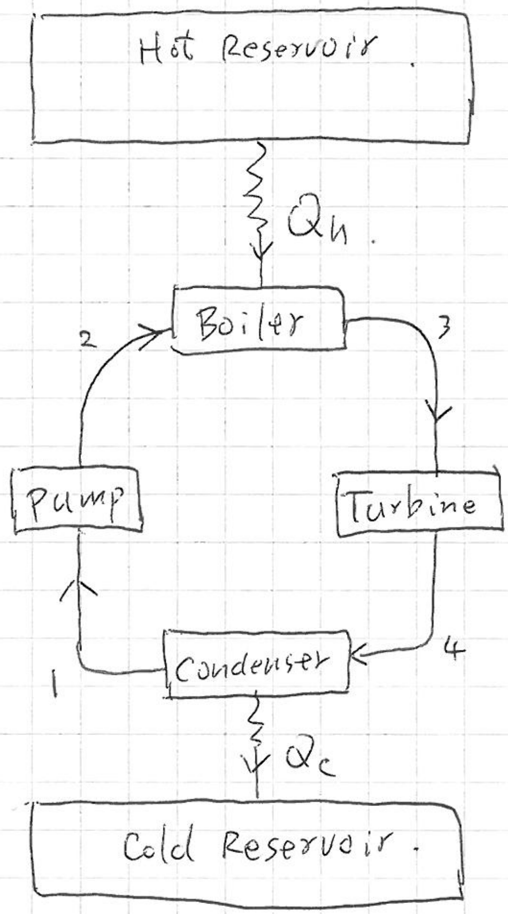
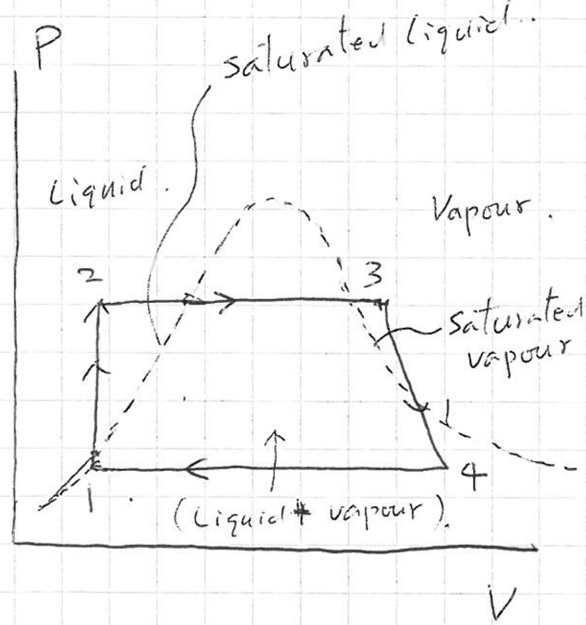
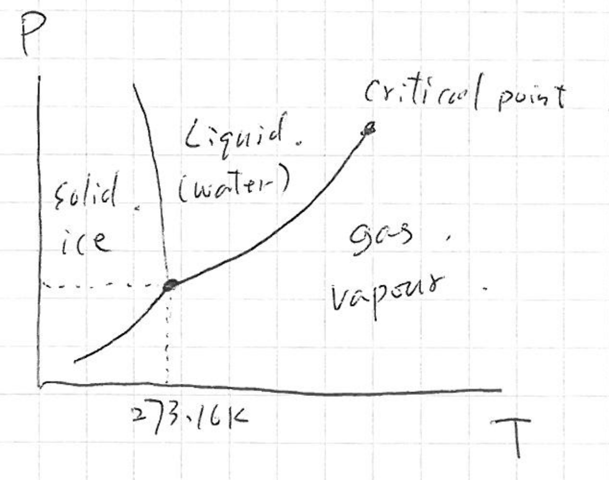
Phys 344

Lecture 19. The Steam Engine

- Rankine cycle of water (NOT ideal gas!)







$1 \to 2$. ~~isobaric (constant P)~~

also nearly adiabatic (and quasistatic). (const. S)

$3 \to 4$ Adiabatic

$$\therefore \quad e = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h} = 1 - \frac{H_4 - H_1}{H_3 - H_2} \approx 1 - \frac{H_4 - H_1}{H_3 - H_1}$$

$$\left(\begin{array}{l} \text{Note: } \Delta H = \text{Heat absorbed when } P = \text{constant.} \\ H = U + PV \\ \Delta H = \Delta U + P\Delta V = \Delta U - \underset{\substack{\uparrow \\ \text{work on system}}}{W} = Q \end{array} \right)$$

How do we calculate e?

— use the steam tables. to find H_1, (H_2), $\underbrace{H_3, H_4}_{\text{(same } S\text{.)}}$

$H_1 = H_2$, $S_3 = S_4$.

- saturated water/vapour — 2 phases coexist.

temperature can be determined by pressure. and vise verse.
$H = H(T)$, $S = S(T)$.

$\left\{ \begin{array}{l} \text{Mixture of water and vapour.} \\ \text{Volume varies depending on } \left(\frac{m_W}{m_V}\right). \\ T \sim P \text{ relation is well defined.} \\ \quad P = f(T) \text{ — unique.} \end{array} \right.$

- superheated steam — H_2O gas.

We need to specify. P, and T.

$H = H(P, T)$, $S = S(P, T)$.

(Note: For a given amount of H_2O.)
1 kg

Note: The table is good for ΔH, ΔS

but not necessarily for S, H.

e.g.: $\begin{cases} P_1 = 0.023 \text{ bar} \\ T_1 = 20°C \end{cases}$ (The partial pressure of H_2O in the atmosphere) all water (very little vapour)

$P_2 = P_3 = 300$ bars.

$T_{max} = T_3 = 600°C$.

① — water
② — water
③ — steam
④ — Mixture.

Consider 1 kg of H_2O.

$H_1 = 84$ kJ

$H_3 = 3444$ kJ.

$S_3 = 6.233$ kJ/K.

4: $\begin{cases} 0.023 \text{ bar} \\ @ 20°C \end{cases}$ $S_4 = S_3 \Rightarrow$ $x S_{water} + (1-x) S_{steam} = S_4$.

$0.297x + 8.667(1-x) = 6.233$.

solve for x:

$0.297x + 8.667 - 8.667x = 6.233$

$$x = \frac{8.667 - 6.233}{8.667 - 0.297} = 0.29$$

@ 4: water : 29%. Vapour : 71%.

$H_4 = 0.29 H_{water} + 0.71 H_{vapour}$

$= 0.29 \times 84 + 0.71 \times 2538 = 1826$ kJ.

$$\therefore \quad e = 1 - \frac{1826 - 84}{3444 - 84} = 48\%.$$

Note: For liquid water, H is not sensitive to P.

($\because$ $H = U + pV$. V is small).

Next: Real Refrigerator.

— Reverse of Rankine cycle.

— can't use water / steam

e.g. CFC.

HFC-134a.

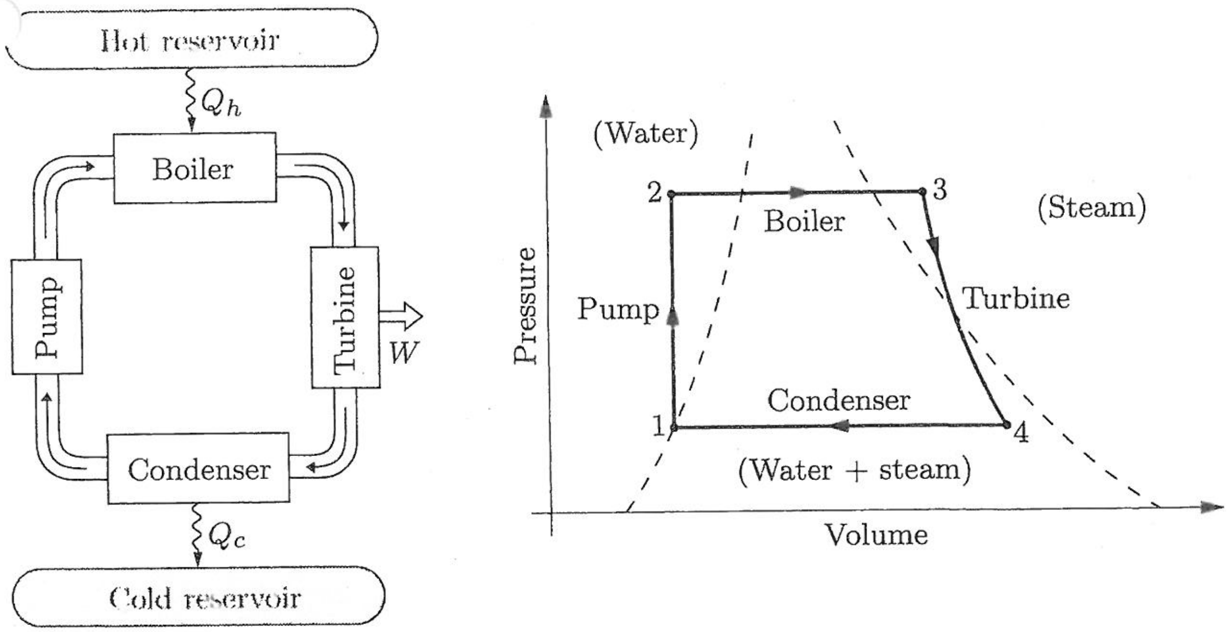


Figure 4.8. Schematic diagram of a steam engine and the associated *PV* cycle (not to scale), called the **Rankine cycle**. The dashed lines show where the fluid is liquid water, where it is steam, and where it is part water and part steam.

T (°C)	P (bar)	H_{water} (kJ)	H_{steam} (kJ)	S_{water} (kJ/K)	S_{steam} (kJ/K)
0	0.006	0	2501	0	9.156
10	0.012	42	2520	0.151	8.901
20	0.023	H_1 84	2538	0.297	8.667
30	0.042	126	2556	0.437	8.453
50	0.123	209	2592	0.704	8.076
100	1.013	419	2676	1.307	7.355

Table 4.1. Properties of saturated water/steam. Pressures are given in bars, where 1 bar = 10^5 Pa ≈ 1 atm. All values are for 1 kg of fluid, and are measured relative to liquid water at the triple point (0.01°C and 0.006 bar). Excerpted from Keenan et al. (1978).

P (bar)		Temperature (°C) 200	300	400	500	600
1.0	H (kJ)	2875	3074	3278	3488	3705
	S (kJ/K)	7.834	8.216	8.544	8.834	9.098
3.0	H (kJ)	2866	3069	3275	3486	3703
	S (kJ/K)	7.312	7.702	8.033	8.325	8.589
10	H (kJ)	2828	3051	3264	3479	3698
	S (kJ/K)	6.694	7.123	7.465	7.762	8.029
30	H (kJ)		2994	3231	3457	3682
	S (kJ/K)		6.539	6.921	7.234	7.509
100	H (kJ)			3097	3374	3625
	S (kJ/K)			6.212	6.597	6.903
300	H (kJ)			2151	3081	3444 H_3
	S (kJ/K)			4.473	5.791	6.233 S_3

Table 4.2. Properties of superheated steam. All values are for 1 kg of fluid, and are measured relative to liquid water at the triple point. Excerpted from Keenan et al. (1978).

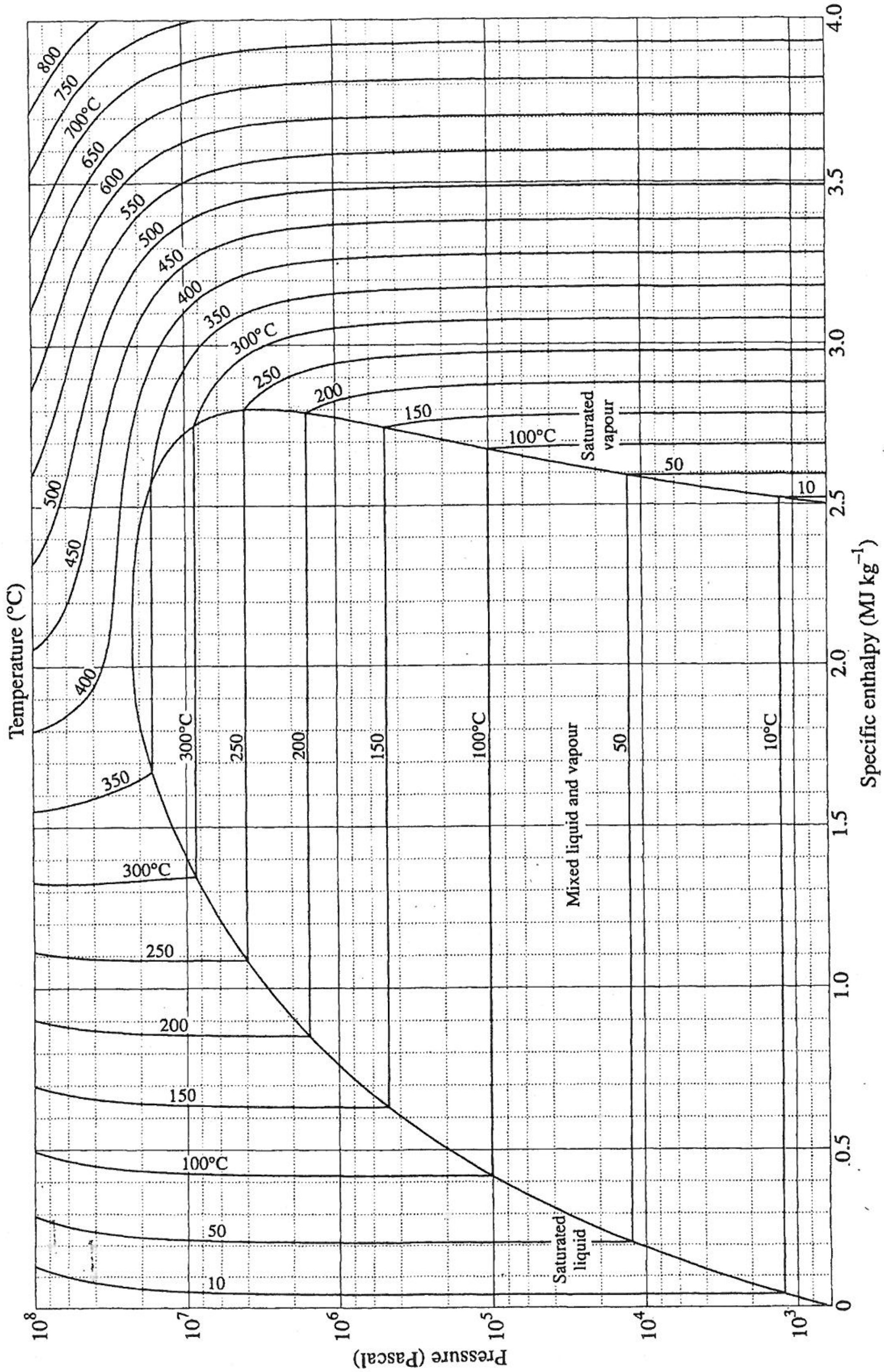

Temperature (°C)
Pressure (Pascal)
Specific enthalpy (MJ kg^{-1})
Saturated vapour
Saturated liquid
Mixed liquid and vapour
10^8
10^7
10^6
10^5
10^4
10^3
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
800
750
700°C
650
600
550
500
450
400
350
300°C
250
200
150
100°C
50
10

Fig. B.6