Department of Air Conditioning and Refrigeration Engineering Technology

Class: 2nd

Subject: Thermodynamics

Assistant. Lecturer: Atheer Saleh

E-mail: **AtheerSaleh@mustaqbal-college.edu.iq**

Steam Power Plants

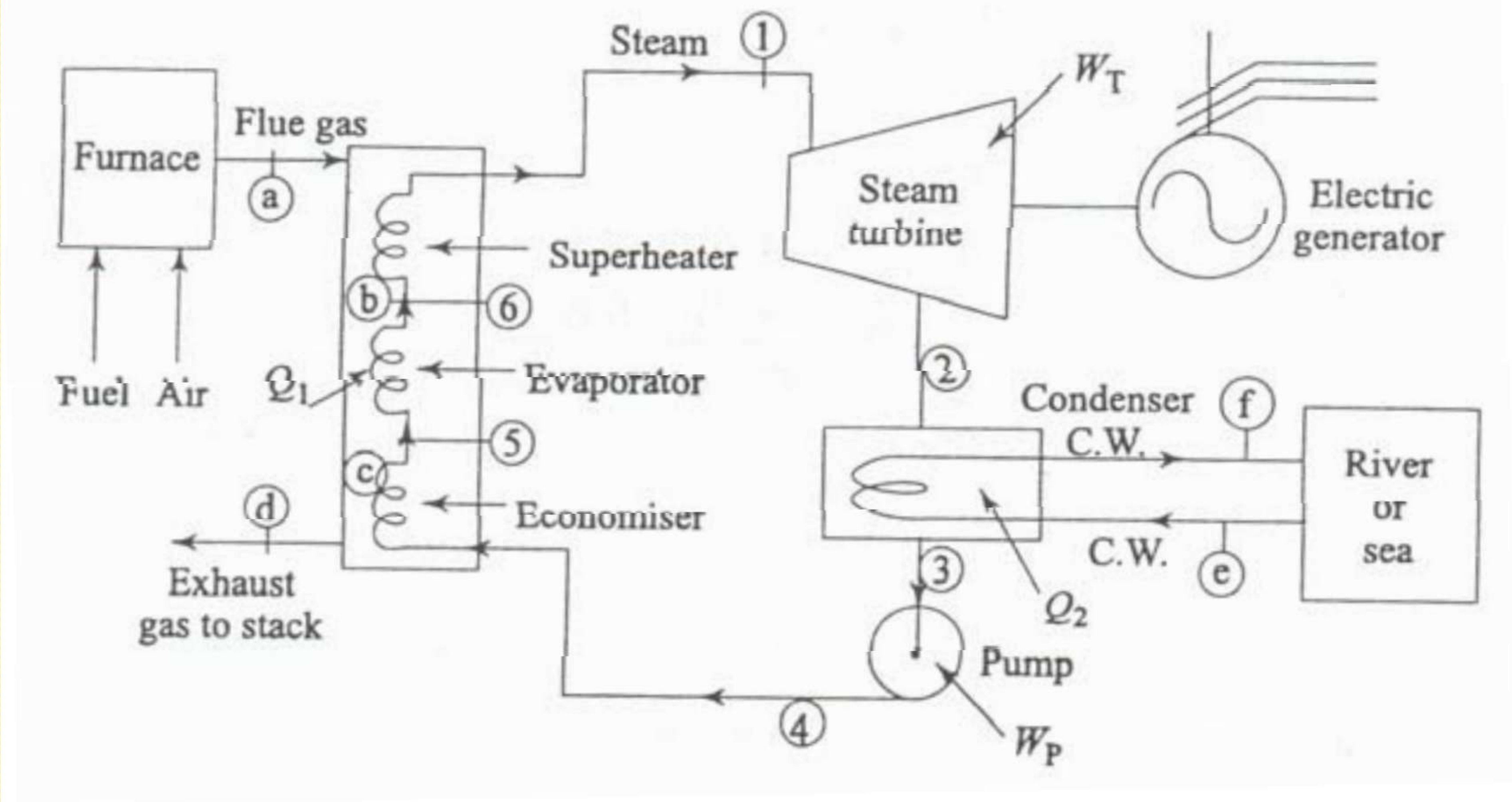


Figure shown : A simple steam power plant

Rankine Cycle

A- Simple ideal Rankine cycle

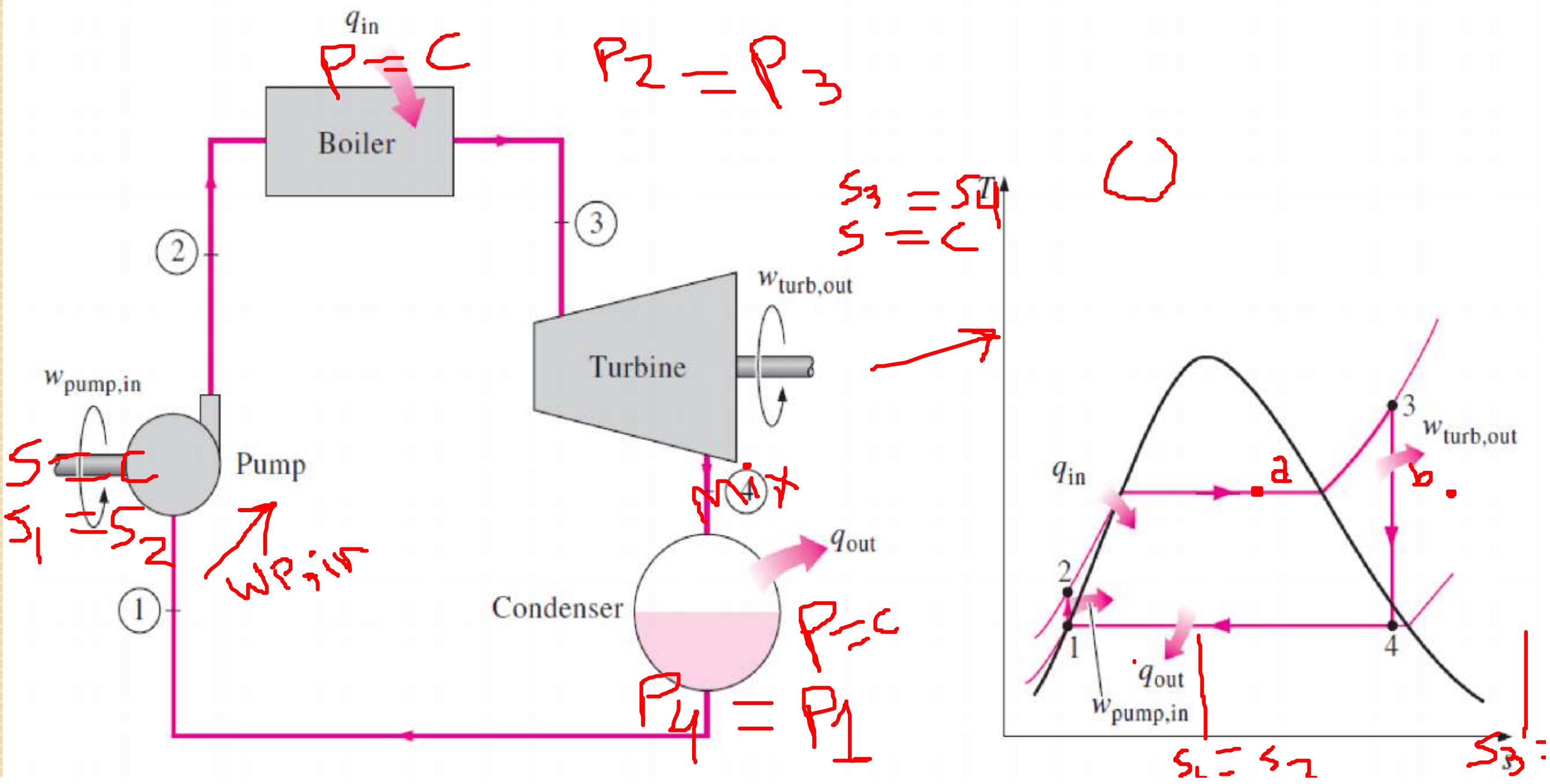
The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

Process (1-2), isentropic compression in a pump

Process (2-3), constant pressure heat addition in a boiler

Process (3-4), isentropic expansion in a turbine

Process (4-1), constant pressure heat rejection in a condenser



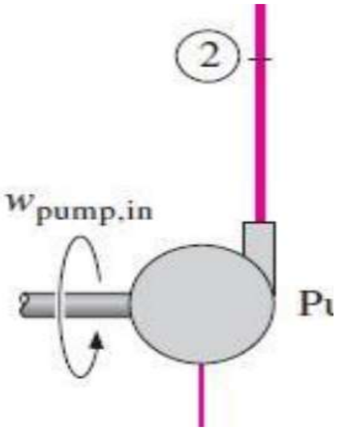
Energy Analysis of the Cycle

Energy Eq. $$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

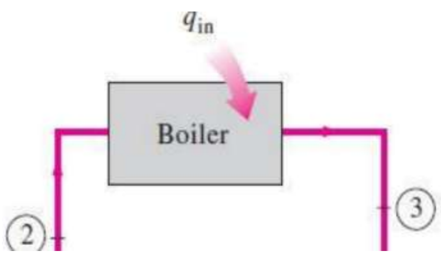
- For pump: $q = 0$ and $w_{pump} = h_2 - h_1$

  or $w_{pump} = v(P_2 - P_1)$

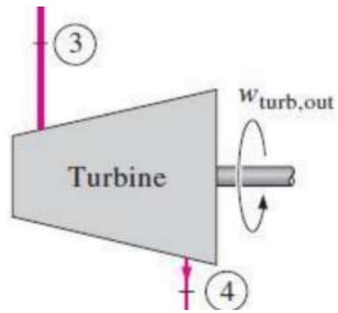
where: $h_1 = h_f$ and $v = v_1 = v_f$ at P_1



- For boiler: $w = 0$ and $q_{in} = h_3 - h_2$



- For turbine: $q = 0$ and $w_{turbine} = h_3 - h_4$

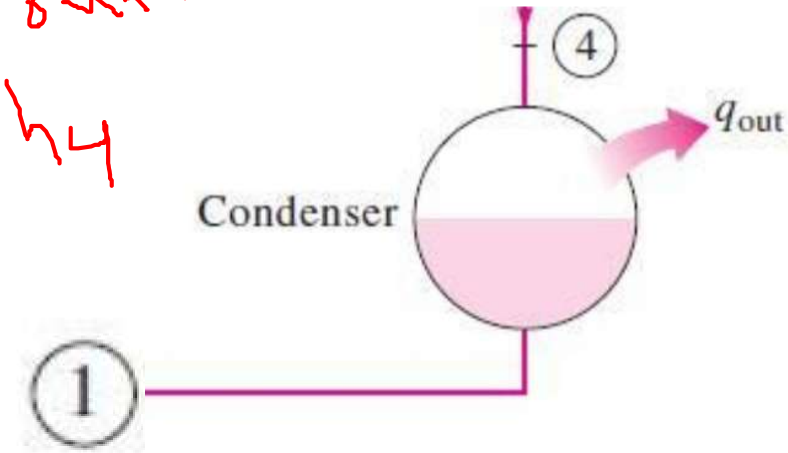


- For condenser: $w = 0$ and $q_{out} = h_4 - h_1$

$q_{out} = ?$

$-q_{out} = h_1 - h_4$

$q_{out} = h_4 - h_1$

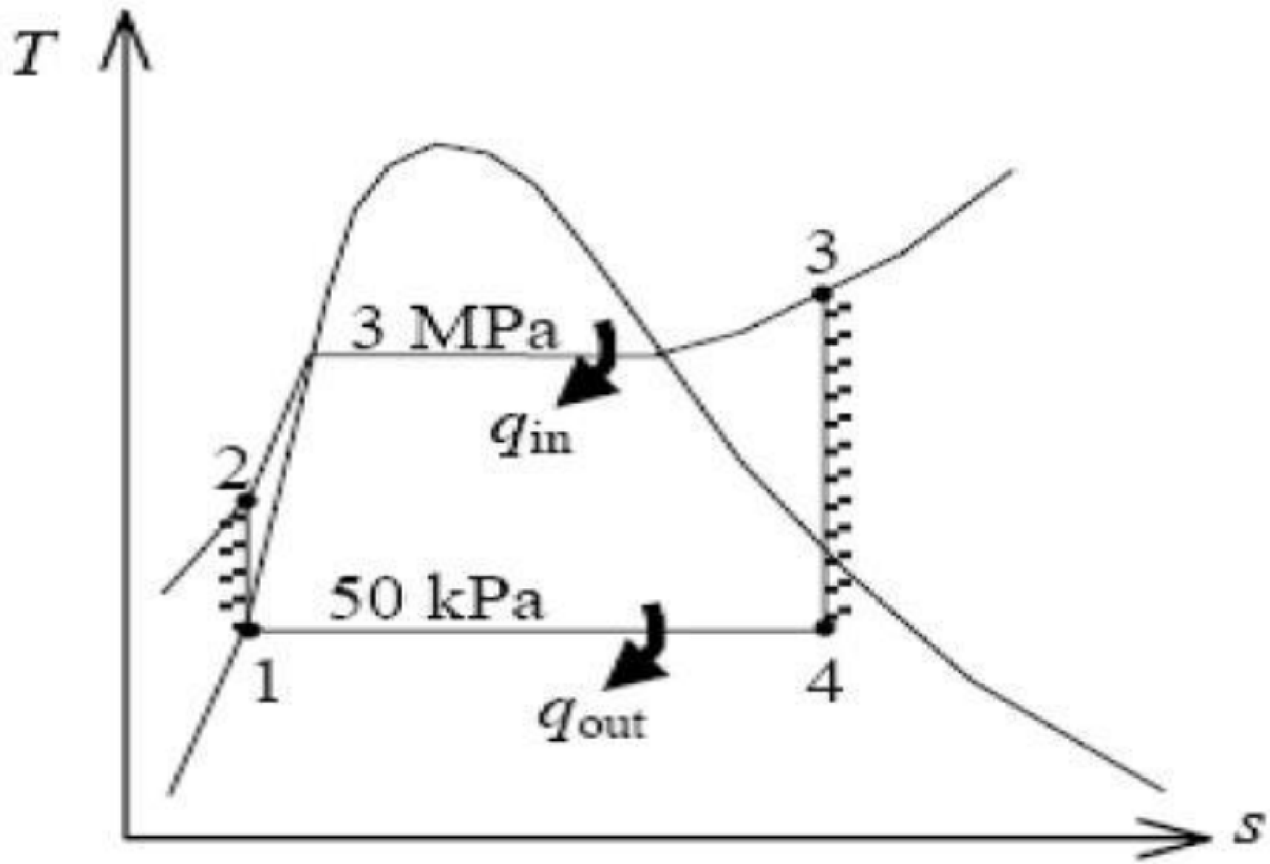


$$w_{net} = w_{turbine} - w_{pump} = q_{in} - q_{out}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Example (5.1): A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a (*T-S*) diagram with respect to the saturation lines, and determine: (a) the thermal efficiency of the cycle (b) the net power output of the power plant.

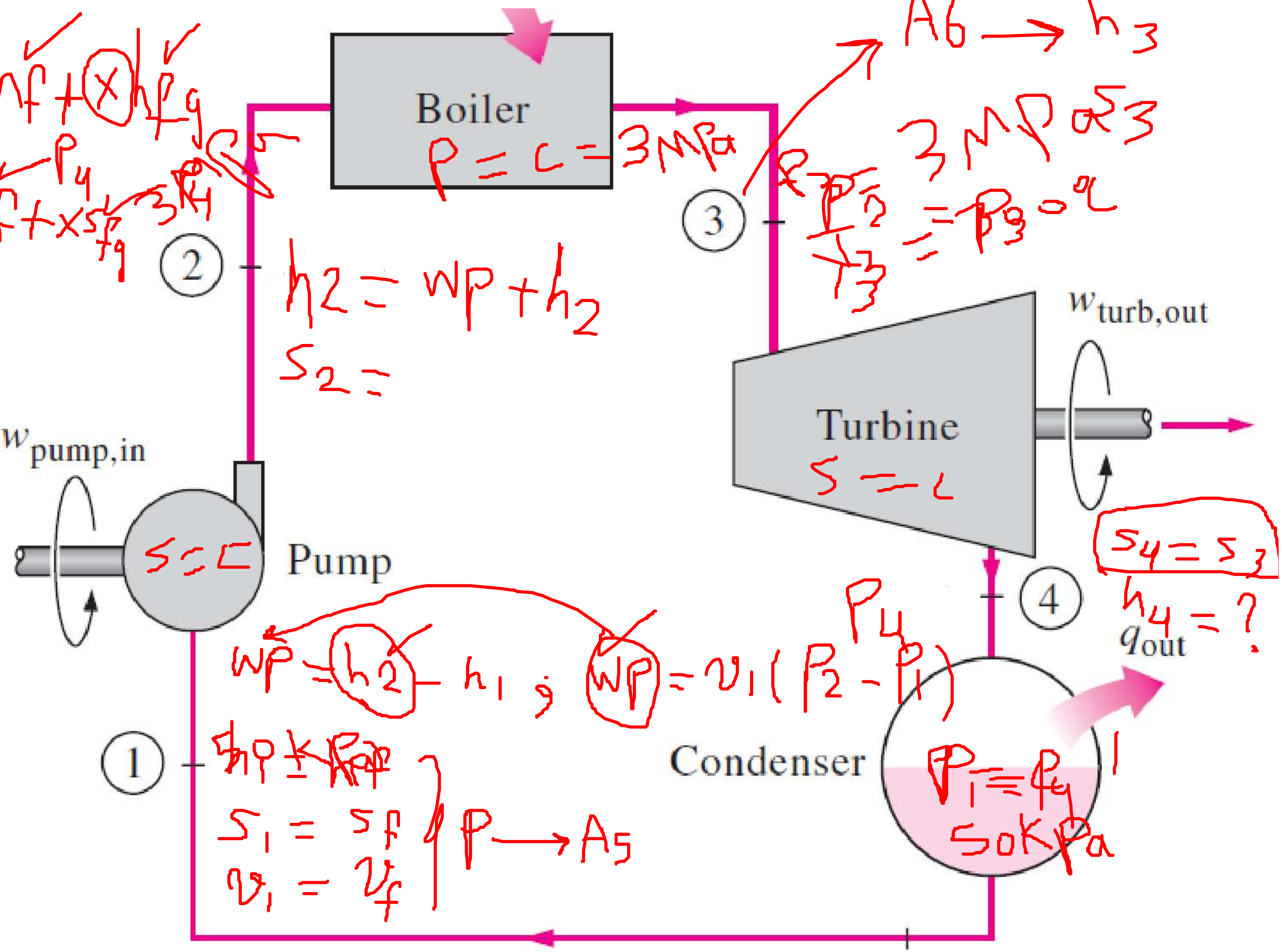
Solution:



$h_4 = h_f + x h_{fg}$

$s_4 = s_f + x s_{fg}$

x_4



$$h_1 = h_f = 340.54 \text{ kJ/kg} \quad \text{at} \quad P_1 = 50 \text{ kPa}$$

$$v_1 = v_f = 0.00103 \text{ m}^3\text{/kg} \quad \text{at} \quad P_1 = 50 \text{ kPa}$$

TABLE A–5

Saturated water—Pressure table

		v_1					h_1					
		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931

$$w_{pump} = v(P_2 - P_1) = 0.00103 \times (\overset{P_2}{3000} - \overset{P_1}{50}) = 3.04 \text{ kJ/kg}$$

$$w_{pump} = h_2 - h_1 \rightarrow h_2 = h_1 + w_{pump} = 340.54 + 3.04 = 343.58 \text{ kJ/kg}$$

$$\text{At } P_3 = 3 \text{ Mpa and } T_3 = 300°\text{C} \rightarrow h_3 = 2994.3 \text{ kJ/kg and } s_3 = 6.5412 \text{ kJ/kg.K}$$

TABLE A–6

Superheated water (*Continued*)

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	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 2.50 MPa (223.95°C)				*P* = 3.00 MPa (233.85°C)				*P* = 3.50 MPa (242.56°C)			
Sat.	0.07995	2602.1	2801.9	6.2558	0.06667	2603.2	2803.2	6.1856	0.05706	2603.0	2802.7	6.1244
225	0.08026	2604.8	2805.5	6.2629								
250	0.08705	2663.3	2880.9	6.4107	0.07063	2644.7	2856.5	6.2893	0.05876	2624.0	2829.7	6.1764
300	0.09894	2762.2	3009.6	6.6459	0.08118	2750.8	2994.3	6.5412	0.06845	2738.8	2978.4	6.4484

v_3 u_3 h_3 s_3

Mix

$$\text{At } P_4 = 50 \text{ kPa and } s_4 = s_3 \rightarrow x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.5412 - 1.0912}{6.5019} = 0.8382$$

$$h_4 = h_f + x_4 . h_{fg} = 340.54 + 0.8382 \times 2304.7 = 2272 \text{ kJ/kg}$$

x

$$q_{in} = h_3 - h_2 = 2994.3 - 343.58 = 2650.6 \text{ kJ/kg}$$

$$q_{out} = h_4 - h_1 = 2272.3 - 340.54 = 1931.8 \text{ kJ/kg}$$

$$w_{net} = q_{in} - q_{out} = 2650.6 - 1931.8 = 718.9 \text{ kJ/kg}$$

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1931.8}{2650.7}$$

$$\boldsymbol{\eta_{th} = 27.1\%} \qquad \textbf{Ans.}$$

$$Power = m^{\circ} \times w_{net} = 35 \times 718.9$$

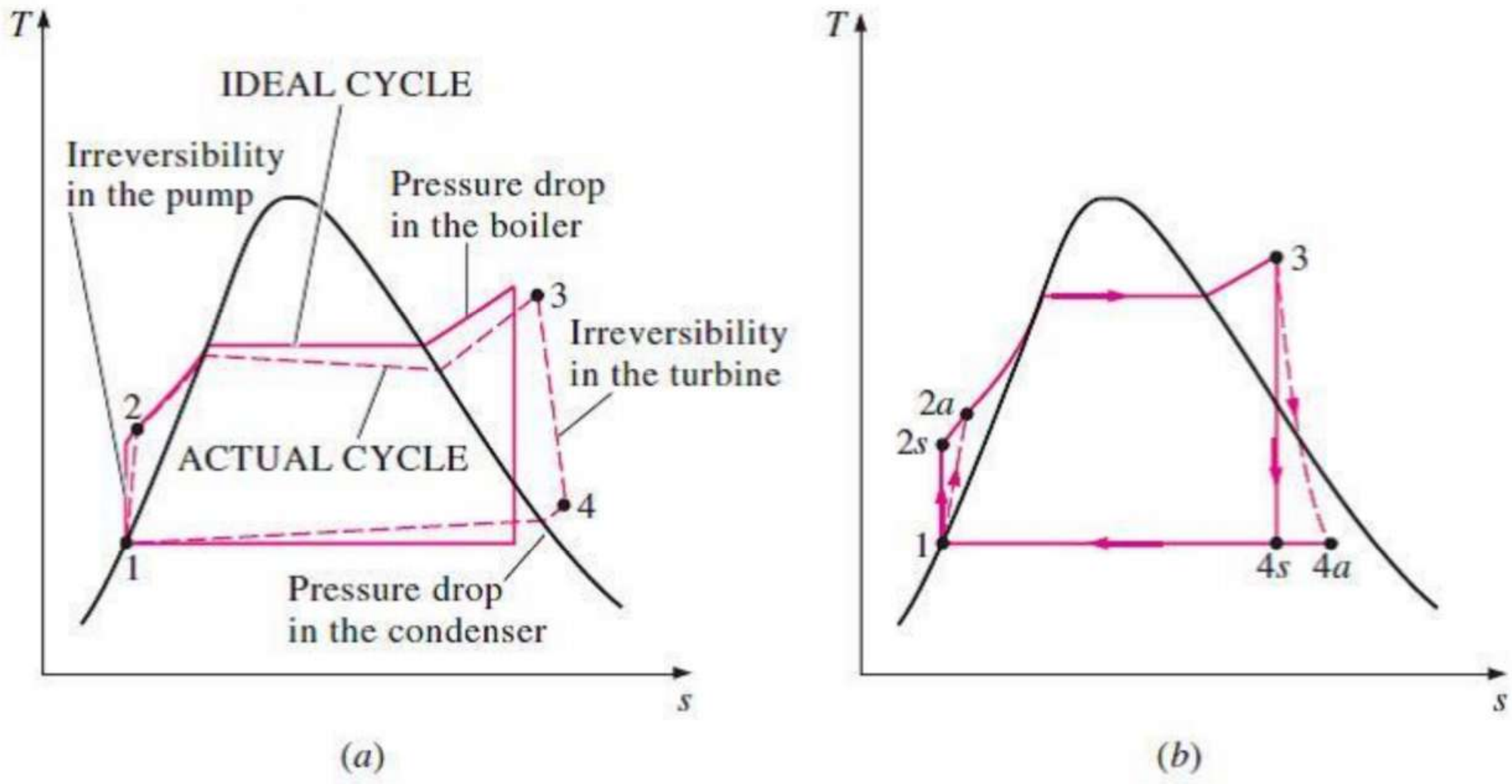
$$\boldsymbol{Power = 25.2 \text{ kW}} \qquad \textbf{Ans.}$$

B- Simple Actual Rankine cycle

$$\eta_P = \frac{w_{Ps}}{w_{Pa}} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \qquad \text{For pump}$$

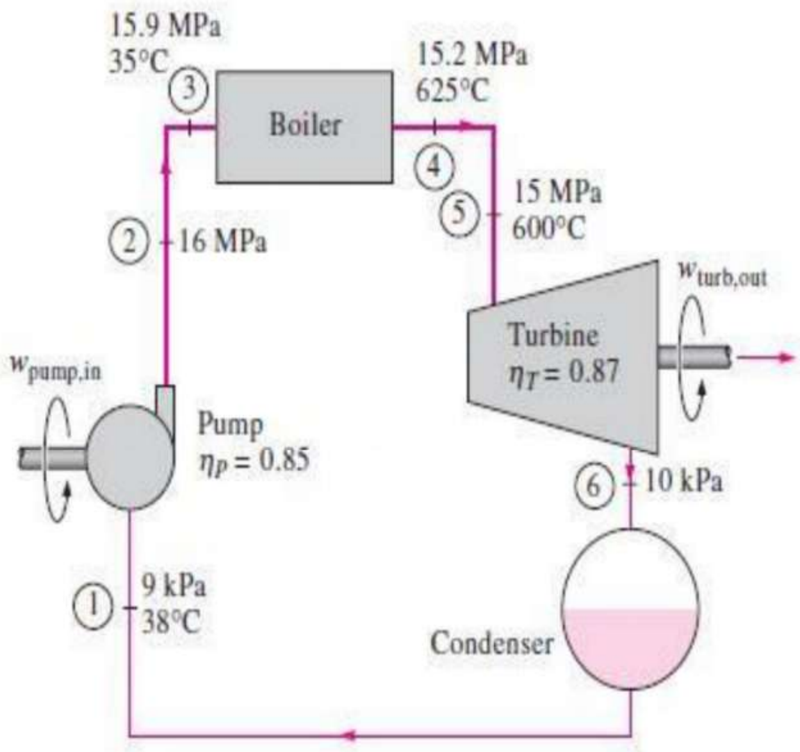
$$\eta_T = \frac{w_{Ta}}{w_{Ts}} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \qquad \text{For turbine}$$

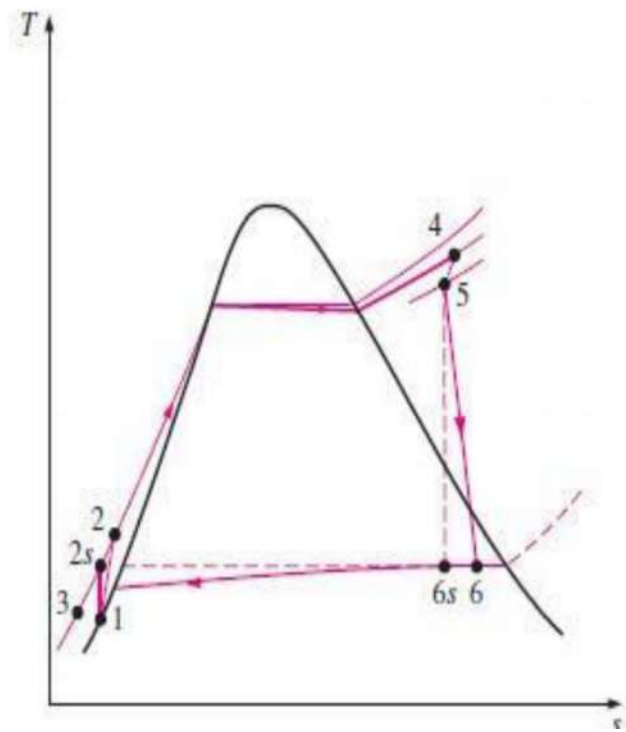
Where states **2a** and **4a** are the actual exit states of the pump and the turbine respectively, and **2s** and **4s** are the corresponding states for the isentropic case.



Example (5.2): A steam power plant operates on the cycle shown in the figure below. If the isentropic efficiency of the turbine is 87% and the isentropic efficiency of the pump is 85%, determine: (a) the thermal efficiency of the cycle (b) the net power output of the plant for a mass flow rate of 15 kg/s.

Solution:





a. The thermal efficiency of the cycle is the ratio of the net work output to the heat input.

$$\eta_P = \frac{w_{Ps}}{w_{Pa}} = \frac{v_1(P_2 - P_1)}{w_{Pa}} \rightarrow w_{Pa} = \frac{v_1(P_2 - P_1)}{\eta_P}$$

$$w_{Pa} = \frac{0.001009 \times (16 \times 10^3 - 9)}{0.85} = 18.98 \text{ kJ/kg}$$

$$\eta_T = \frac{w_{Ta}}{w_{Ts}} \rightarrow w_{Ta} = \eta_T \times w_{Ts} = \eta_T \times (h_5 - h_{6s})$$

$$w_{Ta} = 0.87 \times (3583.1 - 2115.3) = 1277 \text{ kJ/kg}$$

$$w_{net} = w_{Ta} - w_{pa} = 1277 - 18.98 = 1258.02 \text{ kJ/kg}$$

$$q_{add} = h_4 - h_3 = 3647.6 - 160.1 = 3487.5 \text{ kJ/kg}$$

$$\eta_{th} = \frac{w_{net}}{q_{add}} = \frac{1258.02}{3487.5}$$

$\boldsymbol{\eta_{th} = 36.1\%}$ **Ans.**

b. The net power output of the plant is:

$$Power = m^{\circ} \times w_{net} = 15 \times 1258.02$$

$$\boldsymbol{Power = 18.9\ \mathrm{kW}} \qquad \textbf{Ans.}$$

given

$P_1 = 10\,kPa$
$P_2 = 7\,MPa = 7000\,kPa$

$W_{net} = 45\,MW = 45000\,kW$

$m_{cool} = 2000\,kg/s$

$C_p = 4.18\,kJ/kg\,°c$

from steam table

At P_1 : $h_1 = 191.81\,kJ/kg$

$v_1 = 0.00101\,m^3/kg$

work done ; $W_{in} = v_1(P_2 - P_1)$

$= 0.00101\,(7000 - 10)$

$= 7.06\,kJ/kg$

$h_2 = h_1 + W_{in} = 191.81 + 7.06$

$= 198.87\,kJ/kg$

At $P_3 = 7\,MPa$ and $T = 500°c$

$h_3 = 3411.4\,kJ/kg$

$s_3 = 6.8\,kJ/kg.K$

at $P_4 = 10\,kPa$

$x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.8 - 0.6492}{7.4996} = 0.8201$

$h_4 = 191.81 + (0.8201 \times 2392.1) = 2153.6\,kJ/kg$

$q_{in} = (h_3 - h_2)$

$= 3411.4 - 198.87$

$= 3212.5\,kJ/kg$

$q_{out} = (h_4 - h_1)$

$= 2153.6 - 191.81$

$= 1961.8\,kJ/kg$

given

$P_1 = 10 kPa$
$P_2 = 7 MPa = 7000 kPa$

$W_{net} = 45 MW = 45000 kW$

$m_{cool} = 2000 kg/s$

$C_p = 4.18 kJ/kg°C$

from steam table

At P_1 : $h_1 = 191.81 kJ/kg$

$v_1 = 0.00101 m^3/kg$

work done, $W_{in} = v_1 (P_2 - P_1)$

$= 0.00101 (7000 - 10)$

$= 7.06 kJ/kg$

$h_2 = h_1 + W_{in} = 191.81 + 7.06$

$= 198.87 kJ/kg$

$h_2 = h_1 + W_{in} = 191.81 + 7.06$

$= 198.87 \text{ kJ/kg}$

At $P_3 = 5 \text{ MPa}$ and $T = 500°C$

$h_3 = 3411.4 \text{ kJ/kg}$

$s_3 = 6.8 \text{ kJ/kg.K}$

at $P_4 = 10 \text{ kPa}$

$x_4 = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.8 - 0.6492}{7.4996} = 0.8201$

$h_4 = 191.81 + (0.8201 \times 2392.1) = 2153.6 \text{ kJ/kg}$

$q_{in} = (h_3 - h_2)$

$= 3411.4 - 198.87$

$= 3212.5 \text{ kJ/kg}$

$q_{out} = (h_4 - h_1)$

$= 2153.6 - 191.81$

$= 1961.8 \text{ kJ/kg}$

So, $W_{net} = q_{in} - q_{out}$

$$= 3212.5 - 1961.8$$

$$= 1250.7 \text{ KJ/kg}$$

(a) Thermal efficiency of the cycle.

$$\eta = \frac{W_{net}}{q_{in}} = \frac{1250.7}{3212.5} = 38.9\%$$

(b) Mass flow rate of steam.

$$m = \frac{W_{net}}{w_{net}} = \frac{45000}{1250.7} = 36 \text{ kg/s}$$

(c) temperature of cooling water

$$Q_{out} = m \cdot q_{in} = 35.98 \times 1961.8 = 70586 \text{ KJ/s}$$

$$T_{cool} = \frac{Q_{out}}{m_{cool} \cdot C_p} = \frac{70586}{2000 \times 4.18} = \underline{8.4^\circ C}$$