THERMODYNAMIC CYCLES

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LECTURE OUTLINE

- Thermodynamic State Variables.
- Cycle Classifications
- Power Cycles
- Thermodynamic Diagrams & Data
- Rankine Cycle

Thermodynamic State Variables

1. **Pressure (P):** is the force exerted per unit area of the system [Pa] or [atm]

2. Volume (V): is the amount of space occupied by a system (m^3) or liters (L)

3. Temperature (T): measures the average kinetic energy of the particles in a system [K] or [°C]

4. Internal Energy (U): The total energy contained within the system, including both kinetic and potential energy at the molecular level. Joules (J).

5. Enthalpy (H): The total heat content of the system, given by ($H = U + PV$). Joules (J)

Thermodynamic State Variables

6. Entropy (S): A measure of the disorder or randomness in a system. Irreversible heat per unit temperature. Joules per Kelvin (J/K).

7. Gibbs Free Energy (G): The maximum reversible work that a system can perform at constant temperature and pressure, given by ($G = H - TS$). Joules (J)

8. Helmholtz Free Energy (A or F): The energy available to do work at constant volume and temperature, given by ($A = U - TS$). Joules (J)

Thermodynamic State Variables

9. Specific Heat Capacity (C): The amount of heat required to raise the temperature of one kilogram of the substance by one Kelvin. Joules per kilogram per Kelvin (J/kg·K). $\mathbf{C_v}$ is for constant volume and $\mathbf{C_p}$ is for constant pressure.

10. For Ideal gas: $\mathbf{C_p=C_v+R}$, R = gas constant = 8.314 J mol^{-1}. K^{-1}

11. Heat Capacity Ratio: $\gamma=C_p/C_v$

Ideal Gas Laws

Ideal Gas law, where n is the number of moles

$$PV = nRT$$

Ideal Gas at constant entropy (isentropic) ===== No heat is added or lost

$$PV^k = C$$

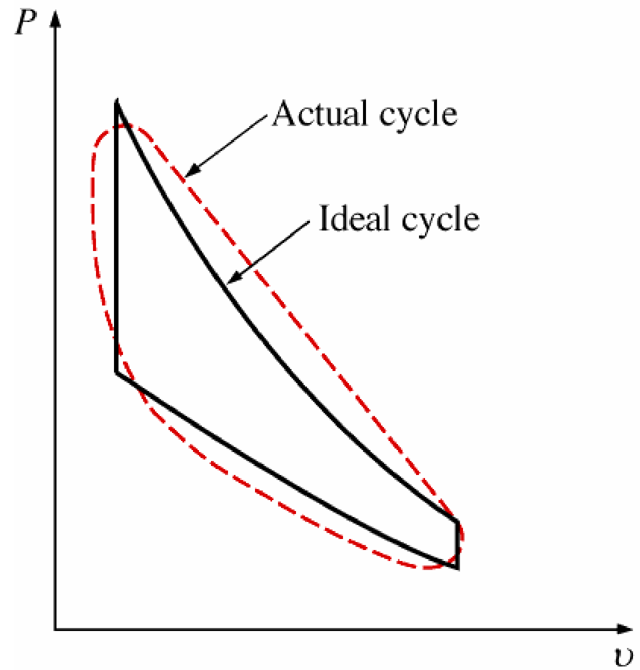
$$k = C_p / C_v$$

Thermodynamic cycles

- **Refrigeration cycles**
- **Power cycles**
  - **Idealised models of real cycles**
    - **Gas power cycles**
      - **Internal combustion engines**
        - Otto cycle
        - Diesel cycle
        - Gas turbine engines (Brayton cycle)
      - **External combustion engines**
        - Ericsson cycle
        - Stirling cycle
    - **Vapour power cycles**
      - **External combustion engines**
        - Rankine cycle
        - Organic rankine cycle
        - Kalina cycle
  - **Ideal cycles**
    - Carnot cycles

Power Cycles

- Otto Cycle
  - Spark Ignition
- Diesel Cycle
- Brayton Cycle
  - Gas Turbine
- Rankine Cycle

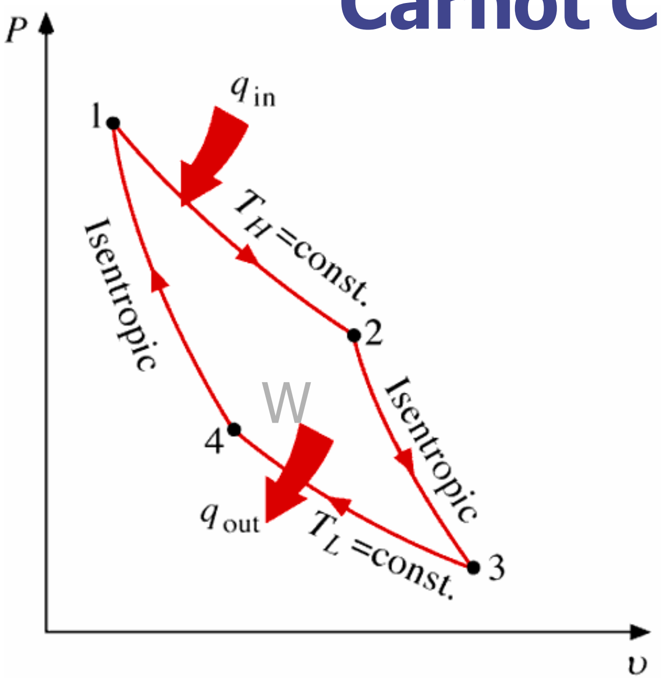


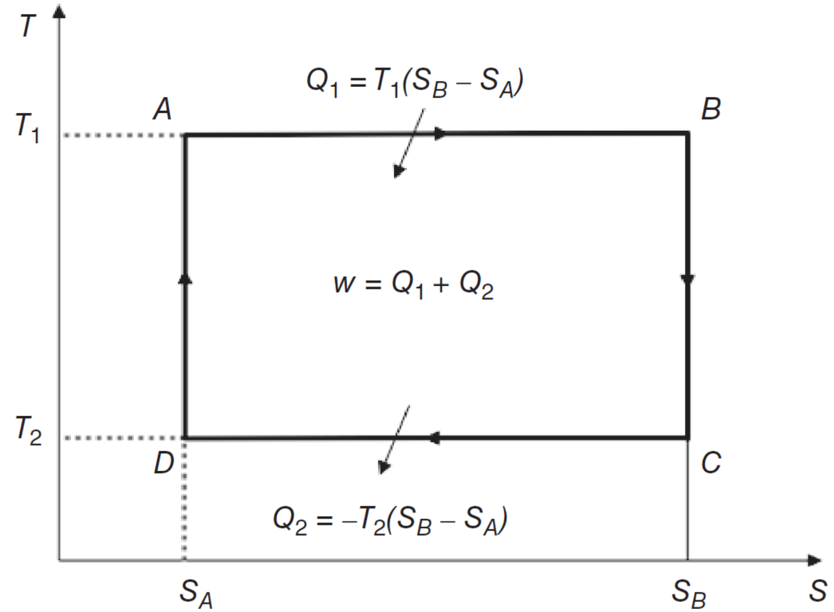
These are all heat engines. They convert heat to work, so the efficiency is:

$$\eta_{th} = \frac{W_{net}}{Q_{in}}$$

Ideal Cycles

Carnot Cycle



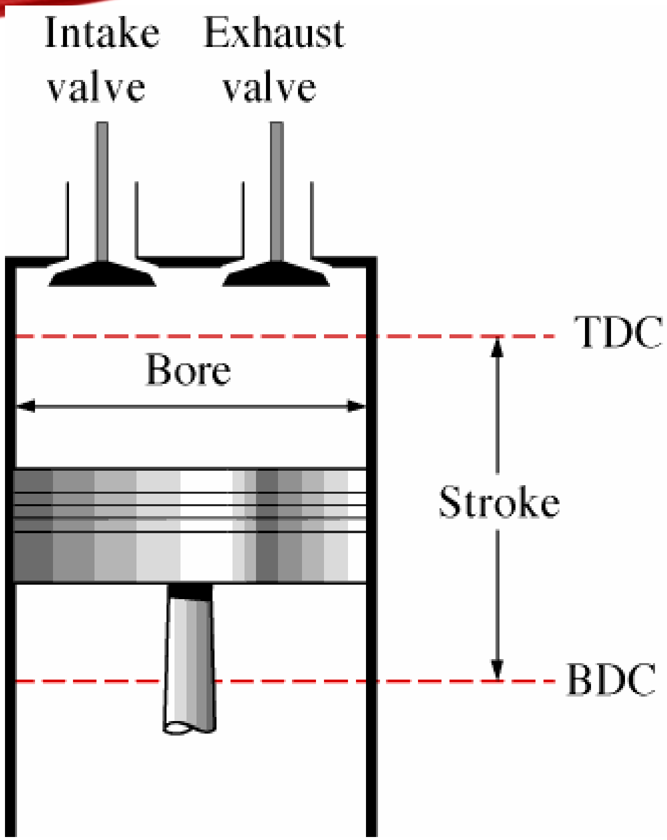


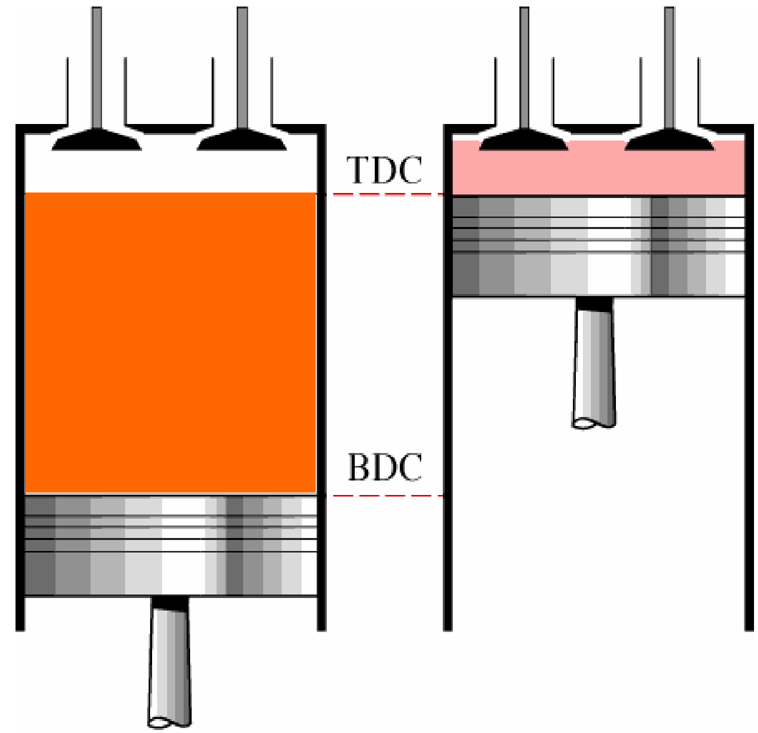
$$W = \oint PdV = \oint TdS \qquad |W| = (T_1 - T_2)\cdot(S_B - S_A)$$

$$Q_H = T_1 \cdot (S_B - S_A) \quad \text{and} \quad Q_C = T_2 \cdot (S_B - S_A)$$

$$\eta = \frac{|W|}{Q_H} = \frac{Q_H - Q_C}{Q_H} = \frac{(T_1 - T_2)\cdot(S_B - S_A)}{T_1 \cdot (S_B - S_A)} \qquad \eta = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

TERMINOLOGY FOR RECIPROCATING DEVICES





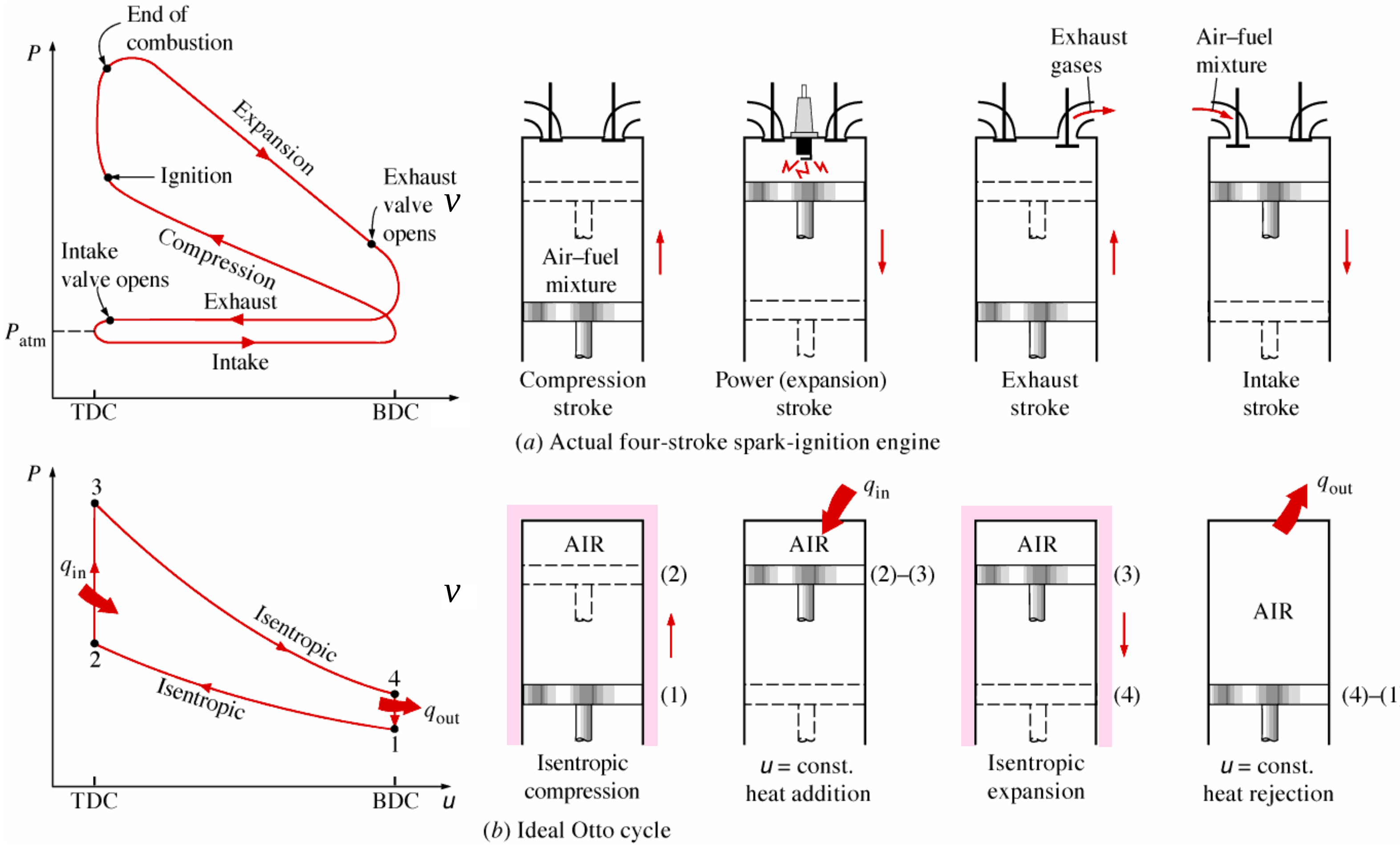
(*a*) Displacement volume

(*b*) Clearance volume

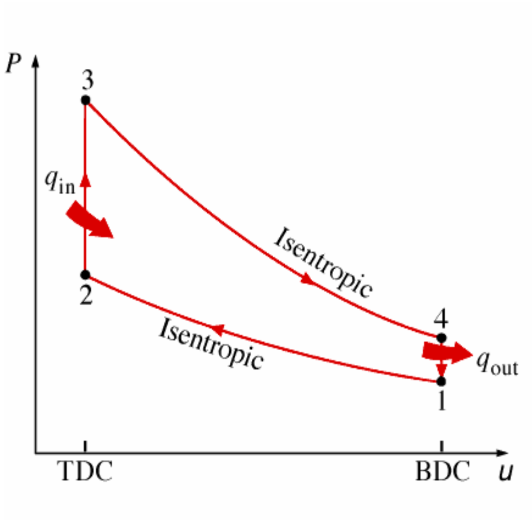
Compression Ratio

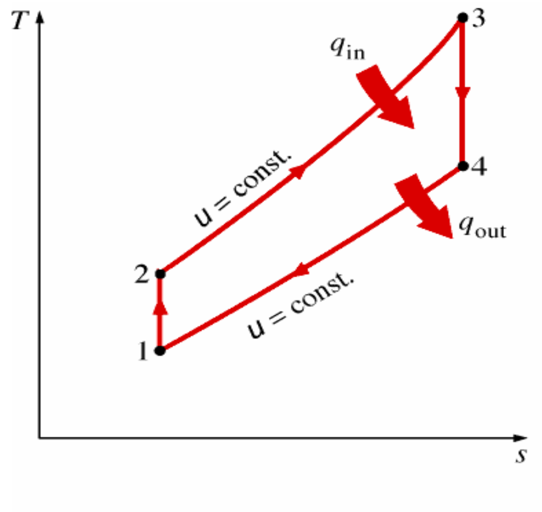
$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}}$$

Otto Cycle



End of combustion
P
Expansion
Ignition
Exhaust valve opens
v
Intake valve opens
Compression
Exhaust
P_{atm}
Intake
TDC
BDC
Exhaust gases
Air–fuel mixture
Air–fuel mixture
Compression stroke
Power (expansion) stroke
Exhaust stroke
Intake stroke
(a) Actual four-stroke spark-ignition engine
P
3
q_{in}
2
Isentropic
Isentropic
4
q_{out}
1
v
TDC
BDC
AIR
(2)
(1)
q_{in}
AIR
(2)–(3)
AIR
(3)
(4)
q_{out}
AIR
(4)–(1)
Isentropic compression
u = const. heat addition
Isentropic expansion
u = const. heat rejection
(b) Ideal Otto cycle





1-2 Isentropic Compression

2-3 Constant Volume Heat Addition

3-4 Isentropic Expansion

4-1 Constant Volume Heat Rejection

Thermal Efficiency of the Otto Cycle

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Apply First Law Closed System to Process 2-3, V = Constant

$$Q_{net,23} - W_{net,23} = \Delta U_{23}$$

$$W_{net,23} = W_{other,23} + W_{b,23} = 0 + \int_2^3 PdV = 0$$

$$Q_{net,23} = \Delta U_{23}$$

$$Q_{net,23} = Q_{in} = mC_v(T_3 - T_2)$$

Apply First Law Closed System to Process 4-1, V = Constant

$$Q_{net,41} - W_{net,41} = \Delta U_{41}$$

$$W_{net,41} = W_{other,41} + W_{b,41} = 0 + \int_4^1 PdV = 0$$

$$Q_{net,41} = \Delta U_{41}$$

$$Q_{net,41} = -Q_{out} = mC_v(T_1 - T_4)$$

$$Q_{out} = -mC_v(T_1 - T_4) = mC_v(T_4 - T_1)$$

$$\eta_{th,\,Otto} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$$

$\rightarrow$

$$\eta_{th,\,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1} \quad \text{and} \quad \frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{k-1}$$

$$v_3 = v_2 \ \text{ and } v_4 = v_1$$

$\rightarrow$

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

or

$$\frac{T_4}{T_1} = \frac{T_3}{T_2}$$

$$\eta_{th,\,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$= 1 - \frac{T_1}{T_2}\underbrace{\frac{(T_4 / T_1 - 1)}{(T_3 / T_2 - 1)}}_{1}$$

$$\eta_{th,\,Otto} = 1 - \frac{T_1}{T_2}$$

Is this the same as the Carnot efficiency?

Efficiency of the Otto Cycle vs. Carnot Cycle

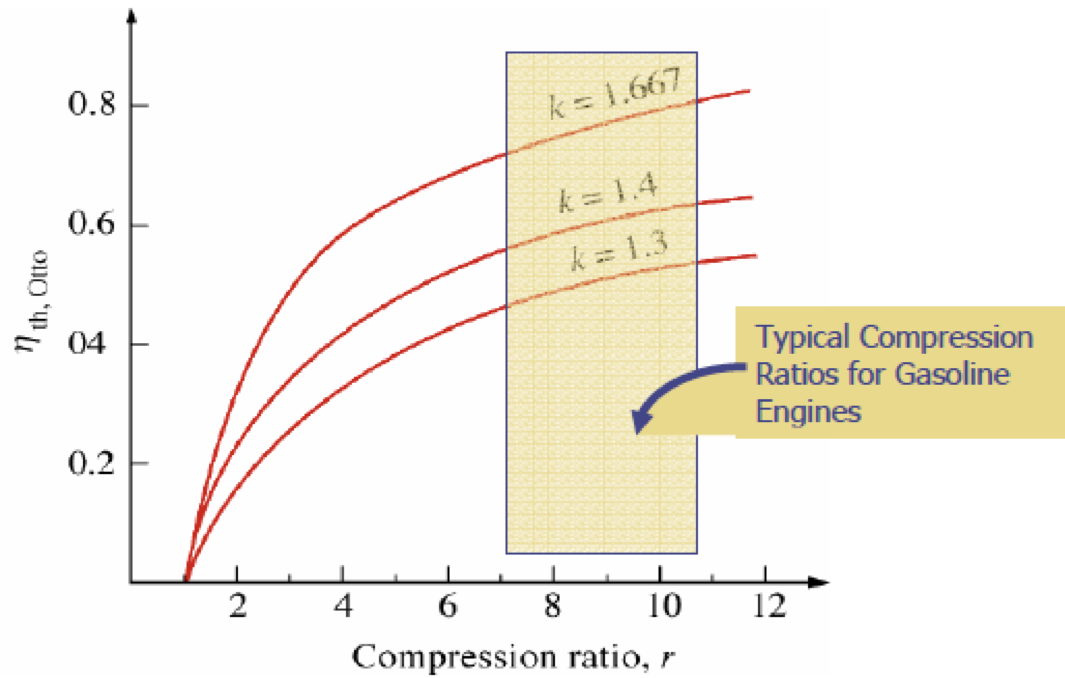
- There are only two temperatures in the Carnot cycle
  - Heat is added at T_H
  - Heat is rejected at T_L
- There are four temperatures in the Otto cycle!!
  - Heat is added over a range of temperatures
  - Heat is rejected over a range of temperatures

Since process 1-2 is isentropic,

$$\boxed{\frac{T_1}{T_2}} = \left(\frac{V_2}{V_1}\right)^{k-1} = \frac{1}{r^{k-1}}$$

$$\eta_{th,\,Otto} = 1 - \boxed{\frac{T_1}{T_2}}$$

$$\rightarrow \quad \eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$



Increasing Compression Ratio
Increases the Efficiency

THERMODYNAMIC DIAGRAMS AND DATA

The P-V-T Diagram

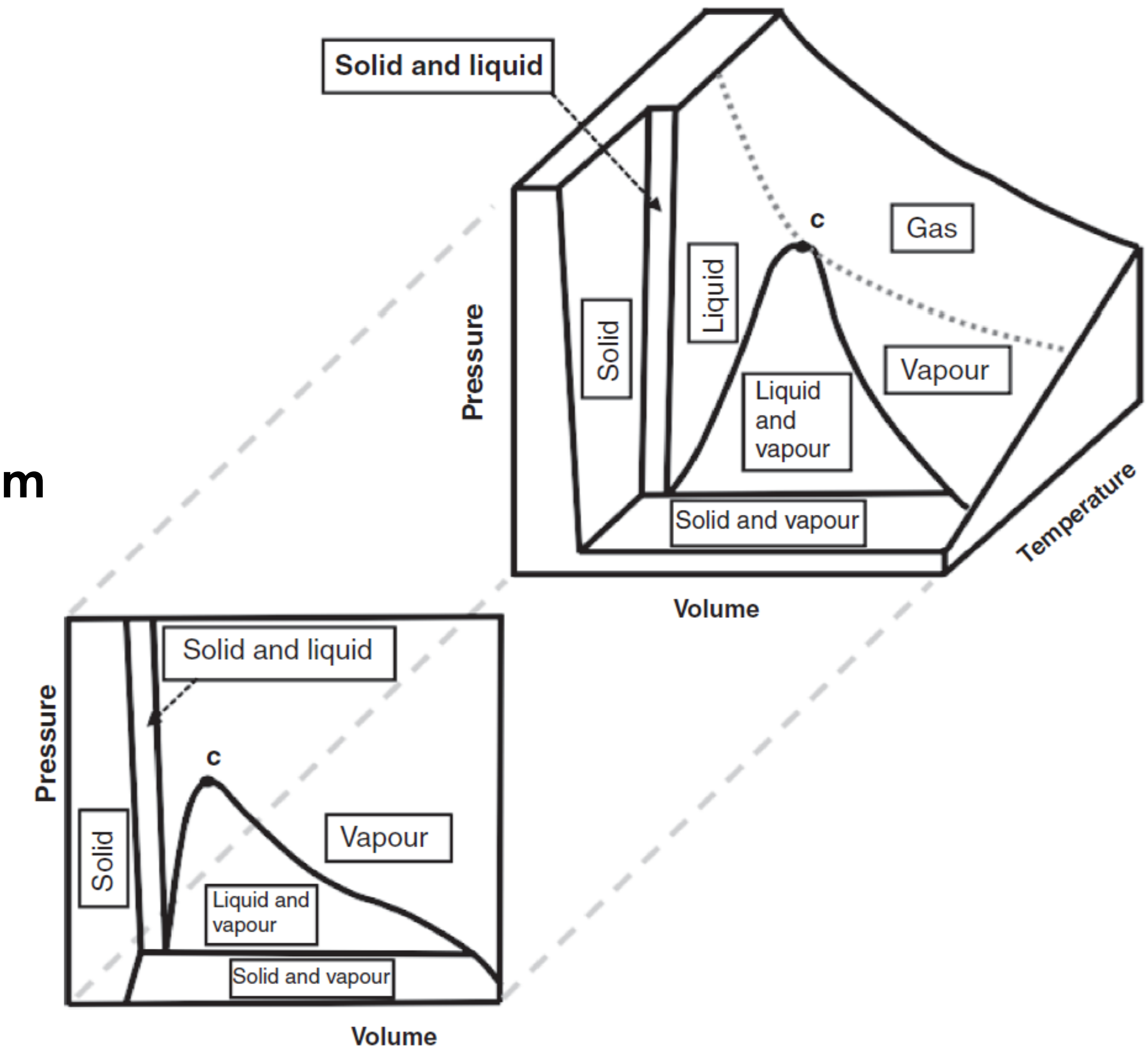


Figure 1.3 *P–V* perspective of a *P–V–T* diagram.

The P-V Diagram

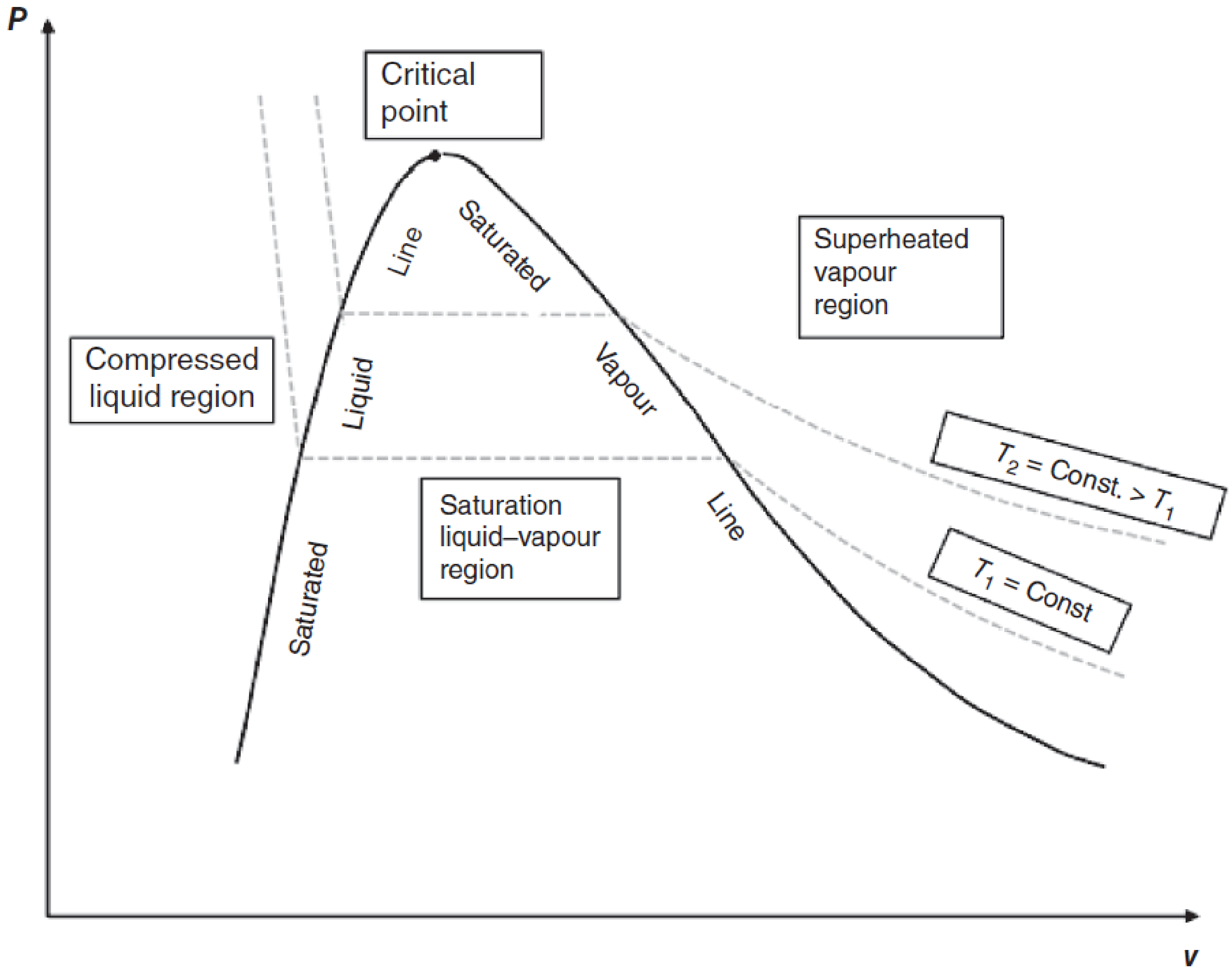


Figure 1.4 *P–V* diagram of a pure substance.

The P-T Diagram

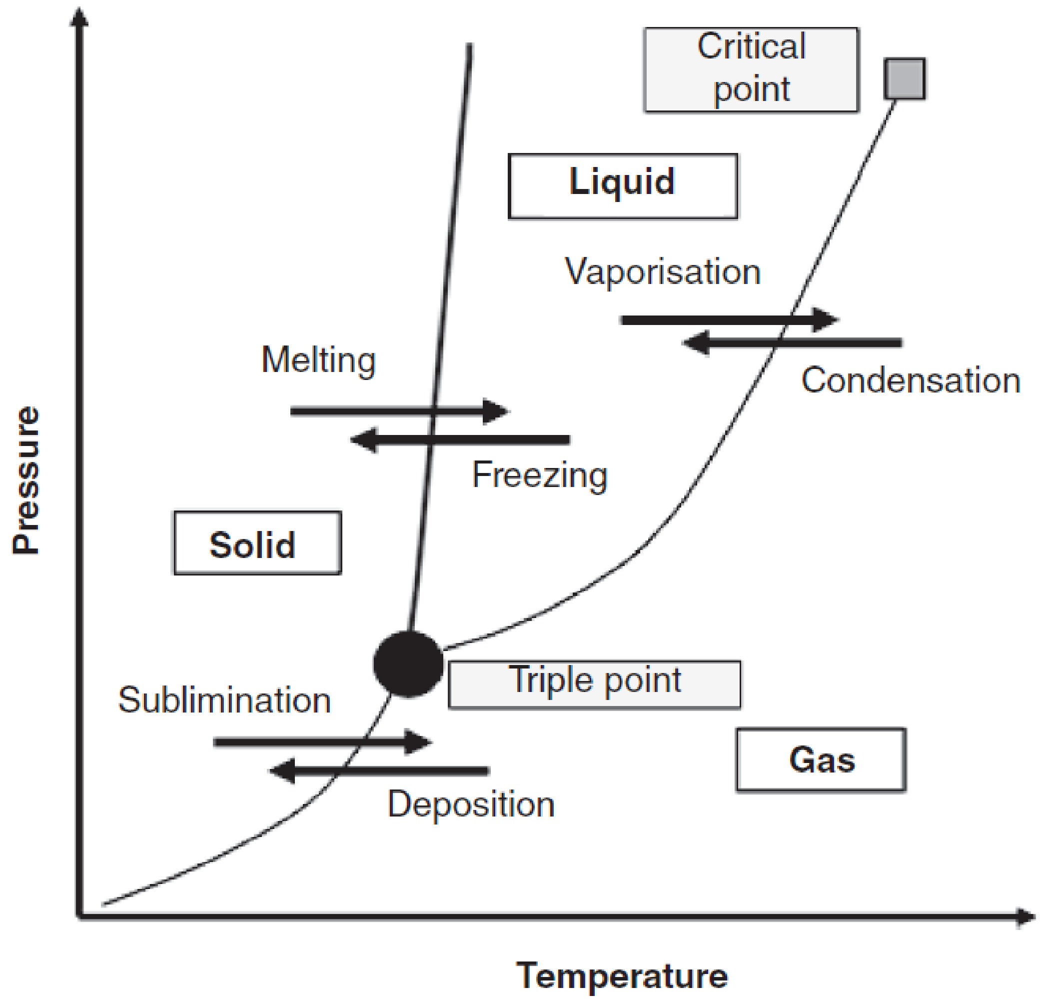


Figure 1.7 *P–T* diagram of a pure substance.

The T-V Diagram

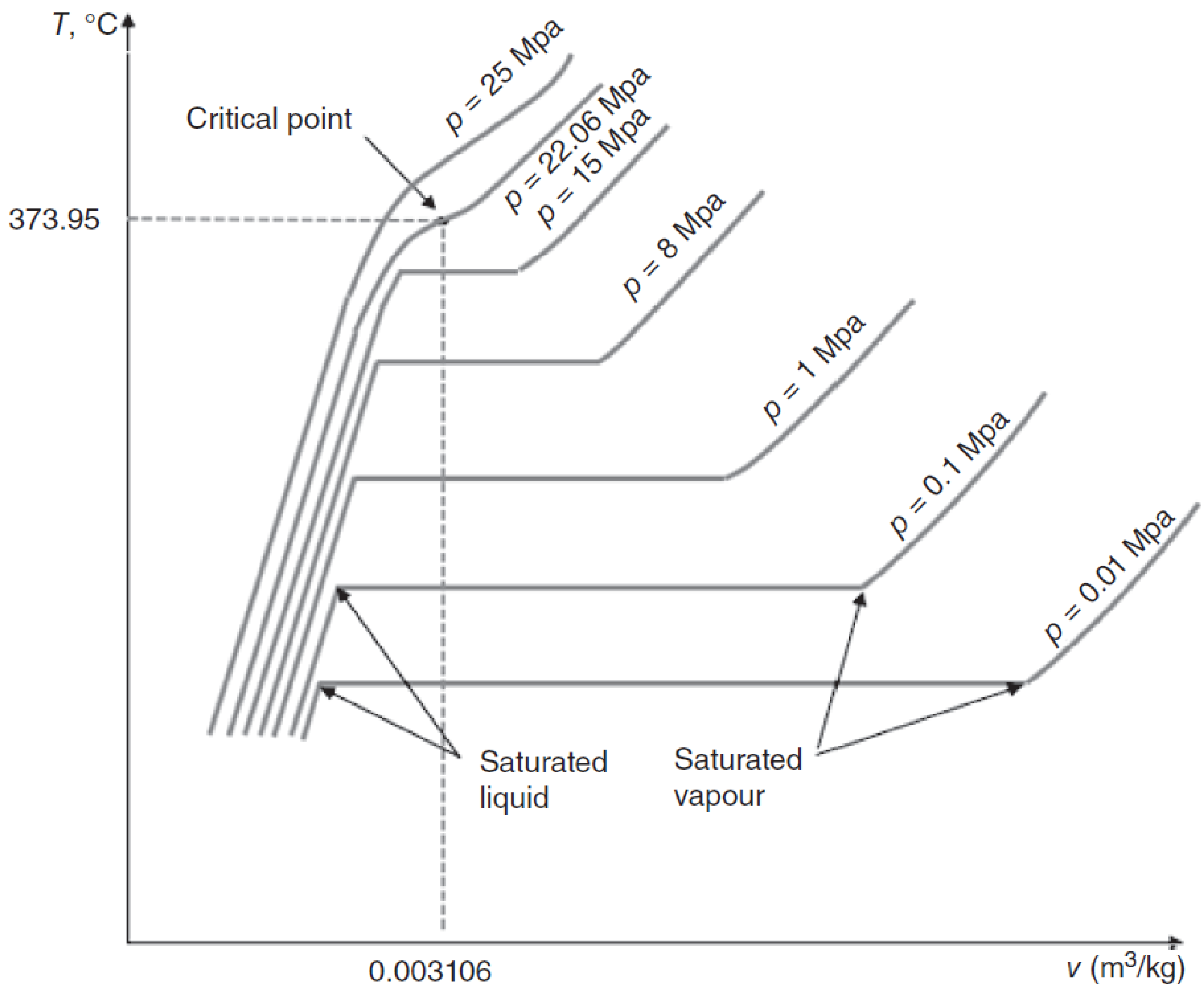


Figure 1.6 *T–V* diagram of a pure substance.

The H-S (Molier) Diagram

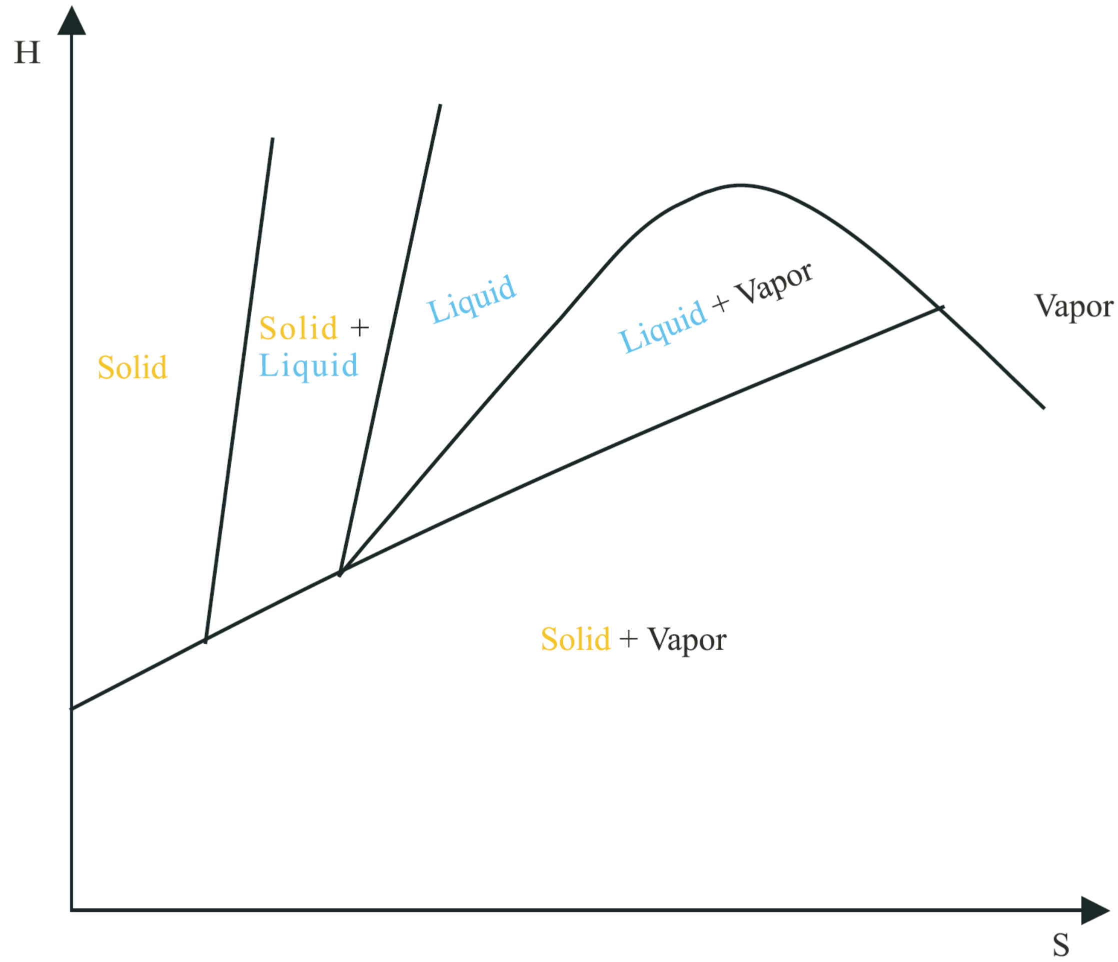
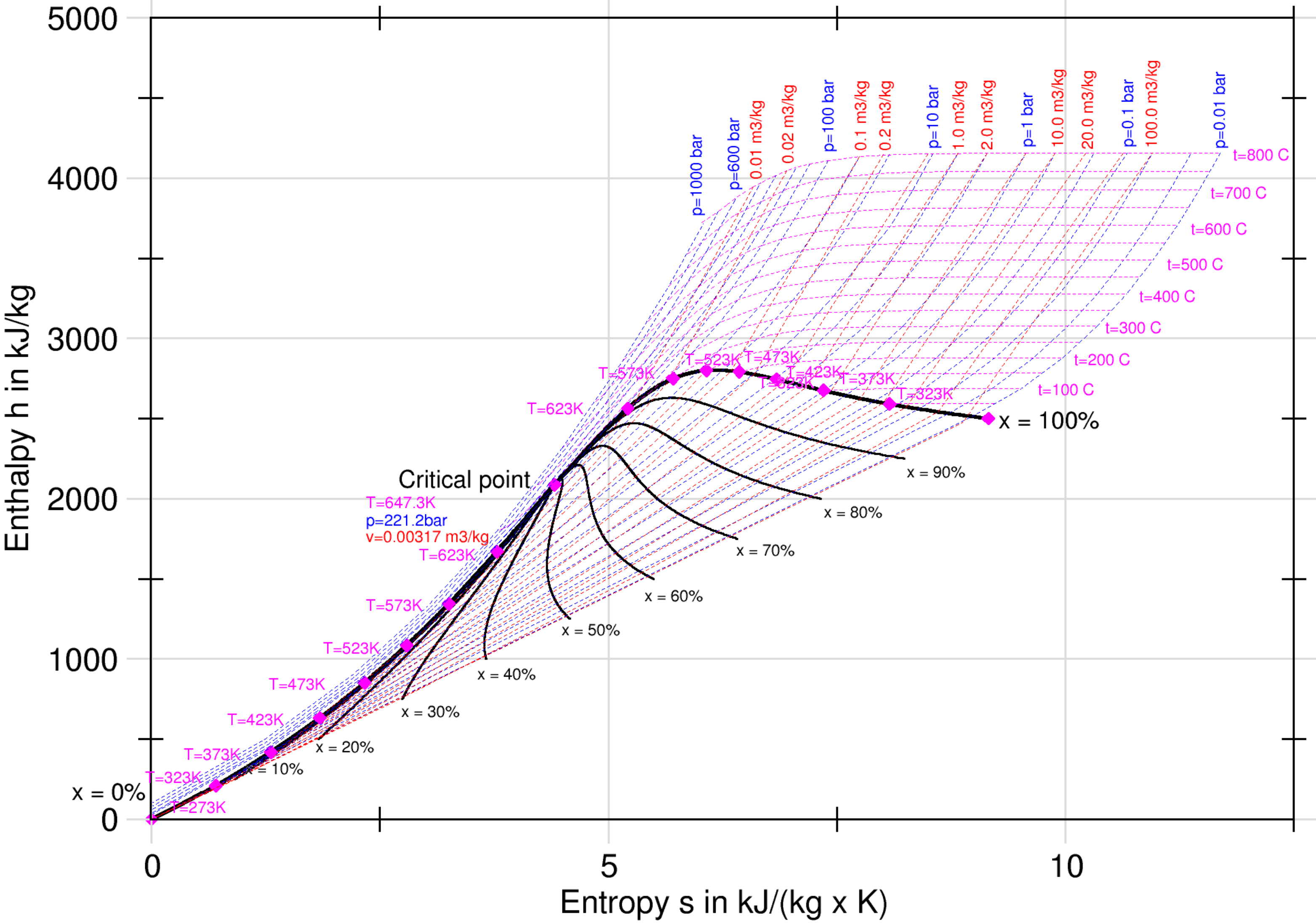


Figure: Enthalpy-entropy (Molier) diagram for a pure substance

Mollier-h, s Diagram

for Water Steam



The T-S Diagram

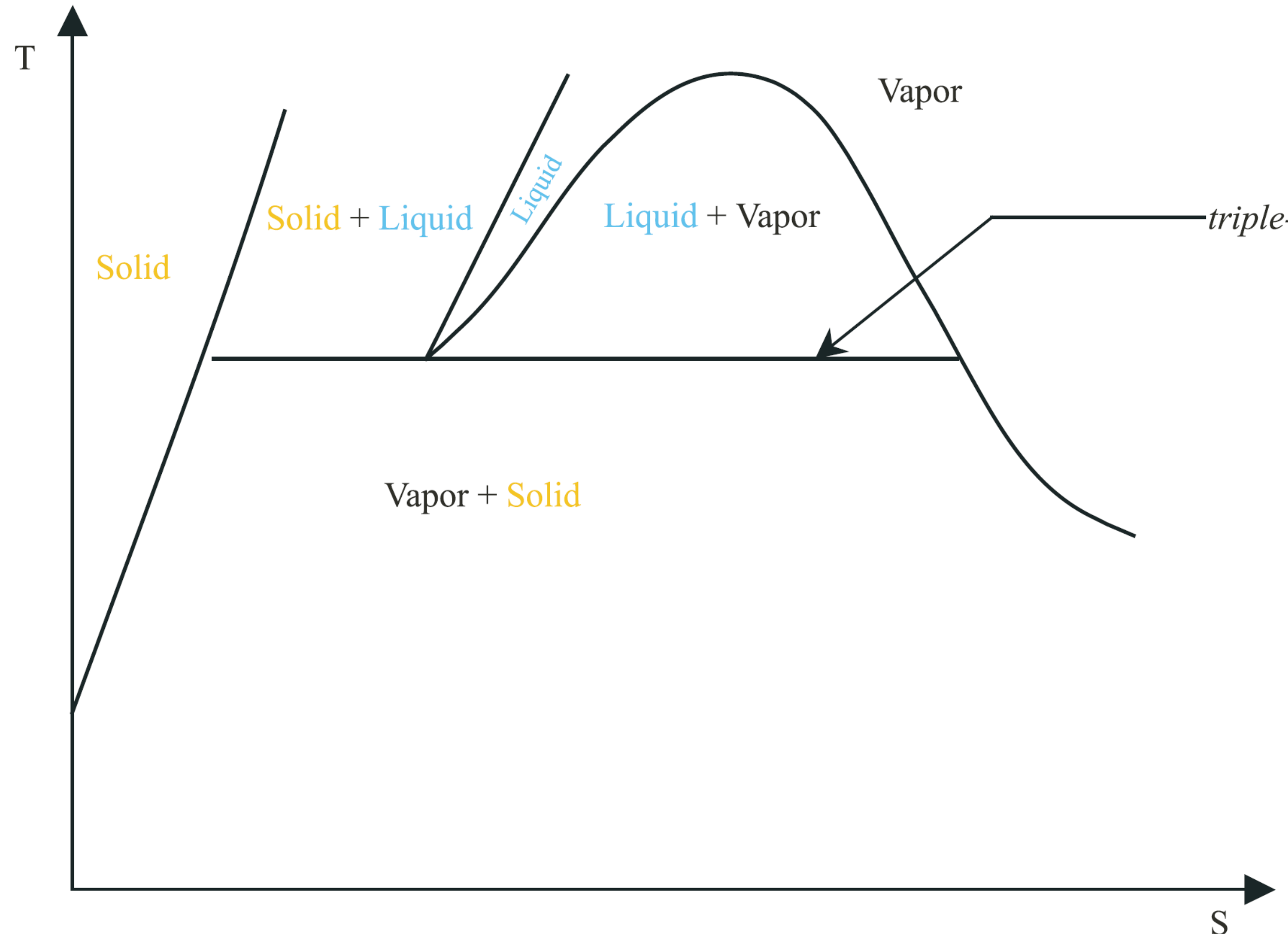


Figure: Temperature-entropy diagram for a pure substance

The Conventional Rankine Cycle

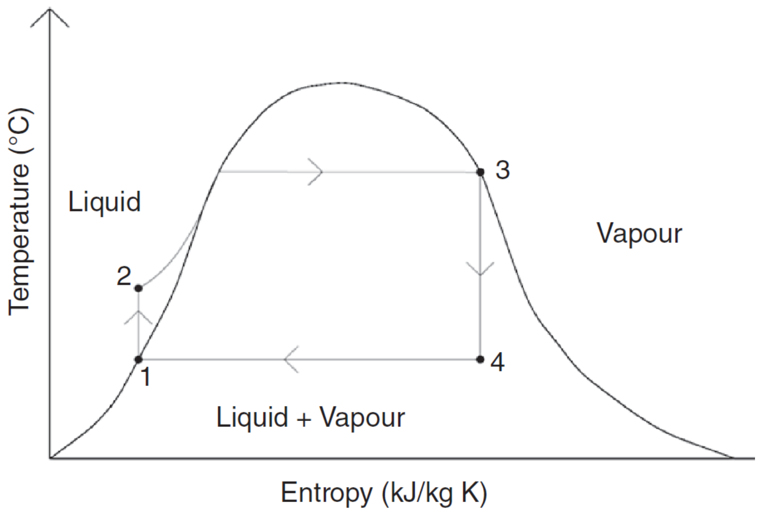
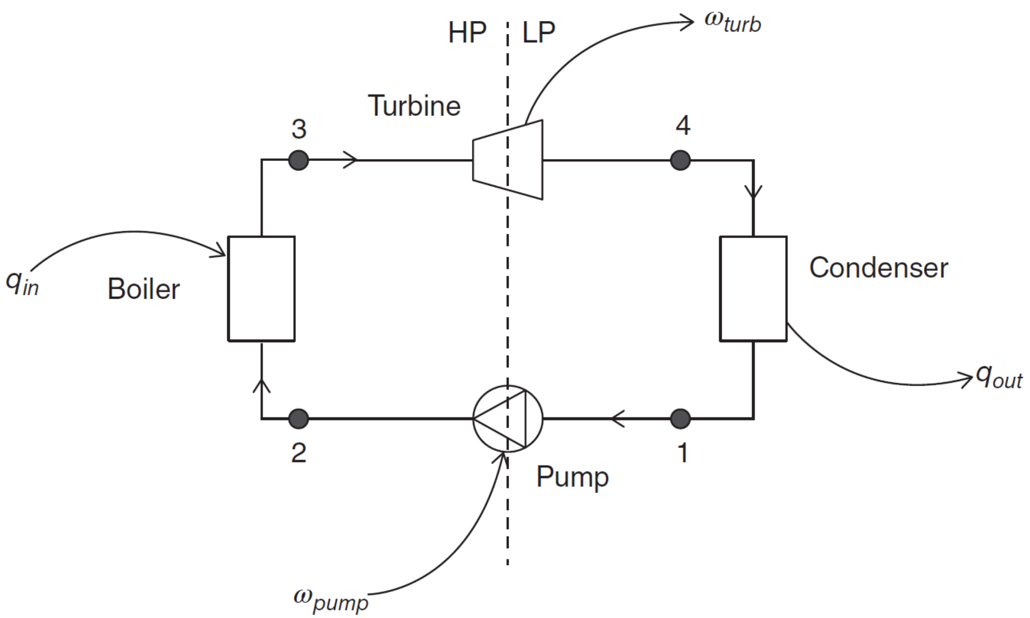


Figure 1.11 *T–s* diagram of the Rankine cycle.



- 1–2: Isentropic compression (pump). The fluid (in liquid state) is compressed while the specific entropy remains constant.
- 2–3: Isobaric heat addition inducing vaporization of the fluid (boiler), i.e. the fluid is heated under constant pressure and this results in a phase transition – the fluid changing from liquid to a mixture of liquid and vapor.
- 3–4: Isentropic expansion (turbine). The fluid is expanded through a turbine while the specific entropy again remains constant.
- 4–1: Isobaric heat rejection inducing liquefaction of the fluid (condenser), i.e. the fluid is cooled down under constant pressure and the vapor condenses

The Ideal Rankine Cycle

To describe the Rankine thermodynamic cycle, five physical variables are required:

1. The pressure P (Pa)
2. The temperature T (K)
3. The steam quality x, which represents the proportion of saturated vapor in a liquid/vapor mixture

$$x = \frac{m_{vapour}}{m_{vapour} + m_{liquid}}$$

where, *vapor* and m_{liquid} correspond, respectively, to the masses (kg) of the vapor and liquid contained in the mixture. (For example, at point number 1 on the T-s diagram, $x(1) = 0$, i.e. the fluid is a fully saturated liquid.)

4. The specific enthalpy of the fluid h (kJ/kg)
5. The specific entropy of the fluid s (kJ/kg K)

ω_{turb}, the work given by the fluid to the turbine (kJ/kg). It is negative as the fluid is giving work:

$$\omega_{turb} = h_4 - h_3 \tag{1.7}$$

ω_{pump}, the work given by the pump to the fluid (kJ/kg). It is positive as the pump gives work to the fluid:

$$\omega_{pump} = h_2 - h_1 \tag{1.8}$$

q_{in}, the heat given by the boiler to the fluid (kJ/kg). It is positive as the boiler gives heat to the fluid:

$$q_{in} = h_3 - h_2 \tag{1.9}$$

q_{out}, the heat given by the fluid to the condenser (kJ/kg). It is negative as the fluid rejects heat:

$$q_{out} = h_1 - h_4 \tag{1.10}$$

So, as the net work (ω_{net}) (kJ/kg) provided by the cycle is governed by:

$$\omega_{net} = \omega_{turb} + \omega_{pump} \tag{1.11}$$

Then the thermal efficiency (η_{th}) of the ideal Rankine cycle can be defined by:

$$\eta_{th} = \frac{|\omega_{turb}|}{q_{in}} \tag{1.12}$$

And hence the overall efficiency (η) of the ideal Rankine cycle can be defined by:

$$\eta = \frac{|\omega_{net}|}{q_{in}} = \frac{|\omega_{turb}| - \omega_{pump}}{q_{in}} \tag{1.13}$$

Substituting Eqs. (1.4)–(1.6) then leads to:

$$\eta = \frac{|h_4 - h_3| - (h_2 - h_1)}{h_3 - h_2} = \frac{h_3 - h_4 - (h_2 - h_1)}{h_3 - h_2} \tag{1.14}$$

In practice however, compared to the output of the turbine, the work input to the pump is very small. In which case, if ω_{pump} can be neglected compared to the other coefficients, we arrive at the useful approximation of:

$$\eta \approx \frac{h_3 - h_4}{h_3 - h_2} \tag{1.15}$$

So to estimate the efficiency of the system, we can also use the first law of thermodynamics which states that the net energy of a system is equal to 0, i.e.

$$\omega_{turb} + \omega_{pump} + q_{in} + q_{out} = 0 \tag{1.16}$$

And further assuming ω_{pump} is neglectable compared to the other coefficients gives:

$$|\omega_{turb}| \approx q_{in} - |q_{out}| \tag{1.17}$$

From which the efficiency of the ideal Rankine cycle can now be estimated from the following formula:

$$\eta \approx \frac{|\omega_{turb}|}{q_{in}} \approx \frac{q_{in} - |q_{out}|}{q_{in}} = 1 - \frac{|q_{out}|}{q_{in}} \tag{1.18}$$

The Superheated Rankine Cycle

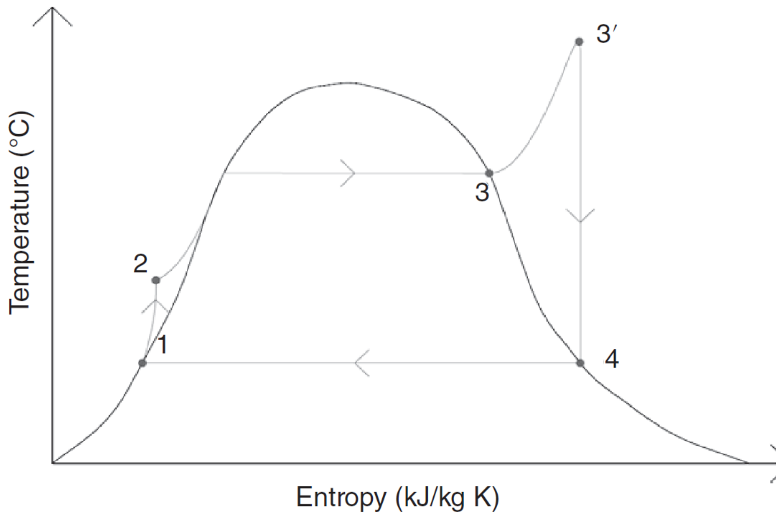


Figure 1.13 T–s diagram of the superheated Rankine cycle.

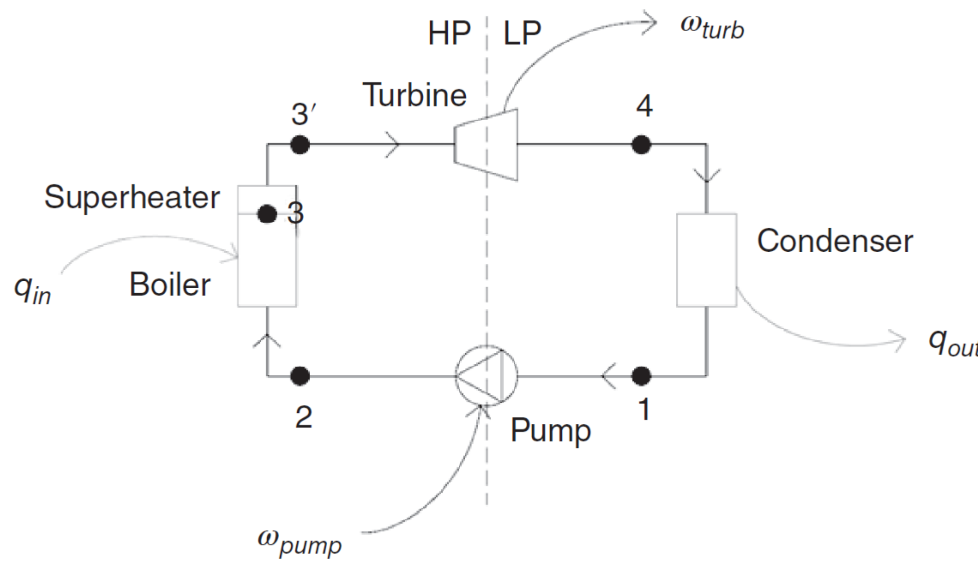
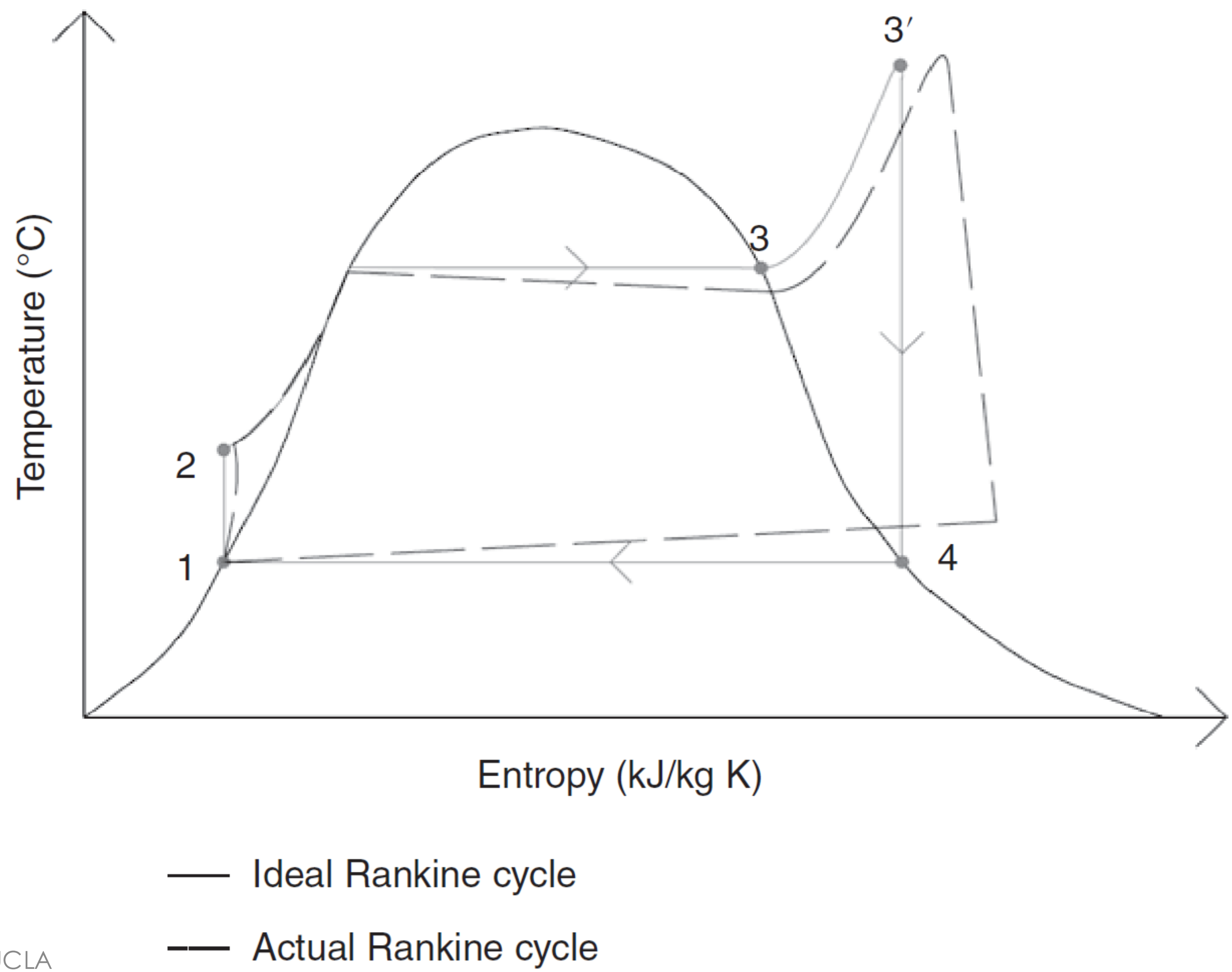


Figure 1.14 Schematic of the superheated Rankine cycle.

The efficiency of the superheated cycle is given by the same equation as the classical Rankine cycle (Eqs. (1.13) and (1.14)) – the difference being in the position of point 3′ (instead of 3), i.e.

$$\eta = \frac{h_3' - h_4 - (h_2 - h_1)}{h_3' - h_2} \tag{1.19}$$

The Actual Rankine Cycle



- In this cycle, friction caused by the moving fluid induces pressure losses or heat loss, and as a result the isobaric transformations described in the ideal Rankine cycle are not exactly isobaric in the actual cycle.

- Pressure drops in the condenser and in the turbine reduce the area of the cycle, as shown on the *T–s* diagram.

- Hence, the specific work of the cycle is lower for the actual cycle than for the ideal cycle.

- Furthermore, the isentropic transformations described in the ideal cycle are not reversible, as they are in the actual cycle: irreversibility deteriorates the performances of the pump and of the turbine. Hence, the efficiency is reduced.

Rankine Cycle with Reheat

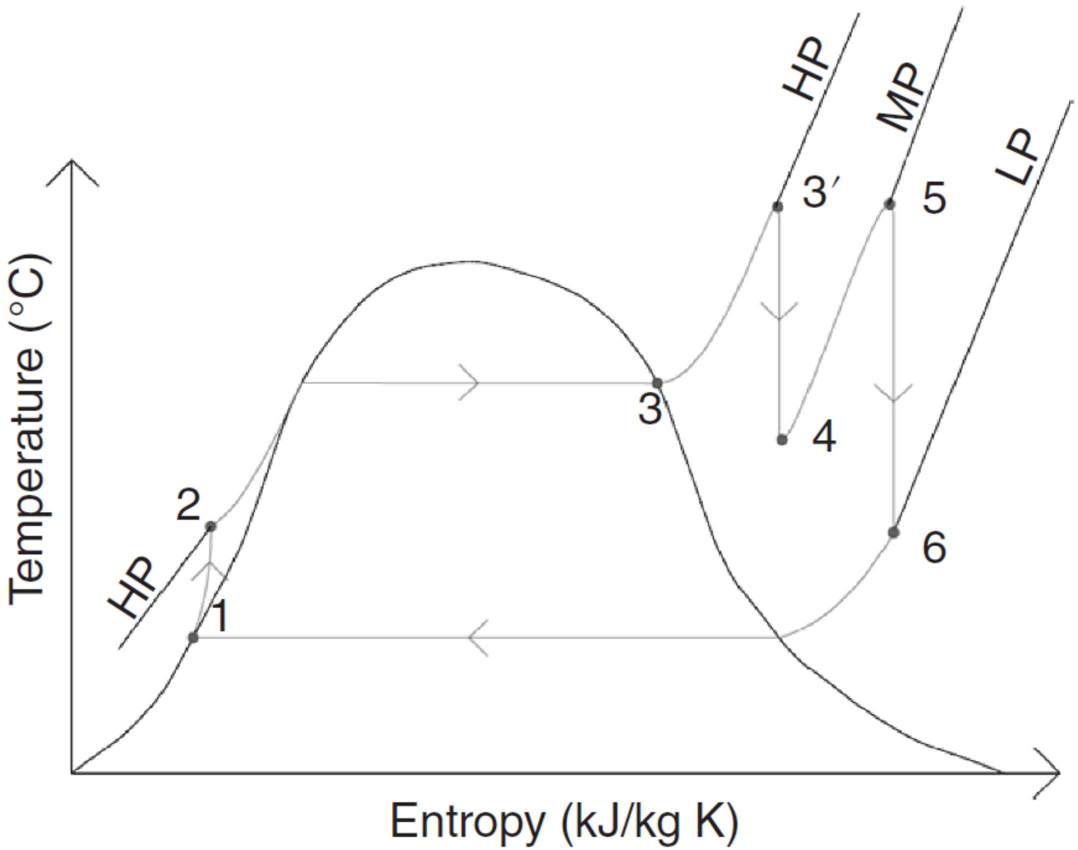


Figure 1.20 T–s diagram of a Rankine cycle with reheat.

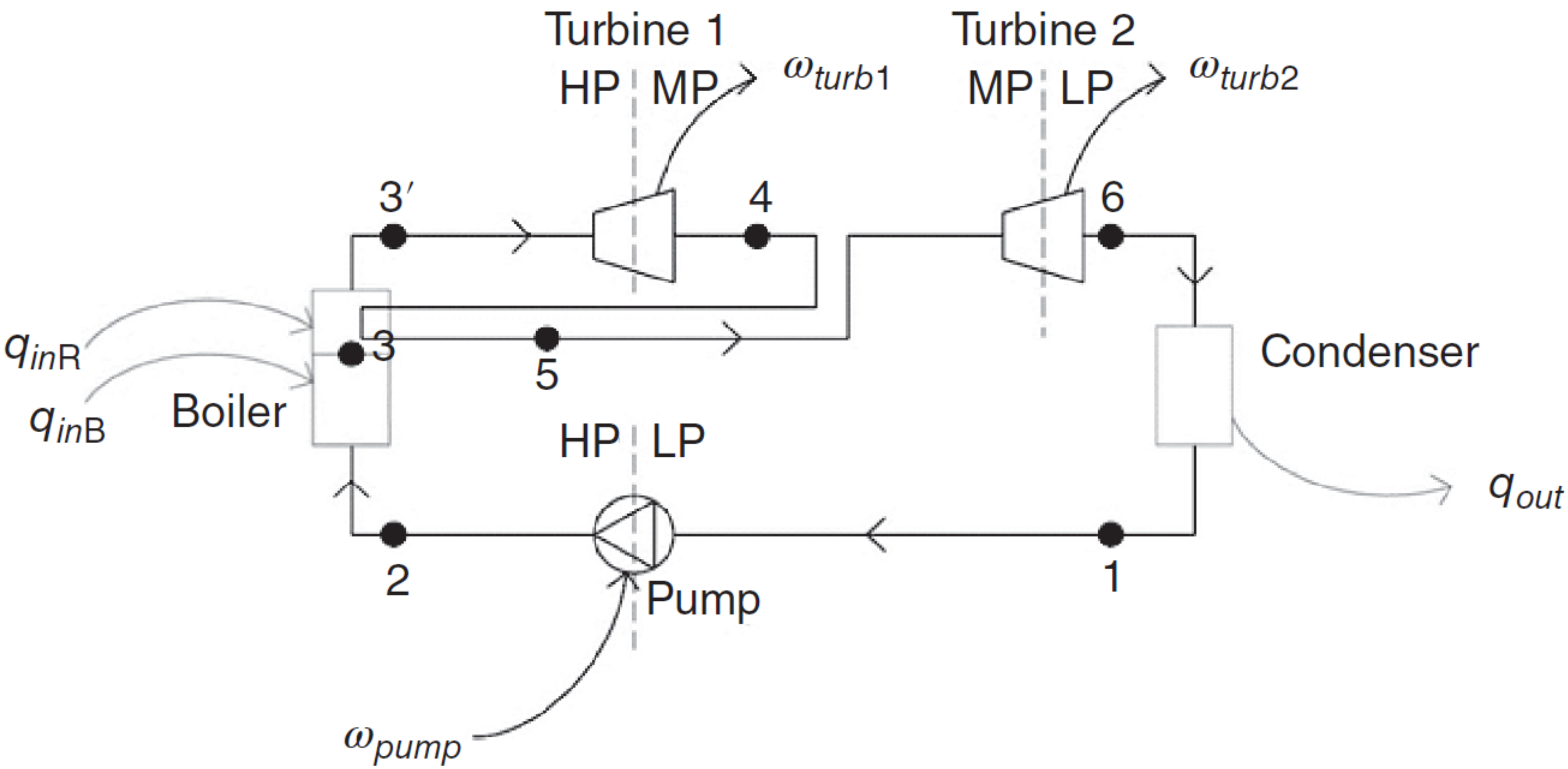


Figure 1.19 Schematic of the Rankine cycle with reheat.

Rankine cycles with reheat also ensure a higher overall mechanical efficiency by using two turbines for the cycle compared to only using one. In this configuration, the overall efficiency of the cycle is given by:

$$\eta = \frac{|\omega_{turb1}| + |\omega_{turb2}| - \omega_{pump}}{q_{inB} + q_{inR}} = \frac{|h_4 - h_3'| + |h_6 - h_5| - (h_2 - h_1)}{h_3' - h_2 + h_5 - h_4}$$

$$= \frac{h_3' - h_4 + h_5 - h_6 - (h_2 - h_1)}{h_3' - h_2 + h_5 - h_4} \quad (1.24)$$

where, q_{inB} corresponds to the heat (kJ/kg) provided by the boiler to the fluid and q_{inR} corresponds to the heat (kJ/kg) provided by the reheater to the fluid (In real-life power plant, the boiler and the superheater use the same heat source.)

Steam Tables: (1) Moran & Shapiro

TABLE A-2

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Temperature Table

H_2O

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24
25	0.03169	1.0029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580	25
26	0.03363	1.0032	40.994	109.06	2411.1	109.07	2439.9	2549.0	0.3814	8.5367	26
27	0.03567	1.0035	38.774	113.25	2412.5	113.25	2437.6	2550.8	0.3954	8.5156	27
28	0.03782	1.0037	36.690	117.42	2413.9	117.43	2435.2	2552.6	0.4093	8.4946	28
29	0.04008	1.0040	34.733	121.60	2415.2	121.61	2432.8	2554.5	0.4231	8.4739	29
30	0.04246	1.0043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533	30
31	0.04496	1.0046	31.165	129.96	2418.0	129.97	2428.1	2558.1	0.4507	8.4329	31
32	0.04759	1.0050	29.540	134.14	2419.3	134.15	2425.7	2559.9	0.4644	8.4127	32
33	0.05034	1.0053	28.011	138.32	2420.7	138.33	2423.4	2561.7	0.4781	8.3927	33
34	0.05324	1.0056	26.571	142.50	2422.0	142.50	2421.0	2563.5	0.4917	8.3728	34
35	0.05628	1.0060	25.216	146.67	2423.4	146.68	2418.6	2565.3	0.5053	8.3531	35
36	0.05947	1.0063	23.940	150.85	2424.7	150.86	2416.2	2567.1	0.5188	8.3336	36
38	0.06632	1.0071	21.602	159.20	2427.4	159.21	2411.5	2570.7	0.5458	8.2950	38
40	0.07384	1.0078	19.523	167.56	2430.1	167.57	2406.7	2574.3	0.5725	8.2570	40
45	0.09593	1.0099	15.258	188.44	2436.8	188.45	2394.8	2583.2	0.6387	8.1648	45

v_f = (table value)/1000

TABLE A-3

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Pressure Table

H_2O

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00
2.50	127.4	1.0672	0.7187	535.10	2537.2	535.37	2181.5	2716.9	1.6072	7.0527	2.50
3.00	133.6	1.0732	0.6058	561.15	2543.6	561.47	2163.8	2725.3	1.6718	6.9919	3.00
3.50	138.9	1.0786	0.5243	583.95	2546.9	584.33	2148.1	2732.4	1.7275	6.9405	3.50
4.00	143.6	1.0836	0.4625	604.31	2553.6	604.74	2133.8	2738.6	1.7766	6.8959	4.00
4.50	147.9	1.0882	0.4140	622.25	2557.6	623.25	2120.7	2743.9	1.8207	6.8565	4.50
5.00	151.9	1.0926	0.3749	639.68	2561.2	640.23	2108.5	2748.7	1.8607	6.8212	5.00
6.00	158.9	1.1006	0.3157	669.90	2567.4	670.56	2086.3	2756.8	1.9312	6.7600	6.00
7.00	165.0	1.1080	0.2729	696.44	2572.5	697.22	2066.3	2763.5	1.9922	6.7080	7.00
8.00	170.4	1.1148	0.2404	720.22	2576.8	721.11	2048.0	2769.1	2.0462	6.6628	8.00
9.00	175.4	1.1212	0.2150	741.83	2580.5	742.83	2031.1	2773.9	2.0946	6.6226	9.00
10.0	179.9	1.1273	0.1944	761.68	2583.6	762.81	2015.3	2778.1	2.1387	6.5863	10.0
15.0	198.3	1.1539	0.1318	843.16	2594.5	844.84	1947.3	2792.2	2.3150	6.4448	15.0
20.0	212.4	1.1767	0.09963	906.44	2600.3	908.79	1890.7	2799.5	2.4474	6.3409	20.0
25.0	224.0	1.1973	0.07998	959.11	2603.1	962.11	1841.0	2803.1	2.5547	6.2575	25.0
30.0	233.9	1.2165	0.06668	1004.8	2604.1	1008.4	1795.7	2804.2	2.6457	6.1869	30.0
35.0	242.6	1.2347	0.05707	1045.4	2603.7	1049.8	1753.7	2803.4	2.7253	6.1253	35.0
40.0	250.4	1.2522	0.04978	1082.3	2602.3	1087.3	1714.1	2801.4	2.7964	6.0701	40.0
45.0	257.5	1.2692	0.04406	1116.2	2600.1	1121.9	1676.4	2798.3	2.8610	6.0199	45.0
50.0	264.0	1.2859	0.03944	1147.8	2597.1	1154.2	1640.1	2794.3	2.9202	5.9734	50.0
60.0	275.6	1.3187	0.03244	1205.4	2589.7	1213.4	1571.0	2784.3	3.0267	5.8892	60.0
70.0	285.9	1.3513	0.02737	1257.6	2580.5	1267.0	1505.1	2772.1	3.1211	5.8133	70.0
80.0	295.1	1.3842	0.02352	1305.6	2569.8	1316.6	1441.3	2758.0	3.2068	5.7432	80.0
90.0	303.4	1.4178	0.02048	1350.5	2557.8	1363.3	1378.9	2742.1	3.2858	5.6772	90.0
100.	311.1	1.4524	0.01803	1393.0	2544.4	1407.6	1317.1	2724.7	3.3596	5.6141	100.
110.	318.2	1.4886	0.01599	1433.7	2529.8	1450.1	1255.5	2705.6	3.4295	5.5527	110.

v_f = (table value)/1000

TABLE A-4

Properties of Superheated Water Vapor

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

H_2O

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 0.06 bar = 0.006 MPa (T_{sat} = 36.16°C)				p = 0.35 bar = 0.035 MPa (T_{sat} = 72.69°C)			
Sat.	23.739	2425.0	2567.4	8.3304	4.526	2473.0	2631.4	7.7158
80	27.132	2487.3	2650.1	8.5804	4.625	2483.7	2645.6	7.7564
120	30.219	2544.7	2726.0	8.7840	5.163	2542.4	2723.1	7.9644
160	33.302	2602.7	2802.5	8.9693	5.696	2601.2	2800.6	8.1519
200	36.383	2661.4	2879.7	9.1398	6.228	2660.4	2878.4	8.3237
240	39.462	2721.0	2957.8	9.2982	6.758	2720.3	2956.8	8.4828
280	42.540	2781.5	3036.8	9.4464	7.287	2780.9	3036.0	8.6314
320	45.618	2843.0	3116.7	9.5859	7.815	2842.5	3116.1	8.7712
360	48.696	2905.5	3197.7	9.7180	8.344	2905.1	3197.1	8.9034
400	51.774	2969.0	3279.6	9.8435	8.872	2968.6	3279.2	9.0291
440	54.851	3033.5	3362.6	9.9633	9.400	3033.2	3362.2	9.1490
500	59.467	3132.3	3489.1	10.1336	10.192	3132.1	3488.8	9.3194
	p = 0.70 bar = 0.07 MPa (T_{sat} = 89.95°C)				p = 1.0 bar = 0.10 MPa (T_{sat} = 99.63°C)			
Sat.	2.365	2494.5	2660.0	7.4797	1.694	2506.1	2675.5	7.3594
100	2.434	2509.7	2680.0	7.5341	1.696	2506.7	2676.2	7.3614
120	2.571	2539.7	2719.6	7.6375	1.793	2537.3	2716.6	7.4668
160	2.841	2599.4	2798.2	7.8279	1.984	2597.8	2796.2	7.6597
200	3.108	2659.1	2876.7	8.0012	2.172	2658.1	2875.3	7.8343
240	3.374	2719.3	2955.5	8.1611	2.359	2718.5	2954.5	7.9949
280	3.640	2780.2	3035.0	8.3162	2.546	2779.6	3034.2	8.1445
320	3.905	2842.0	3115.3	8.4504	2.732	2841.5	3114.6	8.2849
360	4.170	2904.6	3196.5	8.5828	2.917	2904.2	3195.9	8.4175
400	4.434	2968.2	3278.6	8.7086	3.103	2967.9	3278.2	8.5435
440	4.698	3032.9	3361.8	8.8286	3.288	3032.6	3361.4	8.6636
500	5.095	3131.8	3488.5	8.9991	3.565	3131.6	3488.1	8.8342
	p = 1.5 bar = 0.15 MPa (T_{sat} = 111.37°C)				p = 3.0 bar = 0.30 MPa (T_{sat} = 133.55°C)			
Sat.	1.159	2519.7	2693.6	7.2233	0.606	2543.6	2725.3	6.9919
120	1.188	2533.3	2711.4	7.2693				
160	1.317	2595.2	2792.8	7.4665	0.651	2587.1	2782.3	7.1276
200	1.444	2656.2	2872.9	7.6433	0.716	2650.7	2865.5	7.3115
240	1.570	2717.2	2952.7	7.8052	0.781	2713.1	2947.3	7.4774
280	1.695	2778.6	3032.8	7.9555	0.844	2775.4	3028.6	7.6299
320	1.819	2840.6	3113.5	8.0964	0.907	2838.1	3110.1	7.7722
360	1.943	2903.5	3195.0	8.2293	0.969	2901.4	3192.2	7.9061
400	2.067	2967.3	3277.4	8.3555	1.032	2965.6	3275.0	8.0330
440	2.191	3032.1	3360.7	8.4757	1.094	3030.6	3358.7	8.1538
500	2.376	3131.2	3487.6	8.6466	1.187	3130.0	3486.0	8.3251
600	2.685	3301.7	3704.3	8.9101	1.341	3300.8	3703.2	8.5892

TABLE A-5

Properties of Compressed Liquid Water

T °C	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 25 bar = 2.5 MPa (T_{sat} = 223.99°C)				p = 50 bar = 5.0 MPa (T_{sat} = 263.99°C)			
20	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
80	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
140	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
180	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
220	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
Sat.	1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202
	p = 75 bar = 7.5 MPa (T_{sat} = 290.59°C)				p = 100 bar = 10.0 MPa (T_{sat} = 311.06°C)			
20	.9984	83.50	90.99	.2950	.9972	83.36	93.33	.2945
40	1.0045	166.64	174.18	.5696	1.0034	166.35	176.38	.5686
80	1.0256	333.15	340.84	1.0704	1.0245	332.59	342.83	1.0688
100	1.0397	416.81	424.62	1.3011	1.0385	416.12	426.50	1.2992
140	1.0752	585.72	593.78	1.7317	1.0737	584.68	595.42	1.7292
180	1.1219	758.13	766.55	2.1308	1.1199	756.65	767.84	2.1275
220	1.1835	936.2	945.1	2.5083	1.1805	934.1	945.9	2.5039
260	1.2696	1124.4	1134.0	2.8763	1.2645	1121.1	1133.7	2.8699
Sat.	1.3677	1282.0	1292.2	3.1649	1.4524	1393.0	1407.6	3.3596
	p = 150 bar = 15.0 MPa (T_{sat} = 342.24°C)				p = 200 bar = 20.0 MPa (T_{sat} = 365.81°C)			
20	.9950	83.06	97.99	.2934	.9928	82.77	102.62	.2923
40	1.0013	165.76	180.78	.5666	.9992	165.17	185.16	.5646
80	1.0222	331.48	346.81	1.0656	1.0199	330.40	350.80	1.0624
100	1.0361	414.74	430.28	1.2955	1.0337	413.39	434.06	1.2917
140	1.0707	582.66	598.72	1.7242	1.0678	580.69	602.04	1.7193
180	1.1159	753.76	770.50	2.1210	1.1120	750.95	773.20	2.1147
220	1.1748	929.9	947.5	2.4953	1.1693	925.9	949.3	2.4870
260	1.2550	1114.6	1133.4	2.8576	1.2462	1108.6	1133.5	2.8459
300	1.3770	1316.6	1337.3	3.2260	1.3596	1306.1	1333.3	3.2071
Sat.	1.6581	1585.6	1610.5	3.6848	2.036	1785.6	1826.3	4.0139
	p = 250 bar = 25 MPa				p = 300 bar = 30.0 MPa			
20	.9907	82.47	107.24	.2911	.9886	82.17	111.84	.2899
40	.9971	164.60	189.52	.5626	.9951	164.04	193.89	.5607
100	1.0313	412.08	437.85	1.2881	1.0290	410.78	441.66	1.2844
200	1.1344	834.5	862.8	2.2961	1.1302	831.4	865.3	2.2893
300	1.3442	1296.6	1330.2	3.1900	1.3304	1287.9	1327.8	3.1741

v = (table value)/1000

v = (table value)/1000

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

H_2O

(2): https://webbook.nist.gov/chemistry/fluid/

Example on the Ideal Rankine Cycle

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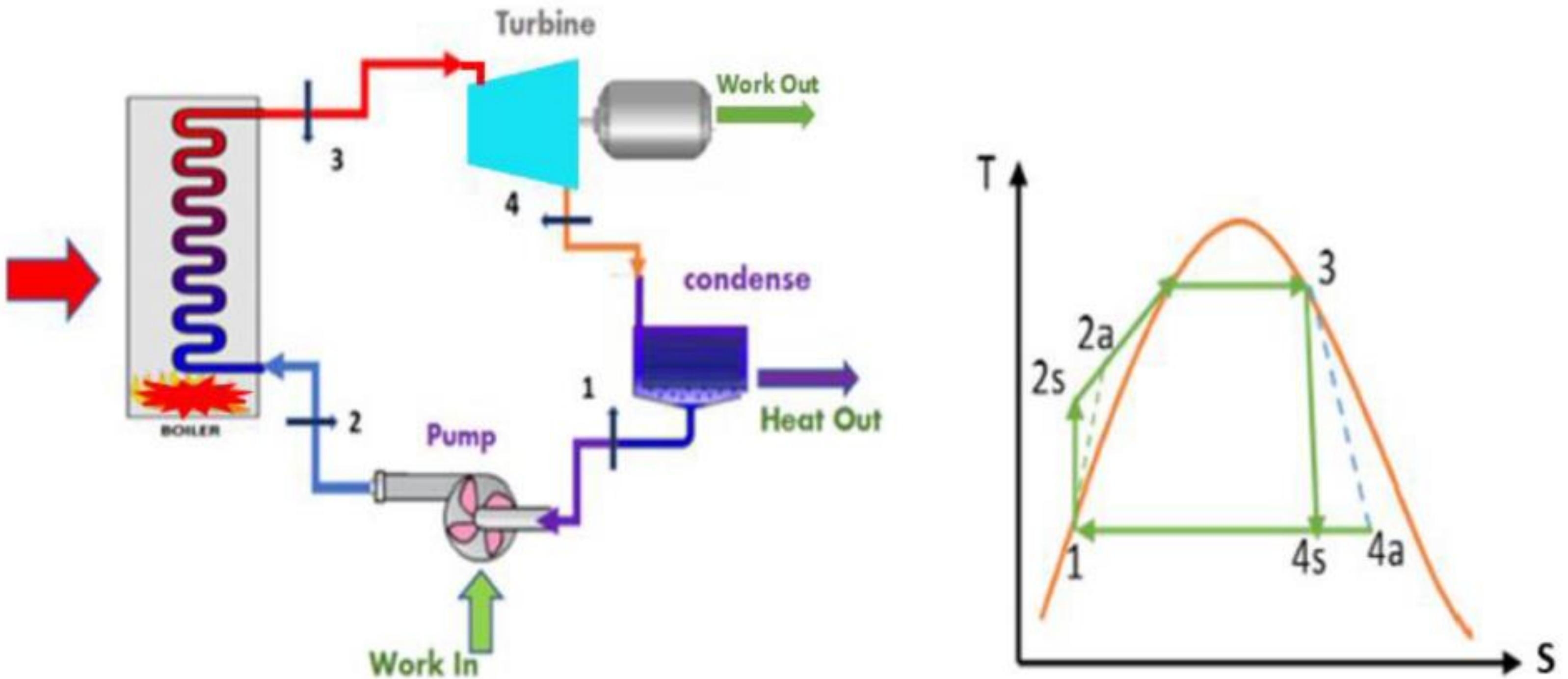

Figure 4.6. The simple Rankine cycle and T-s diagram.

2 Assumptions

For this example, we assume the following conditions:

- Boiler pressure: $P_1 = 8\,\text{MPa}$
- Condenser pressure: $P_2 = 10\,\text{kPa}$
- Turbine inlet temperature: $T_1 = 480°\text{C}$
- Steam is saturated at the outlet of the condenser.

3 State Point Calculations

3.1 State 1: Turbine Inlet (Boiler Outlet)

At the turbine inlet (superheated steam):

$$P_1 = 8\,\text{MPa}$$
$$T_1 = 480°\text{C}$$

From the steam tables for superheated steam at $P_1 = 8\,\text{MPa}$ and $T_1 = 480°\text{C}$:

$$h_1 = 3332\,\text{kJ/kg}$$
$$s_1 = 6.813\,\text{kJ/kg·K}$$

3.2 State 2: Turbine Outlet (Condenser Inlet)

At the turbine outlet:

$$P_2 = 10\,\text{kPa}$$
$$s_2 = s_1 = 6.813\,\text{kJ/kg·K}$$

From the steam tables for saturated steam at $P_2 = 10\,\text{kPa}$, we have:

$$s_g = 8.148\,\text{kJ/kg·K}$$
$$s_f = 0.6492\,\text{kJ/kg·K}$$

Using the quality equation:

$$x_2 = \frac{s_2 - s_f}{s_g - s_f} = \frac{6.813 - 0.6492}{8.148 - 0.6492} = 0.7807$$

Now, we calculate the enthalpy at state 2:

$$h_2 = h_f + x_2(h_g - h_f) = 191.8 + 0.7807(2392.8 - 191.8) = 1909.7\,\text{kJ/kg}$$

3.3 State 3: Pump Inlet (Condenser Outlet)

At the pump inlet, we assume saturated liquid:

$$P_2 = 10\,\text{kPa}$$
$$h_3 = h_f = 191.8\,\text{kJ/kg}$$

3.4 State 4: Pump Outlet (Boiler Inlet)

At the pump outlet:

$$h_4 = h_3 + v_3(P_1 - P_2)$$

From the steam tables, the specific volume of saturated liquid at 10 kPa is:

$$v_3 = 0.001010\,\mathrm{m^3/kg}$$

Now, calculate the enthalpy at state 4:

$$h_4 = 191.8 + 0.001010(8000 - 10) = 199.87\,\mathrm{kJ/kg}$$

4 Work and Heat Calculations

4.1 Turbine Work

The turbine work is calculated as:

$$W_{\text{turbine}} = h_1 - h_2 = 3332 - 1909.7 = 1422.3\,\mathrm{kJ/kg}$$

4.2 Pump Work

The pump work is calculated as:

$$W_{\text{pump}} = h_4 - h_3 = 199.87 - 191.8 = 8.07\,\text{kJ/kg}$$

4.3 Heat Added in the Boiler

The heat added in the boiler is:

$$Q_{\text{in}} = h_1 - h_4 = 3332 - 199.87 = 3132.13\,\text{kJ/kg}$$

4.4 Heat Rejected in the Condenser

The heat rejected in the condenser is:

$$Q_{\text{out}} = h_2 - h_3 = 1909.7 - 191.8 = 1717.9\,\text{kJ/kg}$$

5 Efficiency Calculation

The thermal efficiency of the Rankine cycle is given by:

$$\eta = \frac{W_{\text{net}}}{Q_{\text{in}}}$$

Where the net work is:

$$W_{\text{net}} = W_{\text{turbine}} - W_{\text{pump}} = 1422.3 - 8.07 = 1414.23\,\text{kJ/kg}$$

Thus, the efficiency is:

$$\eta = \frac{1414.23}{3132.13} = 0.4516 \text{ or } 45.16\%$$