


# Ch. 3

## Conservation of Energy



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# Outline

**1. Conservation of Energy**

**2. Examples**

**3. Thermodynamic Properties of Matter**

# The goals of this chapter

- Use the differential form of pure component energy balance in problem solving.
- Use the difference form of pure component energy balance in problem solving.
- Compute changes in energy with changes in  $T$  and  $P$  for the ideal gas
- Compute changes in energy with changes in  $T$  and  $P$  for real liquids using tables and charts of thermodynamic properties

# The conservation of Energy

◆  $\theta = U + M (v^2/2 + \psi)$

$U$ : total internal energy

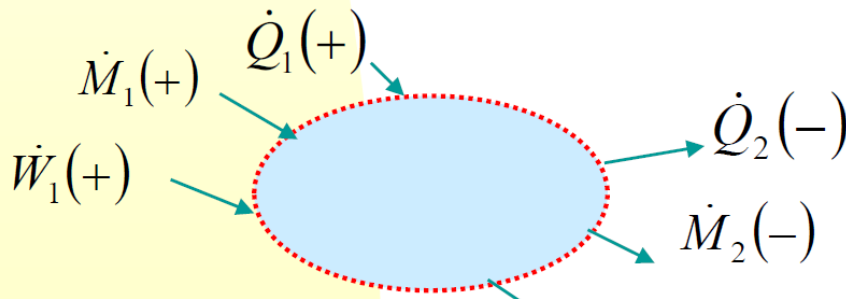
$v^2/2$ : kinetic energy per unit mass

$\psi$ : potential energy per unit mass

$\theta_{gen} = 0$  (energy is a conserved property)

◆ Energy balance equation

$$\frac{d}{dt} \left\{ U + M \left( \frac{v^2}{2} + \psi \right) \right\}_{system} = (\text{Rate at which energy enters the system}) - (\text{Rate at which energy leaves the system})$$



# Energy flow, heat and work

- ❖ Energy flow accompanying mass flow  $\sum \dot{M}_k (\hat{U} + v^2 / 2 + \psi)_k$
- ❖ Heat  $\dot{Q} = \sum \dot{Q}_j$
- ❖ Work:
  - ❖ Shaft work ( $W_s$ ): The mechanical energy flow that occurs without a deformation of the system boundaries (including electrical energy).

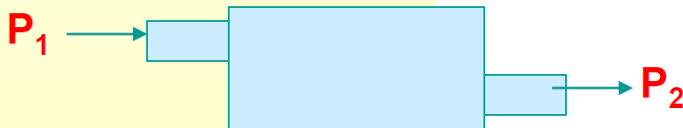
$\dot{W}_s(+)$ : surroundings do work on the system

- ❖  $W_F$ : The work results from the movement of the system boundaries

$$\dot{W}_F = F \frac{dl}{dt} = -P \frac{dV}{dt}$$

$$dV < 0 \Rightarrow W_F > 0$$

- ❖ Flow work: The work of flow in and flow out for open systems ( $P\Delta V$  type)



$$\text{net flow work} = \sum \dot{M}_k (P\hat{V})_k$$

# Energy Balance Equation (EBE)

$$\frac{d}{dt} [U + M(v^2 / 2 + \psi)]_{system} = \sum \dot{M}_k (\hat{U} + v^2 / 2 + \psi)_k + \dot{Q} + \dot{W}_s - \left( P \frac{dV}{dt} \right)_{system} + \sum \dot{M}_k (P\hat{V})_k$$

or

$$\frac{d}{dt} [U + M(v^2 / 2 + \psi)]_{system} = \sum \dot{M}_k (\hat{H} + v^2 / 2 + \psi)_k + \dot{Q} + \dot{W}_s - \left( P \frac{dV}{dt} \right)_{system}$$

where  $H = U + PV$

## ❖ Special cases:

### ❖ Closed system

$$\dot{M}_k = 0, \quad dM / dt = 0$$

$$\left( \frac{dU}{dt} \right)_{system} + M_{system} \frac{d}{dt} (v^2 / 2 + \psi)_{system} = \dot{Q} + \dot{W}_s - \left( P \frac{dV}{dt} \right)_{system}$$

### ❖ Adiabatic process $\dot{Q} = 0$

### ❖ Open steady-state system

$$dM / dt = 0, \quad dV / dt = 0, \quad \frac{d}{dt} [U + M(v^2 / 2 + \psi)]_{system} = 0$$

$$0 = \sum \dot{M}_k (\hat{H} + v^2 / 2 + \psi)_k + \dot{Q} + \dot{W}_s$$

# Difference form of EBE

$$\frac{d}{dt} \left[ U + M \left( v^2 / 2 + \psi \right) \right]_{system} = \sum \dot{M}_k \left( \hat{H} + v^2 / 2 + \psi \right)_k + \dot{Q} + \dot{W}_s - \left( P \frac{dV}{dt} \right)_{system}$$

Integration of  $t$  from  $t = t_1$  to  $t = t_2$

$$\left[ U + M \left( v^2 / 2 + \psi \right) \right]_{t_2} - \left[ U + M \left( v^2 / 2 + \psi \right) \right]_{t_1} =$$

$$\sum \int_{t_1}^{t_2} \dot{M}_k \left( \hat{H} + v^2 / 2 + \psi \right)_k dt + Q + W_s - \int_{V \text{ at } t_1}^{V \text{ at } t_2} P dV$$

where

$$Q = \int_{t_1}^{t_2} \dot{Q} dt$$

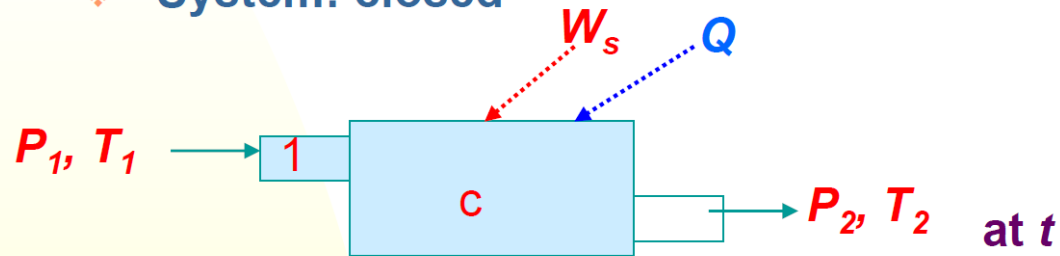
$$W_s = \int_{t_1}^{t_2} \dot{W}_s dt$$

# Examples

- ❖ Illustration 3.2-1 compressor operates at steady-state
  - ❖ Showing that the final results should not depend on the choice of system

$$Q + W_s = (\hat{H}_2 - \hat{H}_1)\Delta M$$

- ❖ System: closed



$$M_2 \hat{U}_2 \Big|_{t+\Delta t} + M_c \hat{U}_c \Big|_{t+\Delta t} - M_1 \hat{U}_1 \Big|_t - M_c \hat{U}_c \Big|_t = W_s + Q - P_1(0 - \hat{V}_1)M_1 - P_2(\hat{V}_2 - 0)M_2$$

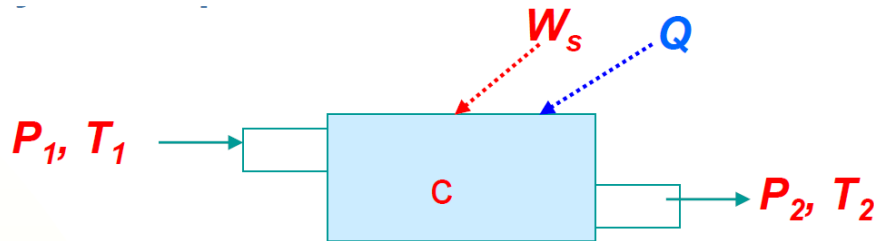
$$\because M_2 \Big|_{t+\Delta t} = M_1 \Big|_t = \Delta M, \quad M_c \hat{U}_c \Big|_{t+\Delta t} = M_c \hat{U}_c \Big|_t$$

$$\therefore \Delta M(\hat{U}_2 - \hat{U}_1) = W_s + Q + P_1 \hat{V}_1 \Delta M - P_2 \hat{V}_2 \Delta M$$

$$\Rightarrow \Delta M(\hat{U}_2 + P\hat{V}_2 - \hat{U}_1 - P\hat{V}_1) = \Delta M(\hat{H}_2 - \hat{H}_1) = W_s + Q$$



# Open system



❖ **Mass balance:**

$$M|_{t+\Delta t} - M|_t = \int_t^{t+\Delta t} \dot{M}_1 dt + \int_t^{t+\Delta t} \dot{M}_2 dt = \Delta M_1 + \Delta M_2 = 0 \Rightarrow \Delta M_1 = -\Delta M_2$$

❖ **Energy balance:**

$$\begin{aligned} [U + M(v^2/2 + \psi)]_{t+\Delta t} - [U + M(v^2/2 + \psi)]_t &= \int_t^{t+\Delta t} \dot{M}_1 (\hat{H}_1 + v_1^2/2 + \psi_1) dt + \\ &\int_t^{t+\Delta t} \dot{M}_2 (\hat{H}_2 + v_2^2/2 + \psi_2) dt + W_s + W_F + Q \end{aligned}$$

*At steady-state*

$$M|_{t+\Delta t} = M|_t, [U + M(v^2/2 + \psi)]_{t+\Delta t} = [U + M(v^2/2 + \psi)]_t$$

$(\hat{H}_i + v_i^2/2 + \psi_i)$  do not change in time

Volume of system ( $V$ ) is constant,  $dV = 0 \Rightarrow W_F = 0$

$$0 = \Delta M_1 \hat{H}_1 + \Delta M_2 \hat{H}_2 + W_s + Q \quad (\text{Neglect the changes of KE \& PE terms})$$

or

$$Q + W_s = (\hat{H}_2 - \hat{H}_1) \Delta M$$

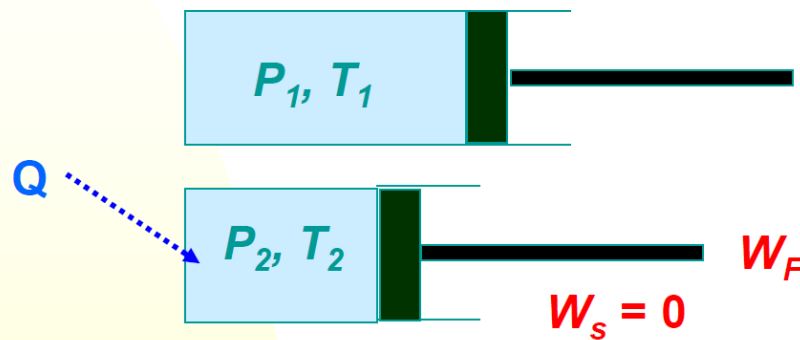
# Examples

## ❖ Illustration 3.2-2

A mass  $M$  of gas is to be compressed from  $(T_1, P_1)$  to  $(T_2, P_2)$  in

- ❖ (a) A one-step process in a frictionless piston & cylinder or
- ❖ (b) by a flow compressor as previous case.

<Sol> (a) closed system: gas within the piston & cylinder



❖ Energy balance:

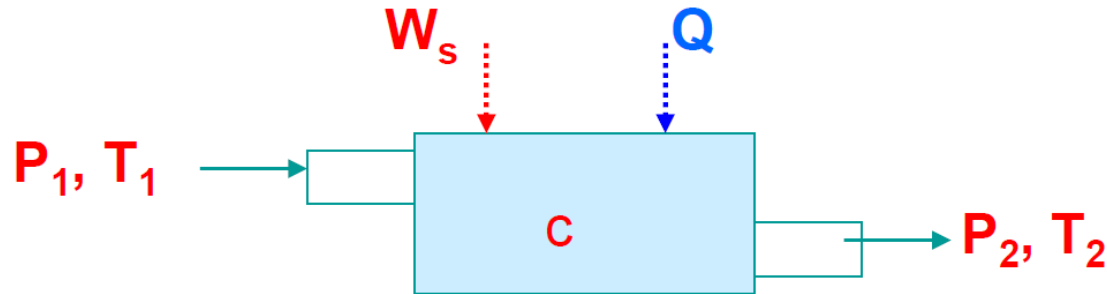
- ❖ No flow-in & flow-out, neglect KE & PE terms

$$Q + W = M(\hat{U}_2 - \hat{U}_1)$$

$$\text{where } W = W_s + W_F = 0 - \int PdV$$

$$Q - \int PdV = M(\hat{U}_2 - \hat{U}_1)$$

# Open system



❖ **Energy balance:**

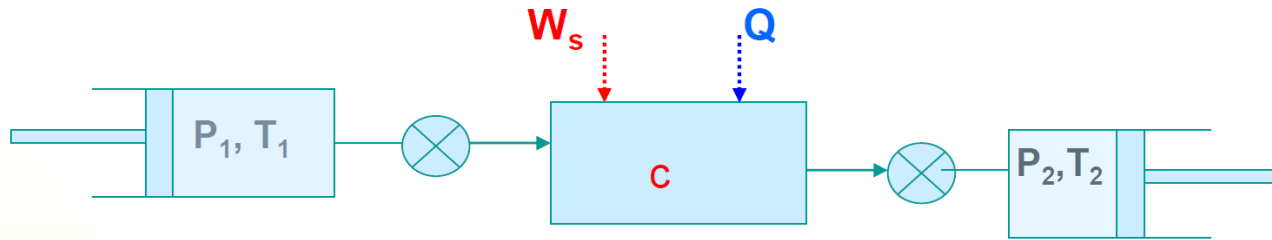
$$Q + W = M(\hat{H}_2 - \hat{H}_1)$$

$$\text{where } W_F = -\int PdV = 0 \Rightarrow W = W_s$$

$$Q + W_s = M(\hat{H}_2 - \hat{H}_1)$$

$$(Q + W)_{(case\ a)} \neq (Q + W)_{(case\ b)}$$

# Process



- ❖ Inject the gas  $M$  into the compressor inlet stream

$$W_1 = -\int P dV = -P_1(-V_1) = P_1 \hat{V}_1 M$$

- ❖ Compress from  $(T_1, P_1)$  to  $(T_2, P_2)$  using a compressor

$$(Q+W)_c = M(\hat{H}_2 - \hat{H}_1)$$

- ❖ Withdraw the gas  $M$  from the compressor (refill the second cylinder)

$$W_2 = -\int P dV = -P_2(V_2) = -P_2 \hat{V}_2 M$$

$$\begin{aligned} Q+W &= (Q+W)_c + W_1 + W_2 \\ &= M(\hat{H}_2 - \hat{H}_1) + P_1 \hat{V}_1 M - P_2 \hat{V}_2 M \\ &= M(\hat{U}_2 - \hat{U}_1) \end{aligned}$$

# Example

## Illustration 3.2-3 Joule-Thomson or isenthalpic expansion



- Assumptions:
  - $Q = 0$
  - KE & PE terms are neglected
- <sol>
  - System: valve (open system)
    - Mass balance
 
$$0 = \dot{N}_1 + \dot{N}_2 \Rightarrow \dot{N}_1 = -\dot{N}_2$$
    - Energy balance
 
$$0 = \dot{N}_1 \underline{H}_1 + \dot{N}_2 \underline{H}_2 = \dot{N}_1 (\underline{H}_1 - \underline{H}_2)$$

$$\Rightarrow \underline{H}_1(T_1, P_1) = \underline{H}_2(T_2, P_2)$$
  - If  $\underline{H}(T, P)$ ,  $T_1$ ,  $P_1$ , and  $P_2$  are given, we can solve  $T_2$  from  $\underline{H}(T_2, P_2)$ 
    - Joule-Thomson expansion
    - Valve: Throttling valve

# Thermodynamic properties of matters

- ❖ Thermodynamic properties ( $P, V, T, U, H, S, A, G, \mu, f, C_v, C_p, \dots$ )
- ❖ state change  $\Rightarrow$  thermodynamic property changes
- ❖ Specify the state of system (degree of freedom)
- ❖ Phase rule:  $F = 2 + C - \Pi$ 
  - ❖ Degree of freedom ( $F$ ) is **2** for a single phase ( $\Pi = 1$ ) and single component ( $C = 1$ ) system.
  - ❖ Thermodynamic properties =  $f(T, P)$  or  $f(T, \underline{V})$
  - ❖ **T** and **P** are easier to measure and manipulate than others
  - ❖ Using volumetric EOS ( $P$ - $\underline{V}$ - $T$ ) or thermal EOS ( $\underline{U}$ - $T$ - $\underline{V}$ ) calculates other thermodynamic properties.
- ❖ Ideal gas law (EOS):  $P\underline{V} = RT$ 
  - ❖  $\underline{U} = f(T), \underline{H} = f(T)$  for ideal gas
  - ❖  $\underline{U} = f(T, \underline{V}), \underline{H} = f(T, P)$  for real fluids

# Temp. dependence of U and H

$$\frac{Q}{N} = C\Delta T = C(T|_{t_2} - T|_{t_1})$$

- ❖ **Q:** heat added to the system between  $t_1$  and  $t_2$
- ❖ **C:** parameter,  $f(T)$

- ❖ **Measurement is made at constant V and with  $W_s = 0$**

$$U|_{t_2} - U|_{t_1} = Q = NC_V(T|_{t_2} - T|_{t_1}) \Rightarrow C_V = \frac{U|_{t_2} - U|_{t_1}}{N(T|_{t_2} - T|_{t_1})} = \frac{\underline{U}|_{t_2} - \underline{U}|_{t_1}}{T|_{t_2} - T|_{t_1}}$$

- ❖ **Definition of  $C_V$**

$$C_V(T, V) = \lim_{\Delta T \rightarrow 0} \frac{\underline{U}|_{t_2} - \underline{U}|_{t_1}}{T|_{t_2} - T|_{t_1}} = \left( \frac{\partial \underline{U}}{\partial T} \right)_V = \left[ \frac{\partial \underline{U}(T, V)}{\partial T} \right]_V$$

- ❖ **Measurement is made at constant P (Volume was changed during the heating process) & definition of  $C_P$**

$$Q = U|_{t_2} - U|_{t_1} + P(V|_{t_2} - V|_{t_1}) = H|_{t_2} - H|_{t_1} = NC_P(T|_{t_2} - T|_{t_1})$$

$$\Rightarrow C_P(T, P) = \left( \frac{\partial \underline{H}}{\partial T} \right)_P = \left[ \frac{\partial \underline{H}(T, P)}{\partial T} \right]_P$$

# Ideal gas heat capacity

- ❖  $H$  and  $U$  of Ideal gases are functions only of temperature.
- ❖  $C_p^*$  and  $C_v^*$  are also dependent on temperature only.

$$C_p^*(T) = \frac{dH}{dT} \quad \text{and} \quad C_v^*(T) = \frac{dU}{dT}$$

$$C_p^* = a + bT + cT^2 + dT^3 + \dots$$

Since  $\underline{H} = \underline{U} + \underline{PV}$ , and for the ideal gas  $\underline{PV} = RT$ , we have  $\underline{H} = \underline{U} + RT$  and

$$C_p^*(T) = \frac{dH}{dT} = \frac{d(\underline{U} + RT)}{dT} = C_v^*(T) + R$$

or

$$C_v^*(T) = C_p^*(T) - R = (a - R) + bT + cT^2 + dT^3 + \dots$$

The constants **a, b, c, d,...** are given in **Appendix A. II.**

- ❖ Solve the energy balance eqs.  $\Rightarrow$  need to know the changes of  $\underline{U}$  and  $\underline{H}$  ( $\Delta\underline{U}$  and  $\Delta\underline{H}$ ) only  $\Rightarrow \underline{H}$  is arbitrary set equal to zero (reference state) .

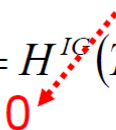


# U and H at T for ideal gas

- ❖ H and U of Ideal gases at T

$$H^{IG}(T_2) = H^{IG}(T_1) + \int_{T_1}^{T_2} C_P^*(T) dT$$

$$\underline{H}^{IG}(T) = \underline{H}^{IG}(T_R) + \int_{T_R}^T C_P^*(T) dT$$



where  $T_R$  is the reference temp. chosen as  $\underline{H}^{IG}(T_R) = 0$ .

$$\begin{aligned} \underline{U}^{IG}(T) &= \underline{U}^{IG}(T_R) + \int_{T_R}^T C_V^*(T) dT = \left[ \underline{H}^{IG}(T_R) - RT_R \right] + \int_{T_R}^T C_V^*(T) dT \\ &= \int_{T_R}^T C_V^*(T) dT - RT_R \end{aligned}$$

- ❖ Assuming that  $C_p^*$  and  $C_v^*$  are temperature-independent

$$\underline{H}^{IG}(T) = C_P^*(T - T_R)$$

$$\underline{U}^{IG}(T) = C_V^*(T - T_R) - RT_R = C_V^*T - C_P^*T_R$$

- ❖ Taken  $T_R = 0$ , then

$$\underline{H}^{IG}(T) = C_P^*T$$

$$\underline{U}^{IG}(T) = C_V^*T$$

- For pure real fluids

- ◆ Thermodynamic properties are not dependent on  $T$  only →  
phase rule  $F = 2 + 1 - \Pi = 3 - \Pi$ ,  $\Pi = 1$ ,  $F = 2$  →  
 $f(T, P)$  or  $f(T, \underline{V})$
- ◆ More complicated than those of ideal gases
- ◆ Experimental data →
  - ★ Tables (e.g., Steam tables, Appendix A. III)
  - ★ Figures (e.g., Figs. 3.3-1 to 3.3-4 for steam, methane, nitrogen, and HFC-134a)
- ◆  $H$ - $S$  chart (Mollier diagram): useful in turbine & compressor problems
- ◆  $H$ - $P$  chart: Useful in refrigeration problems
- ◆  $T$ - $S$  chart: Useful in engine & cycle analysis

## The Thermodynamic Properties of Water and Steam<sup>1</sup>

### THERMODYNAMIC PROPERTIES OF STEAM

#### Saturated Steam: Temperature Table

Temp °C T	Press. kPa P	Specific Volume		Internal Energy		Enthalpy		Entropy				
		Sat. Liquid $\hat{V}^L$	Sat. Vapor $\hat{V}^V$	Sat. Liquid $\hat{U}^L$	Evap. $\Delta\hat{U}$	Sat. Vapor $\hat{H}^V$	Evap. $\Delta\hat{H}$	Sat. Liquid $\hat{S}^L$	Evap. $\Delta\hat{S}$	Sat. Vapor $\hat{S}^V$		
0.01	0.6113	0.001 000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
5	0.8721	0.001 000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001 000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001 001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	2.339	0.001 002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
25	3.169	0.001 003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001 004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001 006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	7.8478	8.3531
40	7.384	0.001 008	19.52	167.56	2262.6	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
45	9.593	0.001 010	15.26	188.44	2248.4	2436.8	188.45	2394.8	2583.2	0.6387	7.5261	8.1648
50	12.349	0.001 012	12.03	209.32	2234.2	2443.5	209.33	2382.7	2592.1	0.7038	7.3725	8.0763
55	15.758	0.001 015	9.568	230.21	2219.9	2450.1	230.23	2370.7	2600.9	0.7679	7.2234	7.9913
60	19.940	0.001 017	7.671	251.11	2205.5	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
65	25.03	0.001 020	6.197	272.02	2191.1	2463.1	272.06	2346.2	2618.3	0.8935	6.9375	7.8310
70	31.19	0.001 023	5.042	292.95	2176.6	2469.6	292.98	2333.8	2626.8	0.9549	6.8004	7.7553
75	38.58	0.001 026	4.131	313.90	2162.0	2475.9	313.93	2321.4	2635.3	1.0155	6.6669	7.6824
80	47.39	0.001 029	3.407	334.86	2147.4	2482.2	334.91	2308.8	2643.7	1.0753	6.5369	7.6122
85	57.83	0.001 033	2.828	355.84	2132.6	2488.4	355.90	2296.0	2651.9	1.1343	6.4102	7.5445
90	70.14	0.001 036	2.361	376.85	2117.7	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
95	84.55	0.001 040	1.982	397.88	2102.7	2500.6	397.96	2270.2	2668.1	1.2500	6.1659	7.4159

Temp °C T	Press. kPa P	Sat. Liquid $\hat{V}^L$	Sat. Vapor $\hat{V}^V$	Sat. Liquid $\hat{U}^L$	Evap. $\Delta\hat{U}$	Sat. Vapor $\hat{U}^V$	Sat. Liquid $\hat{H}^L$	Evap. $\Delta\hat{H}$	Sat. Vapor $\hat{H}^V$	Sat. Liquid $\hat{S}^L$	Evap. $\Delta\hat{S}$	Sat. Vapor $\hat{S}^V$
100	0.101 35	0.001 044	1.6729	418.94	2087.6	2506.5	419.04	2257.0	2676.1	1.3069	6.0480	7.3549
105	0.144 82	0.001 048	1.419	440.92	2072.7	2513.6	441.05	2249.7	2689.8	1.3680	5.9833	7.3550
110	0.143 27	0.001 052	1.2102	461.14	2057.0	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
115	0.169 06	0.001 056	1.0366	482.30	2041.4	2523.7	482.48	2216.5	2699.0	1.4734	5.7100	7.1833
120	0.198 53	0.001 060	0.8919	503.50	2025.8	2529.3	503.71	2202.6	2706.3	1.5276	5.6020	7.1296
125	0.2321	0.001 065	0.7706	524.74	2009.9	2534.6	524.99	2188.5	2713.5	1.5813	5.4962	7.0775
130	0.2701	0.001 070	0.6685	546.02	1993.9	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269

$\hat{V}$  [=] m<sup>3</sup>/kg;  $\hat{U}, \hat{H}$  [=] J/g = kJ/kg;  $\hat{S}$  [=] kJ/kg K

Superheated Vapor

T°C	P = 0.010 MPa (45.81)				P = 0.050 MPa (81.33)				P = 0.10 MPa (99.69)			
	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$
Sat.	4.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	1.6940	2506.1	2675.5	7.3594
50	4.869	2443.9	2592.6	8.1749	—	—	—	—	—	—	—	—
100	7.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614
150	9.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	1.9364	2559.8	2776.4	7.6134
200	11.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343
250	14.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333
300	16.445	2812.1	3076.5	9.2715	5.284	2812.1	3075.5	8.5273	2.659	2812.1	3074.3	8.2158
400	21.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435
500	25.679	3123.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342
600	30.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.7	9.0976
700	34.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	4.490	3479.2	3928.2	9.3398
800	39.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652
900	44.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767
1000	48.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764
1100	53.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659
1200	57.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463
1300	62.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	7.260	4683.5	5409.5	10.5183

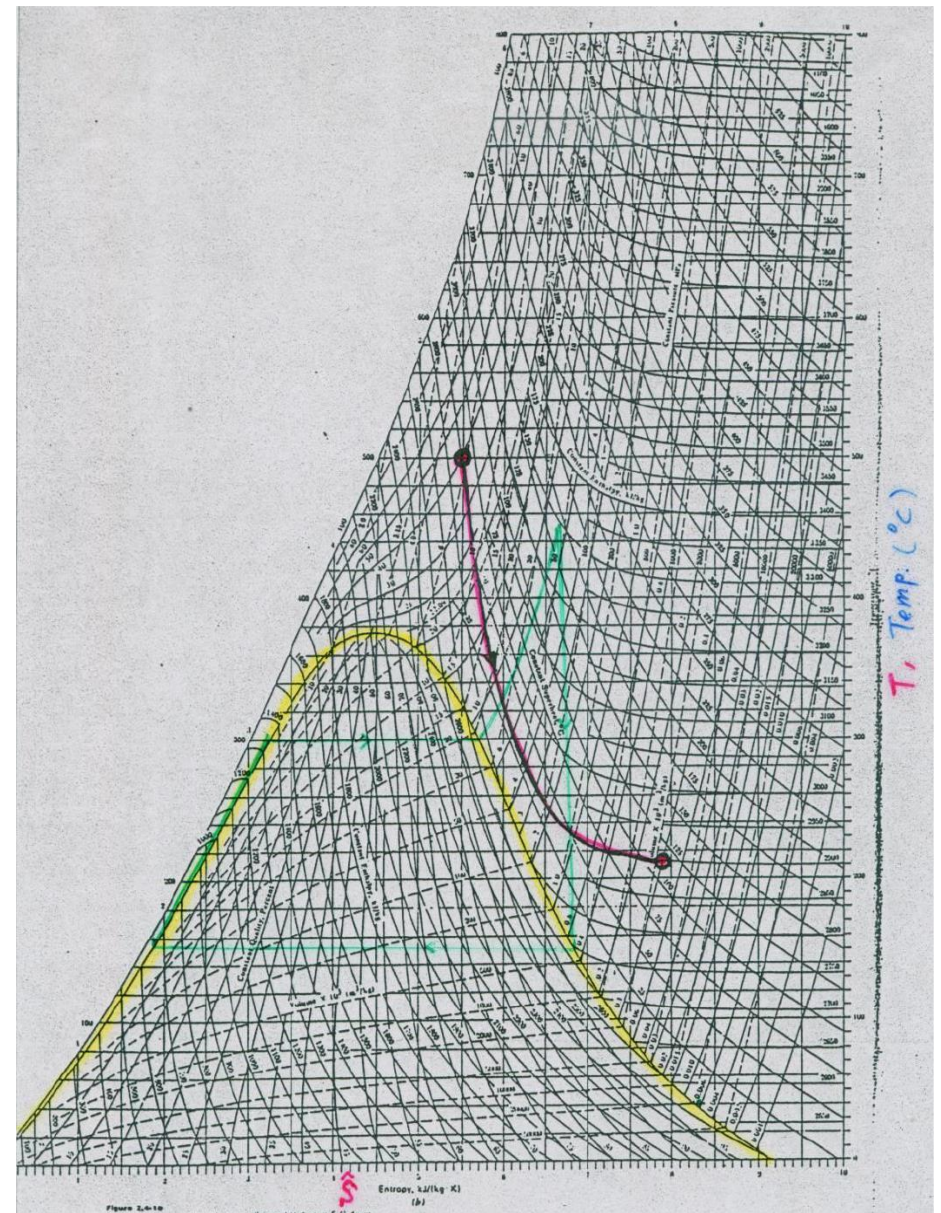
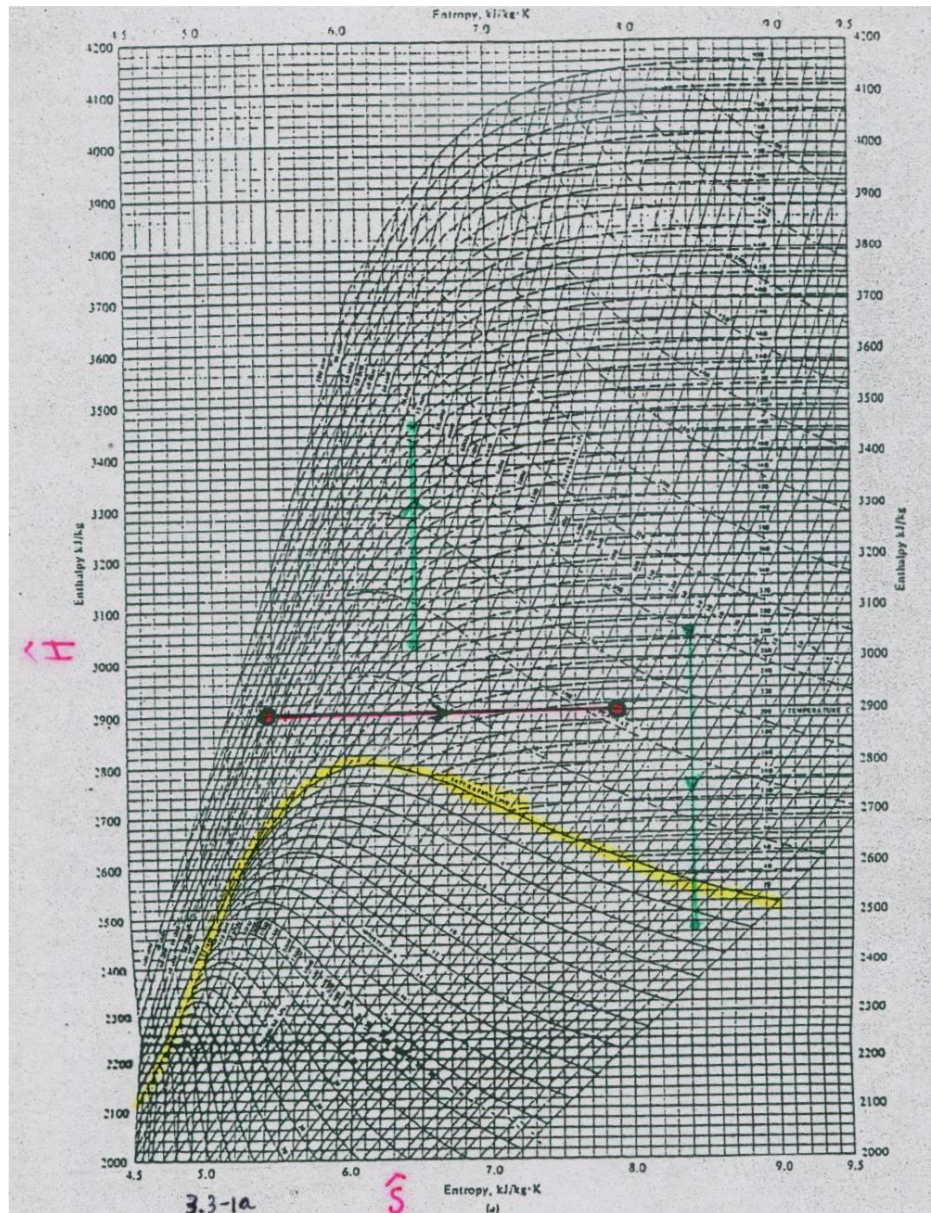
T°C	P = 0.20 MPa (120.23)				P = 0.30 MPa (133.55)				P = 0.40 MPa (143.63)			
	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7966	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.1	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.706	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.3	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

T°C	P = 0.50 MPa (151.86)				P = 0.60 MPa (158.85)				P = 0.80 MPa (170.43)			
	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$	$\hat{V}$	$\hat{U}$	$\hat{H}$	$\hat{S}$
Sat.	0.3749	2561.2	2748.7	6.8213	0.3157	2567.4	2756.8	6.7660	0.2404	2576.8	2769.1	6.6628
200	0.4249	2642.9	2855.4	7.0592	0.3520	2638.9	2850.1	6.9665	0.2608	2630.6	2839.3	6.8158
250	0.4744	2723.5	2960.7	7.2709	0.3938	2720.9	2957.2	7.1816	0.2931	2715.5	2950.0	7.0384
300	0.5226	2802.9	3064.2	7.4599	0.4344	2801.0	3061.6	7.3724	0.3241	2797.2	3056.5	7.2328
350	0.5701	2882.6	3167.7	7.6329	0.4742	2881.2	3165.7	7.5464	0.3544	2878.2	3161.7	7.4089
400	0.6173	2962.3	3271.9	7.7938	0.5137	2962.1	3270.3	7.7079	0.3843	2959.7	3267.1	7.5716
500	0.7109	3128.4	3483.9	8.0873	0.5920	3127.6	3482.8	8.0021	0.4433	3126.0	3480.6	7.8673
600	0.8041	3299.6	3701.7	7.3522	0.6697	3299.1	3700.9	8.2674	0.5018	3297.9	3699.4	8.1333
700	0.8969	3477.5	3925.9	8.5952	0.7472	3477.0	3925.3	8.5107	0.5601	3476.2	3924.2	8.3770
800	0.9896	3662.1	4156.9	8.8211	0.8245	3661.8	4156.5	8.7367	0.6181	3661.1	4155.6	8.6033
900	1.0822	3853.6	4394.7	9.0329	0.9017	3853.4	4394.4	8.9486	0.6761	3852.8	4393.7	8.8153
1000	1.1747	4051.8	4639.1	9.2328	0.9788	4051.5	4638.8	9.1485	0.7340	4051.0	4638.2	9.0153
1100	1.2672	4256.3	4889.9	9.4224	1.0559	4256.1	4889.6	9.3481	0.7919	4255.6	4889.1	9.2050
1200	1.3596	4466.8	5146.5	9.6029	1.1330	4466.5	5146					

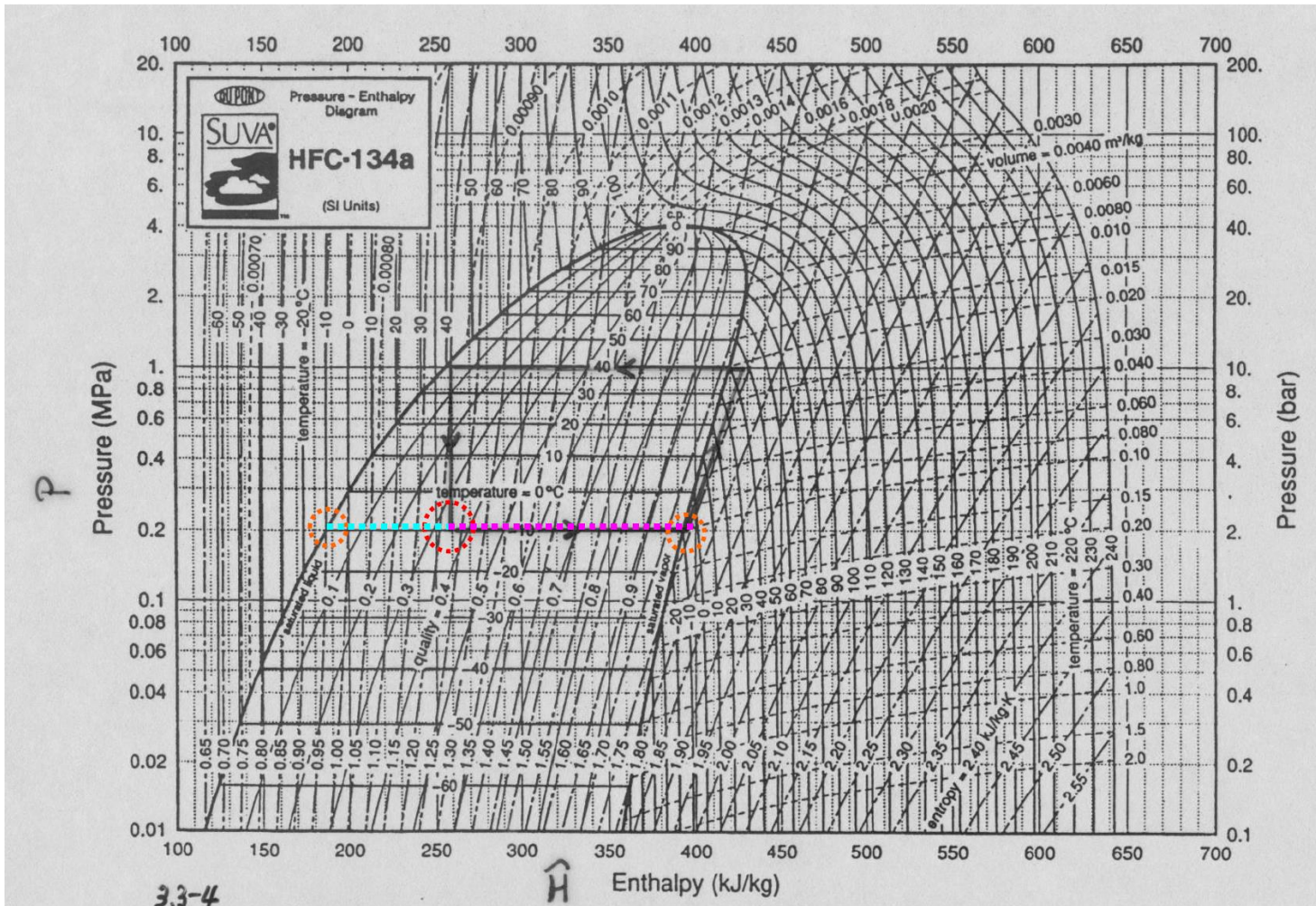


# H-S & TS diagram for steam





# Refrigeration cycle: P-H diagram



# Properties of two-phase mixture: the lever rule

$$\hat{\theta} = \omega^I \hat{\theta}^I + \omega^{II} \hat{\theta}^{II} = \omega^I \hat{\theta}^I + (1 - \omega^I) \hat{\theta}^{II} \quad (3.3-9)$$

- $\omega$  and  $\theta$  are the mass fraction of the system and the value of the variable in phase I, respectively.
- For mixtures of steam and water, the mass fraction of steam is termed the steam “**quality**”, and is frequently expressed as a percent.
- In Figs. 3.3-1 to 3.3-4, the properties of the two-phase mixture will fall along a line connecting the properties of the individual phases. → Eq. (3.3-9) the **lever rule**
- Property changes at different phases

$$\Delta_{vap} \hat{H} = \hat{H}^V - \hat{H}^L$$

$$\Delta_{vap} \underline{H} = \underline{H}^V - \underline{H}^L = \text{molar enthalpy of vaporization}$$

$$\Delta_{fus} \underline{H} = \underline{H}^L - \underline{H}^S = \text{molar enthalpy of melting or fusion}$$

$$\Delta_{sub} \underline{H} = \underline{H}^V - \underline{H}^S = \text{molar enthalpy of sublimation}$$

- Since the value of  $P\underline{V}$  is much smaller than that of  $\underline{U} \rightarrow \underline{H} = \underline{U} + P\underline{V} \approx \underline{U}$
- For incompressible fluids (solids and most liquids far away from their critical points),

$$\left( \frac{d\underline{V}}{dP} \right)_T = 0 \text{ and } \underline{U}, C_p, C_v \text{ are function of } T \text{ only.}$$

- DuLong and Petit correlation  $\Rightarrow C_p$  for solids

$$C_p = 3NR = 24.942 N \frac{J}{mol K}$$

**N:** the number of atoms in the formula unit.

$C_p$  of Pb, Au, Al at 25°C are 26.8, 25.2, and 24.4 (J/mol K), respectively. The predicted  $C_p$  of Fe<sub>3</sub>C is 99.8 (J/mol K); experimental value is 105.9 (J/mol K).

- 1. system choice
- 2. mass and energy balance equations

- 3.  $\underline{H}, \underline{U} \rightarrow P, \underline{V}, T \rightarrow f(P, T)$

Thermal EOS

$$\underline{U} = f(T, \underline{V})$$

Volumetric EOS

$$P = f(T, \underline{V})$$

- 4. balance eqs.  $\rightarrow f(P, T, \text{mass}, W_s, Q)$
- 5. If number of unknown = number of the equations  $\rightarrow$   
 <<the problem can be solved>>  
 If number of unknown  $>$  number of the equations  $\rightarrow$   
 <<need additional balance equations>>  
 e.g. entropy balance equations





# Examples from 3.4-1 to 3.4-8