $Q = 0$ (adiabatic) $\Delta ke = 0, \Delta pe = 0$	$P \uparrow \uparrow, T \uparrow, h \uparrow$ Work is consumed to pressurize fluid.	Compressor (Gas): $W_{comp,in} = m(h_2 - h_1) = m \cdot c_p \cdot (T_2 - T_1)$ Pump (Incompressible Liquid): $W_{pump,in} = m \cdot v \cdot (P_2 - P_1) = m \cdot \Delta P / \rho$ With Δke : $W_{pump} = m[v \cdot (P_2 - P_1) + (V_2^2 - V_1^2)/2000]$
Throttling Valve [Orifice, porous plug, expansion valve]	$W = 0$ $Q = 0$ (adiabatic) $\Delta ke = 0, \Delta pe = 0$	ISENTHALPIC: $h_1 = h_2$ $P \downarrow \downarrow$ (large pressure drop)	$h_2 = h_1$ (Constant Enthalpy!) • Ideal Gas: Since $h = c_p T$, $T_2 = T_1$ (No temperature change!) • Wet Liquid-Vapor (Refrigerant/Steam): $T \downarrow \downarrow$ drastically to $T_{sat}(P_2)$. Exit quality: $x_2 = (h_1 - h_f) / h_{fg}$ • $u_2 = h_1 - P_2 v_2$
Mixing Chamber [T-junction, open feedwater heater]	$W = 0$ $Q = 0$ (well insulated) $\Delta ke = 0, \Delta pe = 0$	$P_1 = P_2 = P_3 = P$ Streams mix at common pressure.	Mass: $m_1 + m_2 = m_3$ • Energy: $m_1 h_1 + m_2 h_2 = m_3 h_3$ Mass ratio: $m_1 / m_2 = (h_3 - h_2) / (h_1 - h_3)$ • (For ideal gas: $(T_3 - T_2)/(T_1 - T_3)$)
Heat Exchanger [Shell-and-tube, radiator, condenser]	$W = 0$ $\Delta ke = 0, \Delta pe = 0$ Fluids do NOT mix.	Hot fluid: $P = \text{const}, T \downarrow$ Cold fluid: $P = \text{const}, T \uparrow$	• Entire Exchanger (Insulated): $m_{hot}(h_{hot,in} - h_{hot,out}) = m_{cold}(h_{cold,out} - h_{cold,in})$ • Single Stream: $Q_{cold} = m_{cold}(h_{c,out} - h_{c,in})$ • $Q_{hot} = m_{hot}(h_{h,in} - h_{h,out})$ • Non-Insulated: $Q_{hot} = Q_{cold} + Q_{loss}$ (If 10% lost $\Rightarrow Q_{cold} = 0.90 Q_{hot}$)

UNSTEADY FLOW (USUF) & TOP 8 HIGH-YIELD EXAM PITFALLS CHECKLIST

Unsteady Uniform-State Uniform-Flow (USUF):

- **Mass Balance:** $m_1 - m_2 = (m_2 - m_1)_{CV}$
- **Energy Balance:** $Q - W + \sum m_i u_i - \sum m_o u_o = (m_2 u_2 - m_1 u_1)_{CV}$
- **Evacuated Tank Filling (Adiabatic, $m_1=0, W=0, Q=0$):**
 $u_2 = h_{line} \Rightarrow \text{For Ideal Gas: } c_p T_2 = c_p T_1 \Rightarrow T_2 = k \cdot T_{line}$
(The tank temperature is ALWAYS hotter than the supply line by factor $k \approx 1.4$!)

Top 8 High-Yield Exam Pitfalls & Traps Checklist:

1. Gage vs Absolute: $P_{abs} = P_{gage} + 14.7 \text{ psi}$ (or $+ 101.3 \text{ kPa}$). Never put gage into $P = \rho R T$!
2. Absolute Temperature: Any single T in formulas MUST be in Kelvin (K) or Rankine (R).
3. Kinetic Energy Conversion: Divide V^2 by 2000 (SI, kJ/kg) or 50,074 (English, Btu/lbm).
4. Throttling Temperature: Ideal gas $\Rightarrow T_1 = T_2$. Refrigerant/steam $\Rightarrow T$ drops to $T_{sat}(P_2)$.
5. Constant-Pressure Heating: For closed system with boundary work, $Q = \Delta H = m(h_2 - h_1)$.
6. Spring Piston: P is linear with V . Boundary work is trapezoid: $W_b = \frac{1}{2}(P_1 + P_2)\Delta V$.
7. Pump Work: $w_{pump} = v(P_{out} - P_{in})$. Use $v = v_f$ at inlet temp. Divide by 5.404 for Btu/lbm.
8. Work Signs: Expansion = $+W_{out}$. Compression/Pump = $+W_{in}$. Turbine produces = $+W_{turb}$.