Vapour & Combined Power Cycles

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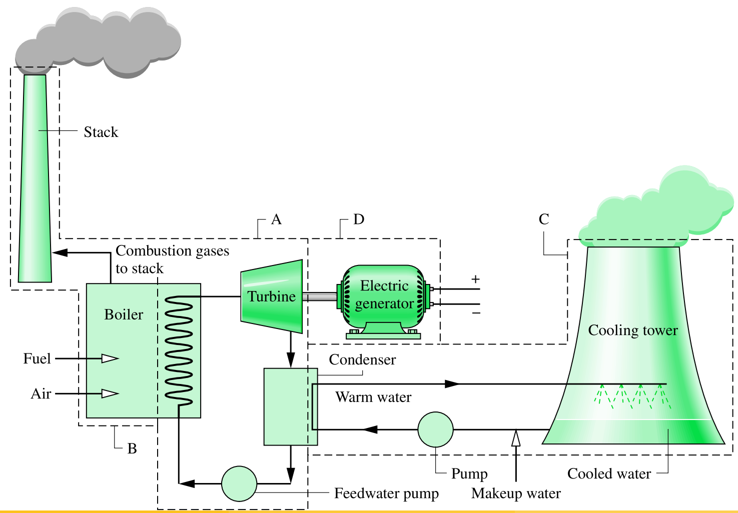
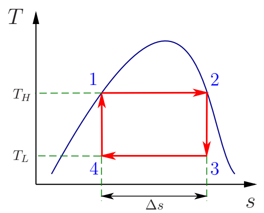
ME 203: Engineering Thermodynamics

Components of a Simple Vapour Power Plant



T193

Carnot Vapour Cycle



T194

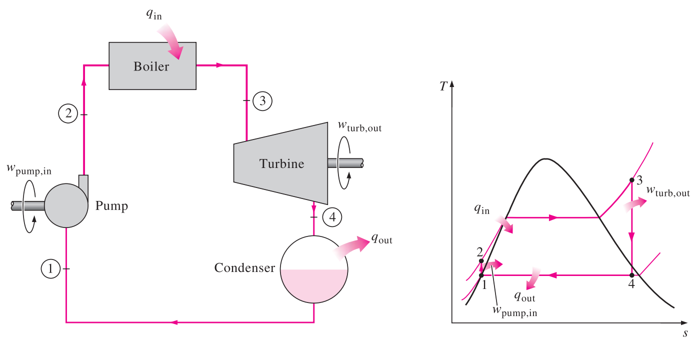
Process	Description
$1 \rightarrow 2$	Reversible, isothermal expansion at T_H
$2 \rightarrow 3$	Reversible, adiabatic expansion from T_H to T_L
$3 \rightarrow 4$	Reversible, isothermal compression at T_L
$4 \rightarrow 1$	Reversible, adiabatic compression from T_L to T_H

- $q_{in} = q_{12} = T_H(s_2 - s_1) = T_H \Delta s$
- $q_{out} = q_{34} = T_L(s_3 - s_4) = T_L \Delta s$
- $w_{net} = q_{net} = q_{in} - q_{out} = (T_H - T_L)\Delta s$
- $\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(T_H - T_L)\Delta s}{T_H \Delta s} = 1 - \frac{T_L}{T_H}$
- Thermal efficiency, η_{th}, increases with increasing heat source temperature, T_H, and with decreasing heat sink temperature, T_L. This general trend is observed for all power cycles.

Carnot Cycle → Rankine Cycle

- Problems with Carnot Cycle:
  - Difficult to isentropically compress a two-phase mixture.
  - Accurate condensation to state point ④ is difficult, where $s_4 = s_1$.
  - Isentropic expansion produces a fluid with a high moisture content at ③, high moisture content causes erosion of turbine blades by liquid droplets.
  - $\eta_{th} = f(T_H)$, as T_L is limited by T_{atm}. For steam, $T_C = 374^oC$, so to be operated within wet region, T_H is severely limited.
- Two Modifications leading to Rankine Cycle:
  1. Wet steam leaving turbine is completely condensed to saturated liquid at turbine exit pressure. Compression is done by pump.
  2. Steam is superheated to a temperature, frequently higher than T_C.

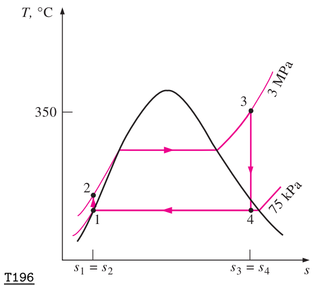
Rankine Cycle



T195

- 1 → 2 : Isentropic compression in a pump
- 2 → 3 : Constant pressure heat addition in a boiler
- 3 → 4 : Isentropic expansion in a turbine
- 4 → 1 : Constant pressure heat rejection in a condenser

▷ [Cengel 10.1]: Ideal Rankine Cycle: Steam enters the turbine at 3 MPa and 350°C, and condenser is at 75 kPa.



T196

⇒ Steady state ⇒ $dE_{cv}/dt = 0$

⇒ $Z_2 = Z_1$ & $\mathbb{V}_2 = \mathbb{V}_1$, $\dot{m}_i = \dot{m}_e = \dot{m}$

⟹ $\boxed{0 = q - w + (h_i - h_e)}$

- Turbine: $q = 0$, $w = w_T = h_3 - h_4$
- Pump: $q = 0$, $w = w_P = h_1 - h_2$
- Boiler: $w = 0$, $q = q_B = h_3 - h_2$
- Condenser: $w = 0$, $q = q_C$
- h_2 is in compressed state & difficult to estimate. Hence, $w_P = -\int_1^2 v dP$.

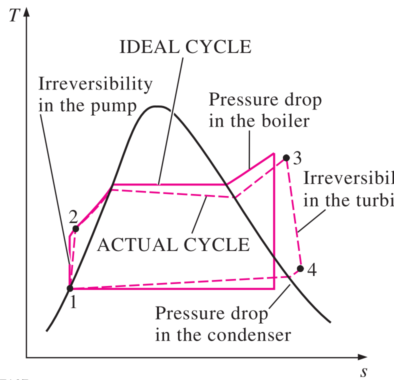
⇒ $w_{net} = w_T + w_P = (713.0 - 3.03)$ kJ/kg $= 710.0$ kJ/kg. ▶ $w_T \gg w_P$.

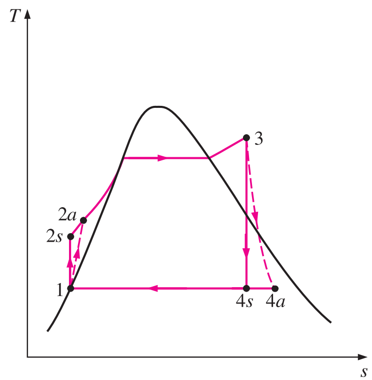
⇒ $q_{in} = q_B = h_3 - h_2 = 2728.6$ kJ/kg

⟹ Thermal efficiency, $\eta_{th} = \frac{w_{net}}{q_{in}} = 0.260 = 26.0\%$ ◀

⟹ Back work ratio, $bwr = |\frac{w_P}{w_T}| = 0.0043$ ◀

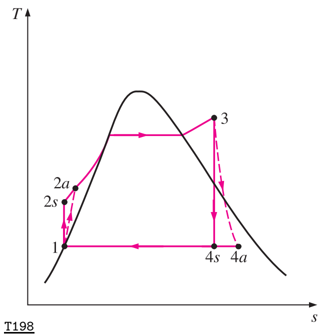
Deviation of Actual Vapour Power Cycle





T197

▷ Example: Actual Rankine Cycle: Steam enters the turbine at 3 MPa and 350°C, and condenser is at 75 kPa and $\eta_{isen} = 95\%$ for pump and turbine.



T198

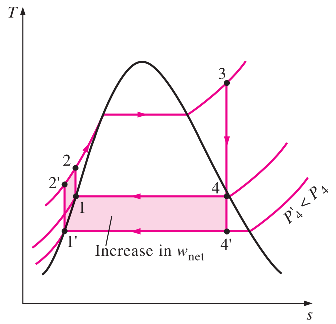
⇒ $\eta_t = \frac{\dot{w}_t}{\dot{w}_t|_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$

⇒ $\eta_c = \frac{-\dot{w}_c|_s}{-\dot{w}_c} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$

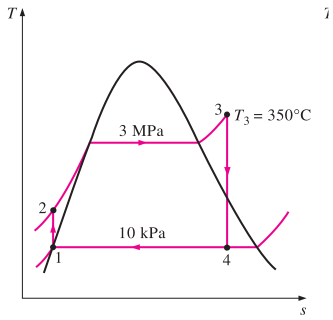
- $w_c = -\int_1^{2s} vdP = -v_1(P_B - P_C)$
- $h_{2a} = h_1 + \frac{v_1(P_B - P_C)}{\eta_c}$
- $q_{2a-3} = h_3 - h_{2a}$

- $q_{in} = 2727.2$ kJ/kg.
- $w_t = 676.97$ kJ/kg.
- $w_p = 3.19$ kJ/kg.
- $\eta_{th} = 24.71\%$◀

Effect of Lowering Condenser Pressure



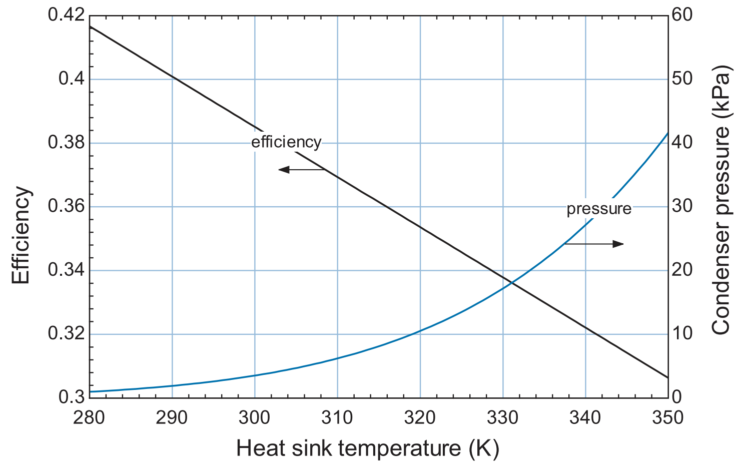
T199



T218

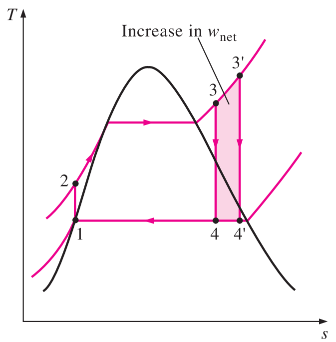
- $P_{cond} = P_{sat}(T_{cond})$: $T_{cond} - T_{atm} \simeq 10 - 15^oC$.
- $P_{cond} \downarrow :\Longrightarrow w_{net} \uparrow$, $\eta_{th} \uparrow$ & $x_4 \downarrow$. Higher moisture decreases turbine efficiency and erodes its blades. In general, $x_4 \geq 0.9$ is maintained. Lower P_{cond} promotes leakage.

$\mathbf{P_B = 2.64\ MPa,\ T_H = 800\ K}$

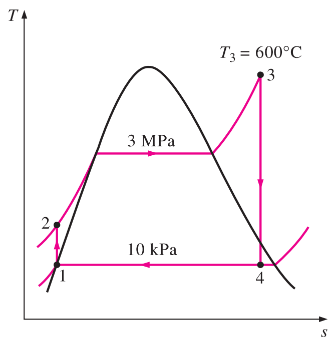


T217

Effect of Super-heating Steam to Higher Temperature



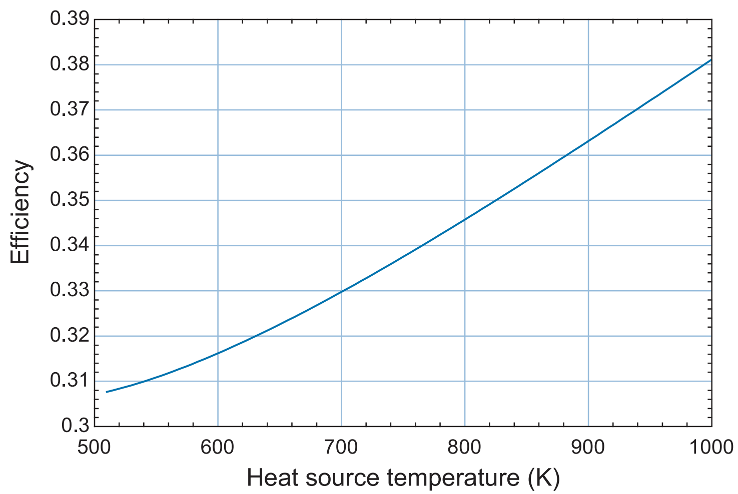
T200



T219

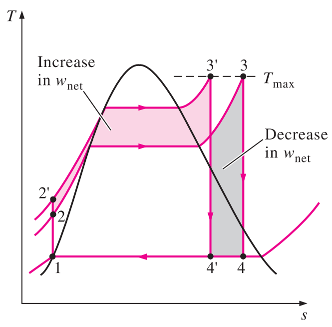
- $T_{max} \uparrow :\Longrightarrow w_{net} \uparrow$, $\eta_{th} \uparrow$ & $x_4 \uparrow$.
- Higher average temperature of heat addition increases η_{th}. T_{max} is limited by metallurgical considerations. In general, $T_{max} = 620^oC$.

$\mathbf{P_B = 2.64\ MPa,\ T_L = 325\ K}$

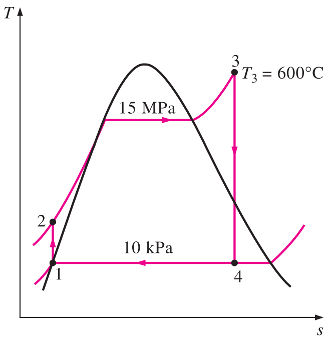


T216

Effect of Increasing Boiler Pressure



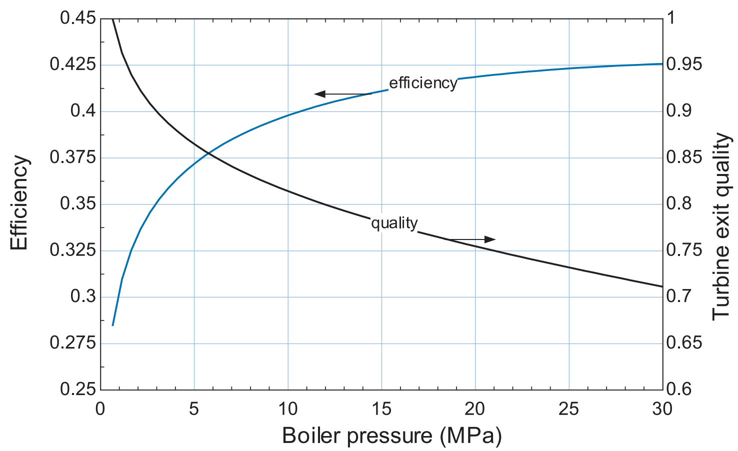
T201



T220

- For fixed T_{max} : $P_B \uparrow :\Longrightarrow \eta_{th} \uparrow$ & $x_4 \downarrow$. Higher η_{th} is achieved because of higher average temperature of heat addition.

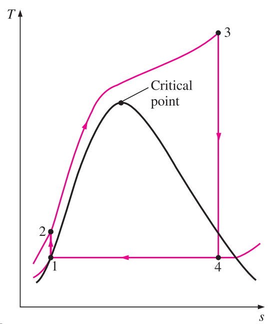
$\mathbf{T_H = 800\ K,\ T_L = 325\ K}$



T215

Effects of Operating Parameters on Ideal Rankine Cycle Efficiency

Boiler Pressure	[MPa]	3.0	3.0	**3.0**	**15.0**
Max. Temperature	[°C]	350	**350**	**600**	600
Cond. Pressure	[kPa]	**75**	**10**	10	10
Heat added	[kJ/kg]	2729	2921	3488	3376
Turbine work	[kJ/kg]	713	979	1302	1467
Pump work	[kJ/kg]	3.03	3.02	3.02	15.1
Thermal efficiency	[%]	26.0	33.4	37.3	43.0
x_4	[-]	0.886	0.812	0.915	0.804

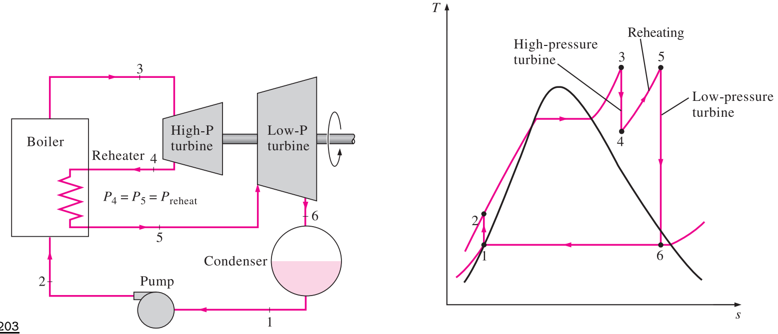


T202

A supercritical Rankine cycle

- Some modern power plants operate at supercritical pressure ($P \approx 30$ MPa $> P_C = 22.06$ MPa) and have $\eta_{th} \sim 40\%$ for fossil-fuel plants and $\eta_{th} \sim 34\%$ for nuclear power plants.
- Lower η_{th} of nuclear power plants are due to lower maximum temperatures used due to safety reasons.

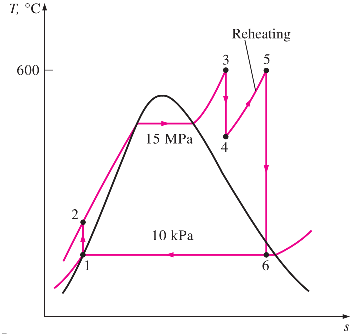
Ideal Reheat Rankine Cycle



T203

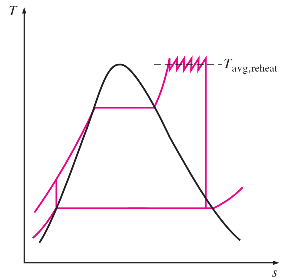
- $q_{in} = q_{23} + q_{45} = (h_3 - h_2) + (h_5 - h_4)$
- $w_{turb} = w_{34} + w_{56} = (h_3 - h_4) + (h_5 - h_6)$
- Average temperature of heat addition is increased $:\Longrightarrow \eta_{th} \uparrow$. Moisture quality at turbine exit is also improved.

$P_{reheat} = 4.0$ MPa



T205

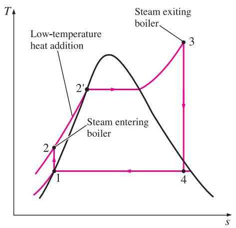
Average temperature at which heat is transferred during reheating increases as the number of reheat stages is increased.



T204

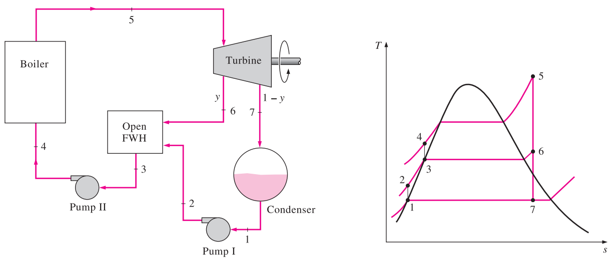
Heat added	= 3897.2 [kJ/kg]
Turbine work	= 1768.5 [kJ/kg]
Pump work	= -15.1 [kJ/kg]
Thermal efficiency	= 45.0 [%]

Ideal Regenerative Rankine Cycle with Open FWH



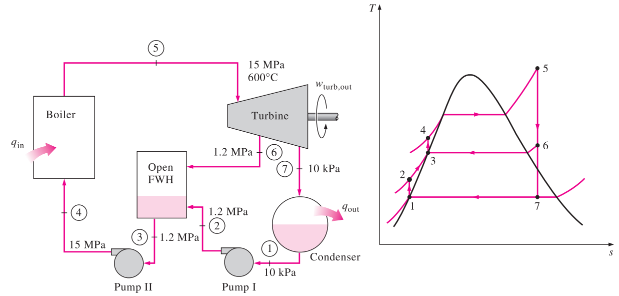
T206

$T_{av}(2 \rightarrow 2')$ is low $\Rightarrow \eta_{th} \downarrow$. A practical regeneration process in steam power plants is accomplished by extracting, or bleeding, steam from the turbine at various points. The device where the feed-water is heated by regeneration is called a regenerator, or a feed-water heater (FWH).



T207

▷ [Cengel 10.5]: Ideal Regenerative Rankine Cycle with Opem FWH.

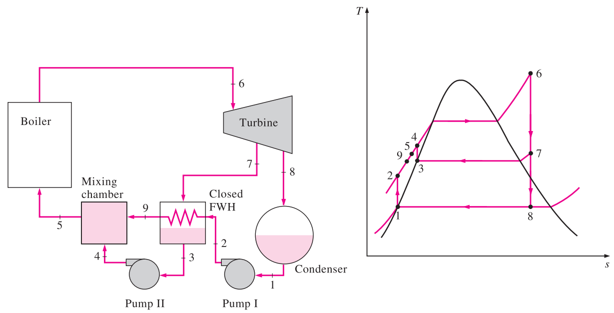


T210

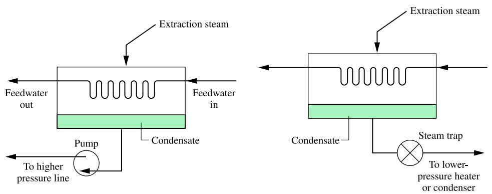
- $q_{in} = h_5 - h_4 = 2769.2$ kJ/kg
- Energy balance (at FWH): $yh_6 + (1 - y)h_2 = 1 \cdot h_3 \rightarrow y = 0.227$.
- $w_t = (h_5 - h_6) + (1 - y)(h_6 - h_7) = 1299.1$ kJ/kg
- $w_P = (1 - y)w_{P,I} + w_{P,II} =$ -16.58 kJ/kg

$\Longrightarrow \eta_{th} = 46.3\%$ ◀

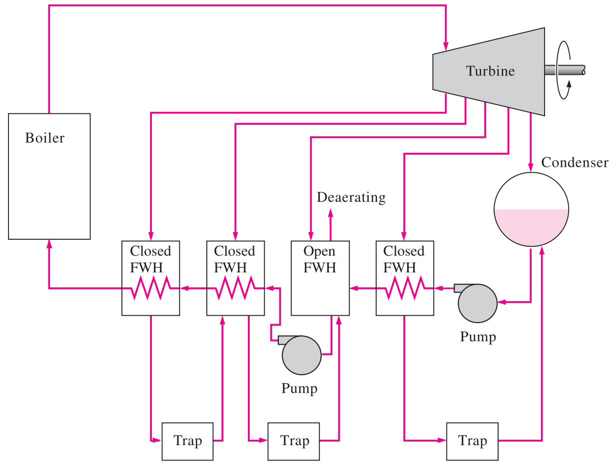
Closed Feed-water Heaters



T208



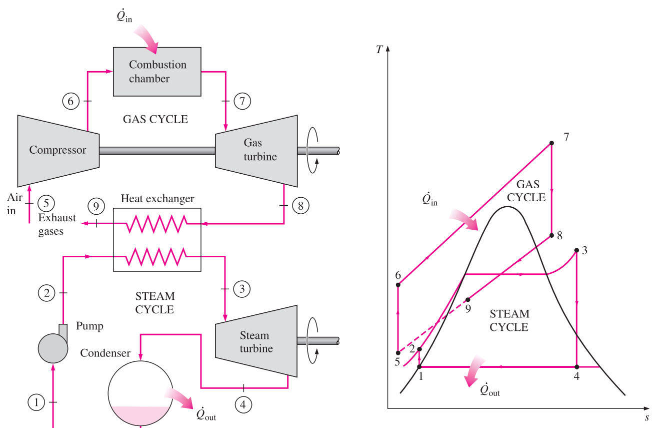
T221



T209

A steam power plant with one open FWH and three closed FWH.

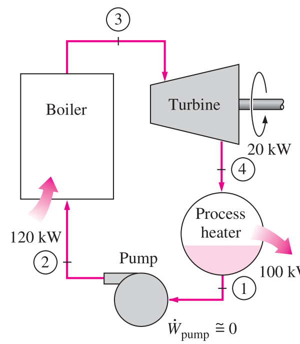
Combined Gas-Vapour Power Cycle



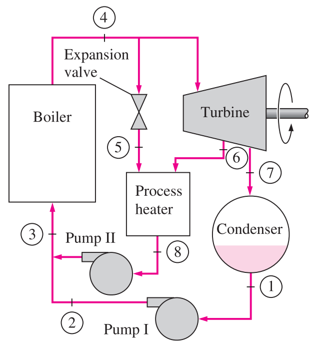
T214

Heat Exchanger → HRSG ≡ Heat Recovery Steam Generator

Cogeneration: CHP ≡ Combined Heating & Power



T211

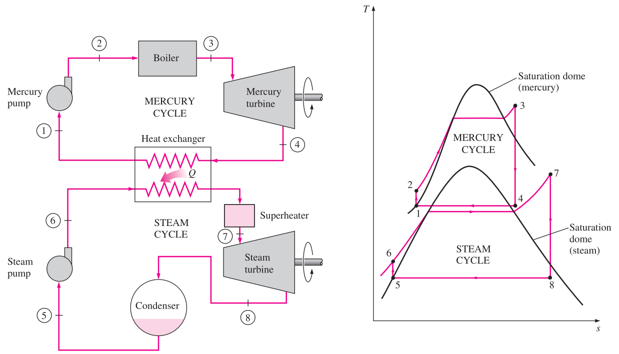


T212

- Cogeneration is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source.
- Utilization factor, $\epsilon_u = \frac{\dot{W}_{net}+\dot{Q}_P}{\dot{Q}_{in}} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$.

Binary Vapour Cycle

- For Mercury: P_C = 18 MPa, T_C = 898°C.
- At 0.07 kPa, T_{sat} = 32°C & at 7.0 kPa, T_{sat} = 273°C.
- $\eta_{th} \geqslant 50\%$ are possible with binary-vapour cycle.



T213