ESO 201A: Thermodynamics
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Vapor Power Cycle: part 2

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Learning Objectives

- Analyze *vapor power cycles* in which the working fluid is alternately vaporized and condensed.
- Investigate ways to modify the *basic Rankine vapor power cycle* to increase the cycle thermal efficiency.
- Analyze the *reheat and regenerative* vapor power cycles.
- Perform second-law analysis of vapor power cycles
- Analyze power generation coupled with process heating called *cogeneration*.
- Analyze power cycles that consist of two separate cycles known as combined cycles

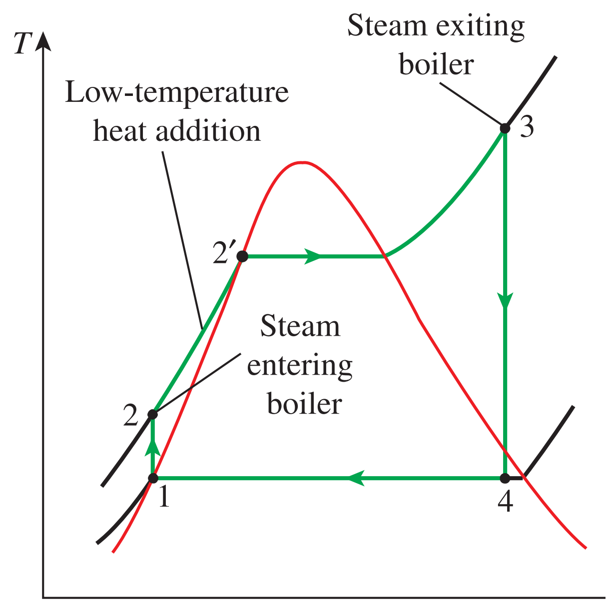
The Ideal Regenerative Rankine Cycle

Heat transferred to working fluid during 2-2' is at low temperature- thus reducing average T, and lowering cycle efficiency.

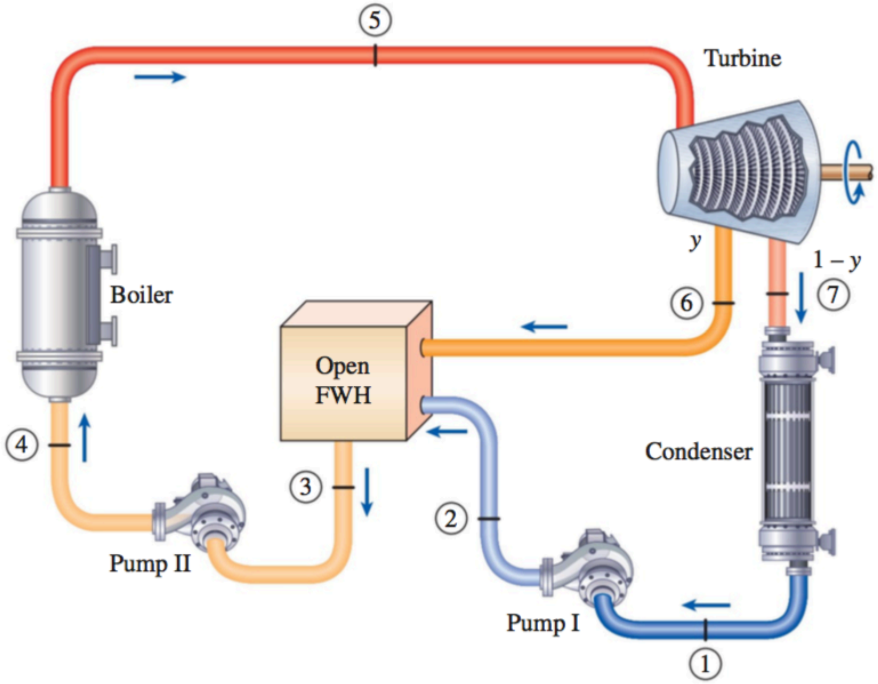
Increase the temperature of the water leaving the pump and entering the boiler (feed water

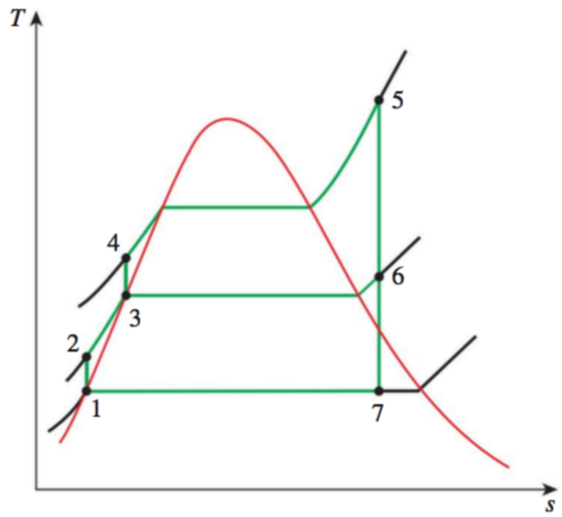
- *use steam (bleeding) from turbine by using a device called regenerator or feedwater heater (FWH)*

- Helps to prevent corrosion in the boiler by removing the air that leaks in at condenser
- FWH is basically HE , where heat is transferred from steam to the feedwater either by mixing (open feedwater heater) or without mixing (closed feed water heater)



Ideal regenerative Rankine cycle: Open feedwater heater



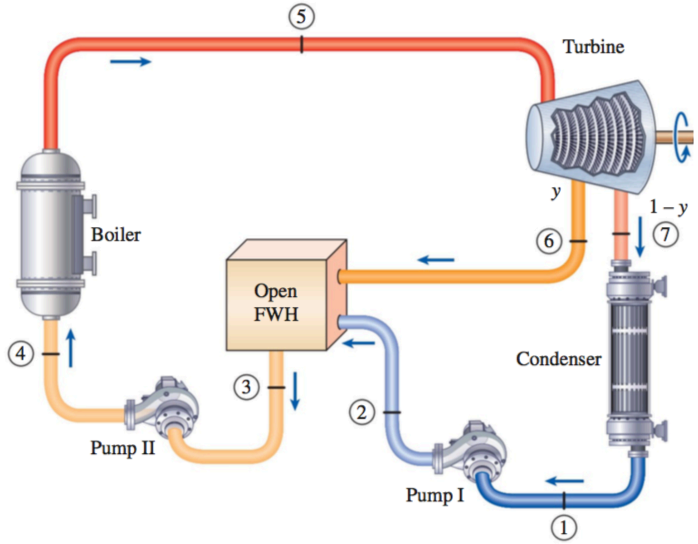


$$y = \dot{m}_6/\dot{m}_5$$

$$w_{\text{pump I,in}} = v_1(P_2 - P_1)$$

$$w_{\text{pump II,in}} = v_3(P_4 - P_3)$$

Ideal regenerative Rankine cycle: Open feedwater heater



$$q_{\text{in}} = h_5 - h_4$$

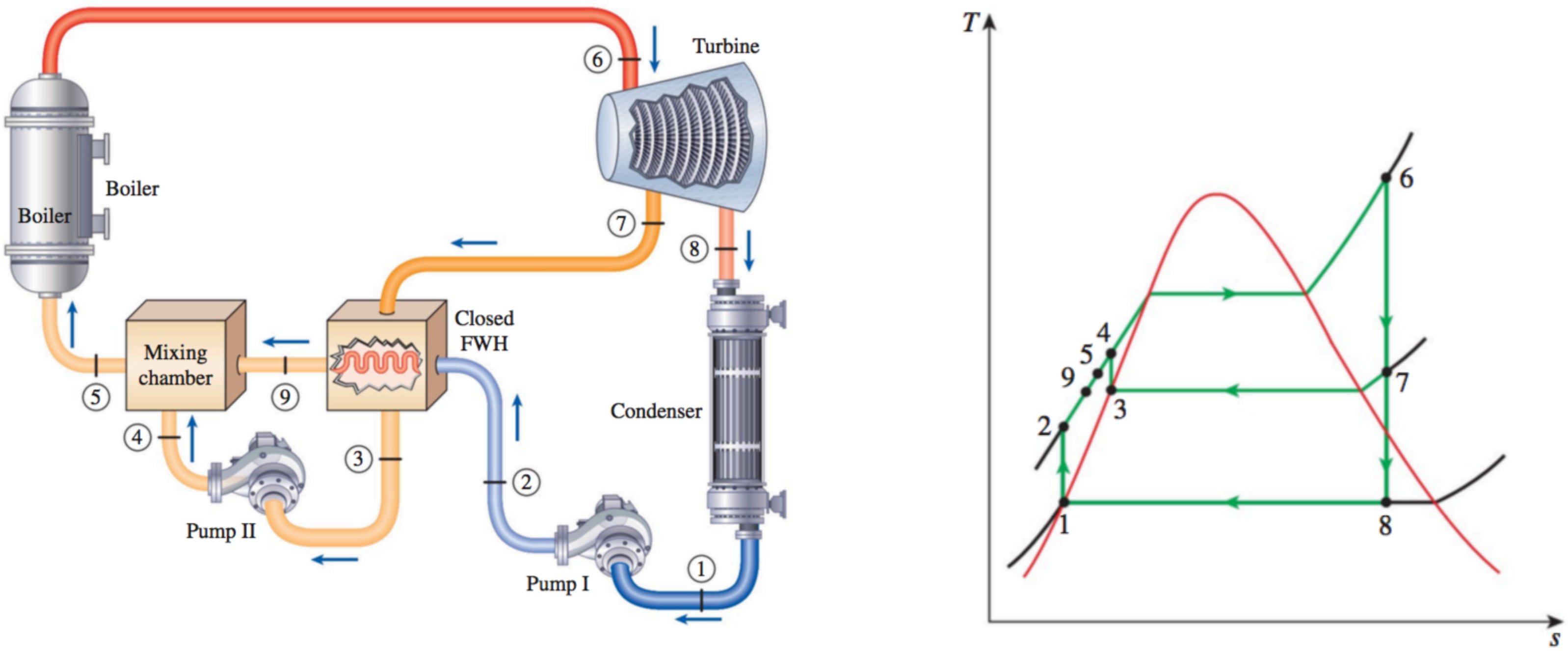
$$q_{\text{out}} = (1 - y)(h_7 - h_1)$$

$$w_{\text{turb,out}} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

$$w_{\text{pump,in}} = (1 - y)w_{\text{pump I,in}} + w_{\text{pump II,in}}$$

Ideal regenerative Rankine cycle: Closed feedwater heater

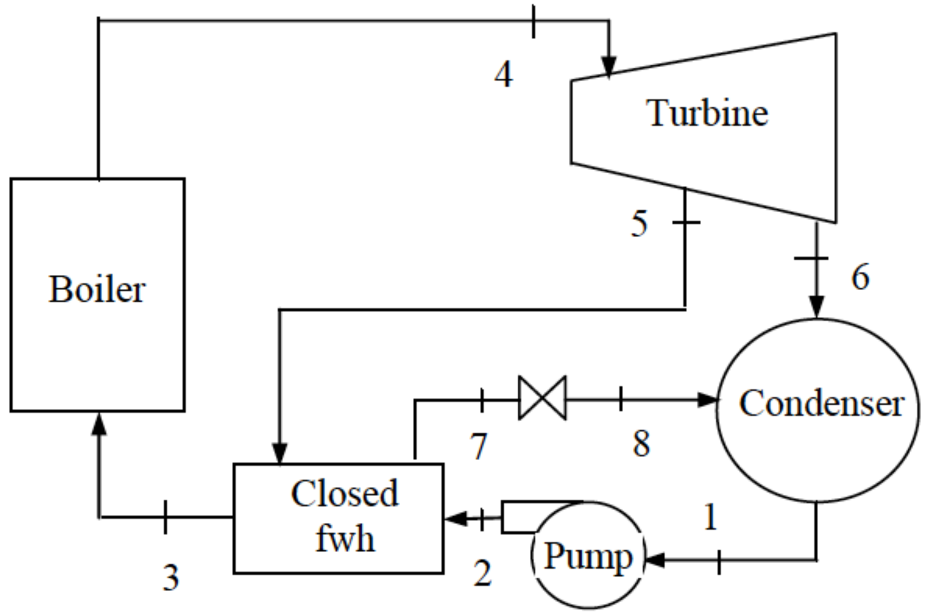
Another type of feedwater heater frequently used in steam power plants is the **closed feedwater heater**, in which heat is transferred from the extracted steam to the feedwater without any mixing taking place. The two streams now can be at different pressures, since they do not mix.



The ideal regenerative Rankine cycle with a closed feedwater heater.

Example

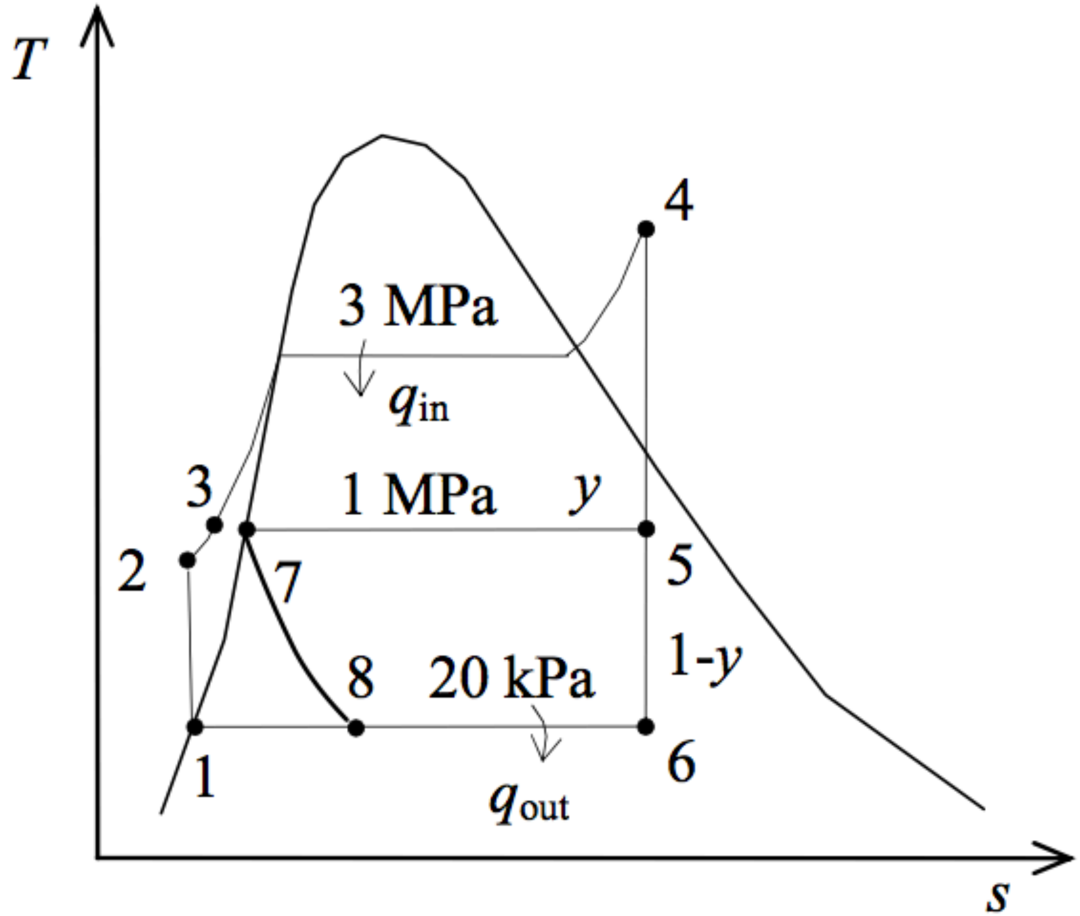
Consider a steam power plant that operates on the ideal regenerative Rankine cycle with a closed feedwater heater as shown in the figure. The plant maintains the turbine inlet at 3000 kPa and 350°C; and operates the condenser at 20 kPa. Steam is extracted at 1000 kPa to serve the closed feedwater heater, which discharges into the condenser after being throttled to condenser pressure. Calculate the work produced by the turbine, the work consumed by the pump, and the heat supply in the boiler for this cycle per unit of boiler flow rate.



Analysis From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,20\,\text{kPa}} = 251.42\ \text{kJ/kg}$$

$$v_1 = v_{f@\,20\,\text{kPa}} = 0.001017\ \text{m}^3/\text{kg}$$



$$
\begin{aligned}
w_{\text{p,in}} &= \boldsymbol{v}_1 (P_2 - P_1) \\
&= (0.001017\ \text{m}^3/\text{kg})(3000 - 20)\text{kPa} \left(\frac{1\ \text{kJ}}{1\ \text{kPa} \cdot \text{m}^3} \right) \\
&= 3.03\ \text{kJ/kg}
\end{aligned}
$$

$$
h_2 = h_1 + w_{\text{p,in}} = 251.42 + 3.03 = 254.45\ \text{kJ/kg}
$$

$$
\left.
\begin{aligned}
P_4 &= 3000\ \text{kPa} \\
T_4 &= 350°\text{C}
\end{aligned}
\right\}
\begin{aligned}
h_4 &= 3116.1\ \text{kJ/kg} \\
s_4 &= 6.7450\ \text{kJ/kg} \cdot \text{K}
\end{aligned}
$$

$$
\left.
\begin{aligned}
P_5 &= 1000\ \text{kPa} \\
s_5 &= s_4
\end{aligned}
\right\}
h_5 = 2851.9\ \text{kJ/kg}
$$

$$\left.\begin{array}{l} P_6 = 20\ \text{kPa} \\ s_6 = s_4 \end{array}\right\} \begin{array}{l} x_6 = \dfrac{s_6 - s_f}{s_{fg}} = \dfrac{6.7450 - 0.8320}{7.0752} = 0.8357 \\ h_6 = h_f + x_6 h_{fg} = 251.42 + (0.8357)(2357.5) = 2221.7\ \text{kJ/kg} \end{array}$$

For an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure

$$\left.\begin{array}{l} P_7 = 1000\ \text{kPa} \\ x_7 = 0 \end{array}\right\} \begin{array}{l} h_7 = 762.51\ \text{kJ/kg} \\ T_7 = 179.9°\text{C} \end{array}$$

$$h_8 = h_7 = 762.51\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 3000\ \text{kPa} \\ T_3 = T_7 = 209.9°\text{C} \end{array}\right\} h_3 = 763.53\ \text{kJ/kg}$$

An energy balance on the heat exchanger gives the fraction of steam extracted from the turbine $(= \dot{m}_5 / \dot{m}_4)$ for closed feedwater heater:

$$\sum \dot{m}_i h_i = \sum \dot{m}_e h_e$$

$$\dot{m}_5 h_5 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$y h_5 + 1 h_2 = 1 h_3 + y h_7$$

Rearranging,

$$y = \frac{h_3 - h_2}{h_5 - h_7} = \frac{763.53 - 254.45}{2851.9 - 762.51} = 0.2437$$

Then,

$$w_{\mathrm{T,out}} = h_4 - h_5 + (1-y)(h_5 - h_6) = 3116.1 - 2851.9 + (1 - 0.2437)(2851.9 - 2221.7) = \mathbf{740.9\ kJ/kg}$$

$$w_{\mathrm{P,in}} = \mathbf{3.03\ kJ/kg}$$

$$q_{\mathrm{in}} = h_4 - h_3 = 3116.1 - 763.53 = \mathbf{2353\ kJ/kg}$$

Also, $$w_{\text{net}} = w_{\text{T,out}} - w_{\text{P,in}} = 740.9 - 3.03 = 737.8 \text{ kJ/kg}$$

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = \frac{737.8}{2353} = 0.3136$$

Second Law of Analysis of Vapor Power Cycles

Ideal Rankine cycle is only internally reversible

A second-law analysis of these cycles reveals where the largest irreversibilities occur and what their magnitudes are.

Exergy destruction for a steady-flow system

$$\dot{X}_{\text{dest}} = T_0 \dot{S}_{\text{gen}} = T_0(\dot{S}_{\text{out}} - \dot{S}_{\text{in}}) = T_0\left(\sum_{\text{out}} \dot{m}s + \frac{\dot{Q}_{\text{out}}}{T_{b,\text{out}}} - \sum_{in} \dot{m}s - \frac{\dot{Q}_{\text{in}}}{T_{b,\text{in}}}\right)$$

$$x_{\text{dest}} = T_0 s_{\text{gen}} = T_0\left(s_e - s_i + \frac{q_{\text{out}}}{T_{b,\text{out}}} - \frac{q_{\text{in}}}{T_{b,\text{in}}}\right)$$

Unit mass, steady-flow, one-inlet, one-exit

Second Law of Analysis of Vapor Power Cycles

The exergy destruction associated with a *cycle* depends on the magnitude of the heat transfer with the high- and low-temperature reservoirs involved, and their temperatures. It can be expressed on a unit mass basis as

$$x_{\text{dest}} = T_0\left(\sum \frac{q_{\text{out}}}{T_{b,\text{out}}} - \sum \frac{q_{\text{in}}}{T_{b,\text{in}}}\right) \quad \text{(kJ/kg)}$$

Exergy destruction of a cycle

$$x_{\text{dest}} = T_0\left(\frac{q_{\text{out}}}{T_L} - \frac{q_{\text{in}}}{T_H}\right) \quad \text{(kJ/kg)}$$

For a cycle with heat transfer only with a source and a sink

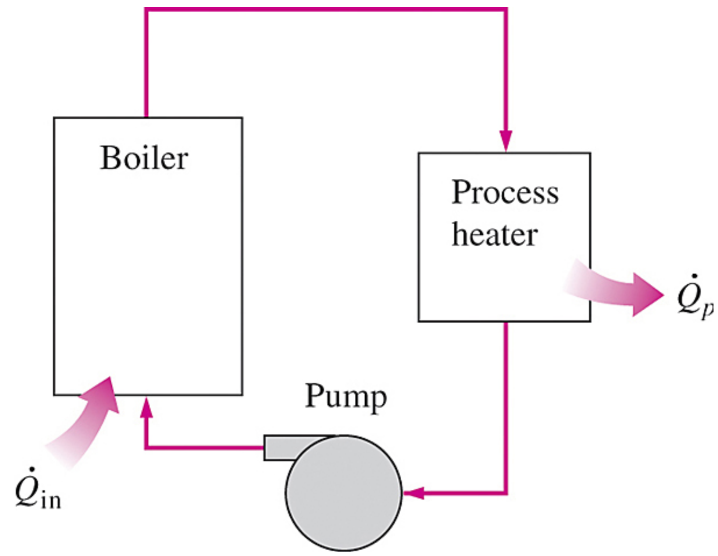
$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \quad \text{(kJ/kg)}$$

Stream exergy

A second-law analysis of vapor power cycles reveals where the largest irreversibilities occur and where to start improvements.

Cogeneration

- Many industries such as are chemical, pulp and paper, oil production and refining, steel making, food processing, and textile industries. require energy input in the form of heat, called ***process heat***.
- Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C.
- Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.
- It makes sense to use the already-existing work potential to produce power instead of letting it go to waste.
- The result is a plant that produces electricity while meeting the process-heat requirements of certain industrial processes (cogeneration plant)

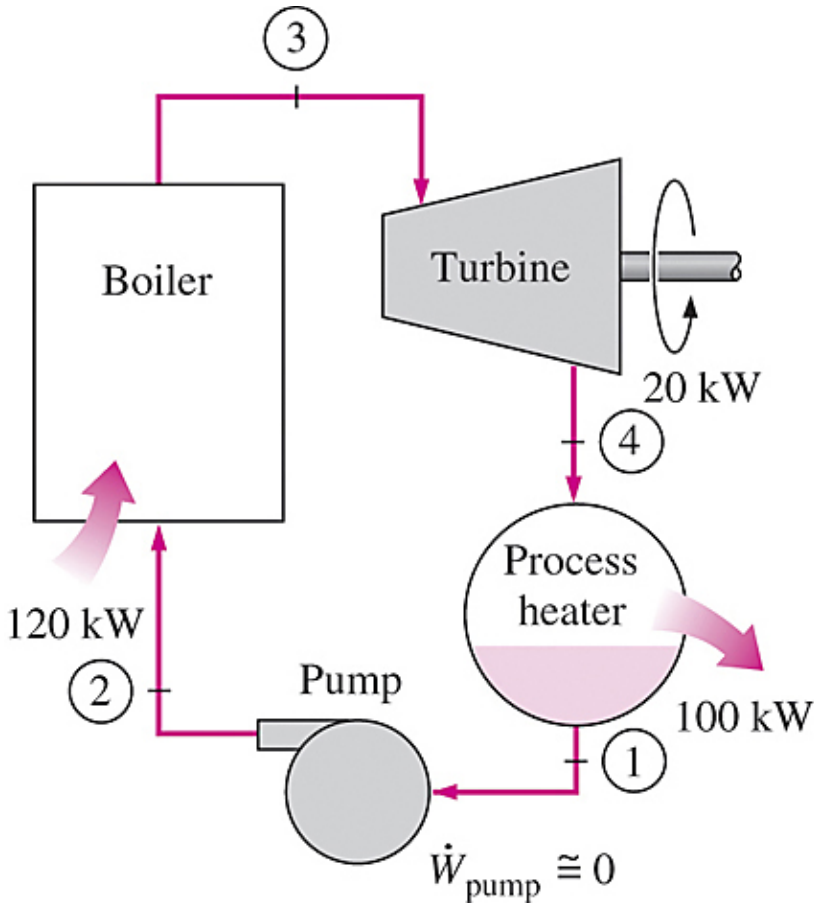


A simple process-heating plant

Cogeneration: The production of more than one useful form of energy (such as process heat and electric power) from the same energy source.

Cogeneration

Utilization factor $\epsilon_u = \dfrac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \dfrac{\dot{W}_{net} + \dot{Q}_p}{\dot{Q}_{in}}$

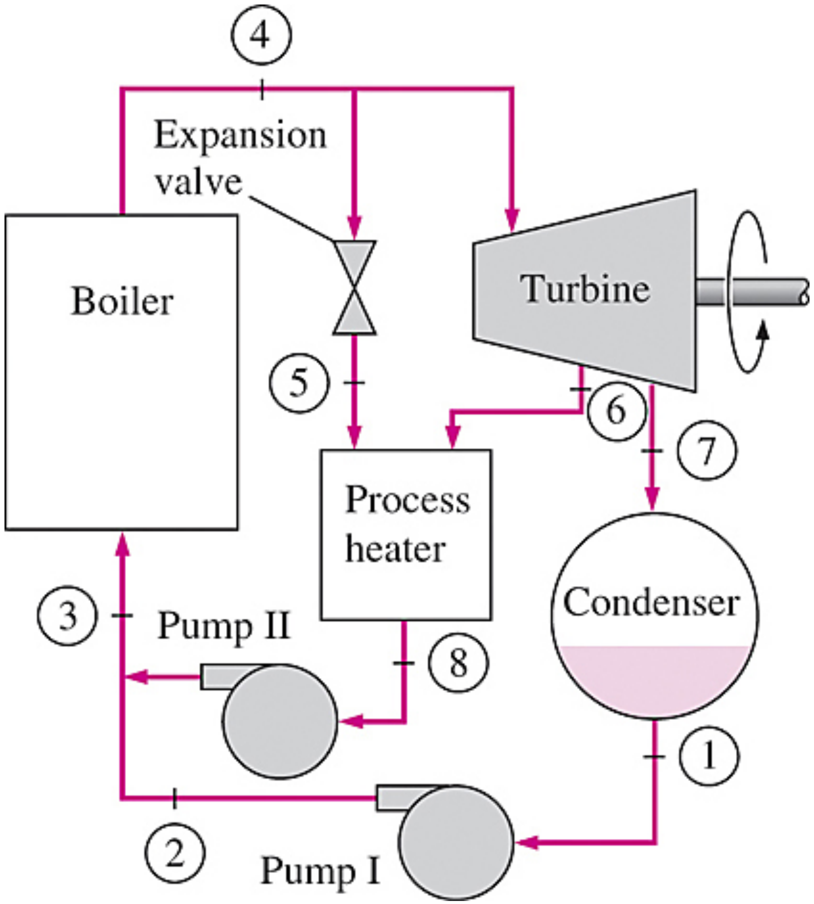


$$\epsilon_u = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

- The utilization factor of the ideal steam-turbine cogeneration plant is 100%.
- Actual cogeneration plants have utilization factors as high as 80%.
- Some recent cogeneration plants have even higher utilization factors.

An ideal steam –turbine cogeneration plant. Out of 120 kW input heat, 100 kW is used as process heat and 20 kW is used as turbine work.

Cogeneration



A cogeneration plant with adjustable loads.

At times of high demand for process heat, all the steam is routed to the process-heating units and none to the condenser ($m_7 = 0$). The waste heat is zero in this mode.

If this is not sufficient, some steam leaving the boiler is throttled by an expansion or pressure-reducing valve to the extraction pressure P_6 and is directed to the process-heating unit.

Maximum process heating is realized when all the steam leaving the boiler passes through the PRV ($m_5 = m_4$). No power is produced in this mode.

When there is no demand for process heat, all the steam passes through the turbine and the condenser ($m_5 = m_6 = 0$), and the cogeneration plant operates as an ordinary steam power plant.

$$\dot{Q}_{\text{in}} = \dot{m}_3(h_4 - h_3)$$

$$\dot{Q}_{\text{out}} = \dot{m}_7(h_7 - h_1)$$

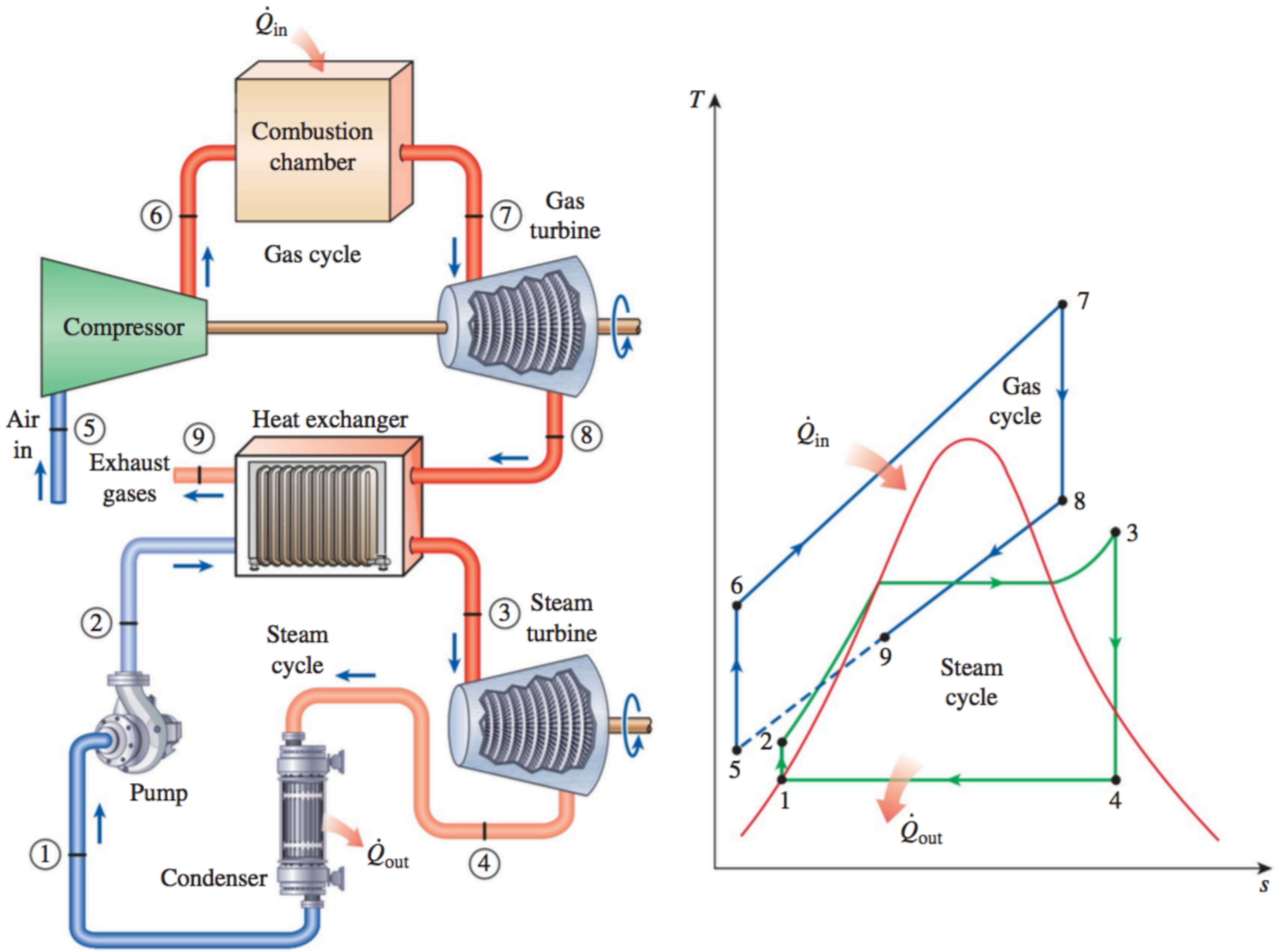
$$\dot{Q}_p = \dot{m}_5 h_5 + \dot{m}_6 h_6 - \dot{m}_8 h_8$$

$$\dot{W}_{\text{turb}} = (\dot{m}_4 - \dot{m}_5)(h_4 - h_6) + \dot{m}_7(h_6 - h_7)$$

Combined Gas-Vapor Cycle

- A popular modification involves a gas power cycle topping a vapor power cycle, which is called the **combined gas–vapor cycle**, or just the **combined cycle**.
- The combined cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam-turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually.
- It makes engineering sense to take advantage of the very desirable characteristics of the gas-turbine cycle at high temperatures *and* to use the high-temperature exhaust gases as the energy source for the bottoming cycle such as a steam power cycle. The result is a combined gas–steam cycle.
- Recent developments in gas-turbine technology have made the combined gas–steam cycle economically very attractive.
- The combined cycle increases the efficiency without increasing the initial cost greatly. Consequently, many new power plants operate on combined cycles, and many more existing steam- or gas-turbine plants are being converted to combined-cycle power plants.
- Thermal efficiencies over 50% are reported.

Combined Gas-Vapor Cycle



Combined gas–steam power plant.

Summary

- The Carnot vapor cycle
- Rankine cycle: The ideal cycle for vapor power cycles
  - Energy analysis of the ideal Rankine cycle
- Deviation of actual vapor power cycles from idealized ones
- How can we increase the efficiency of the Rankine cycle?
  - Lowering the condenser pressure (*Lowers* $T_{low,avg}$)
  - Superheating the steam to high temperatures (*Increases* $T_{high,avg}$)
  - Increasing the boiler pressure (*Increases* $T_{high,avg}$)
- The ideal reheat Rankine cycle
- The ideal regenerative Rankine cycle
  - Open feedwater heaters
  - Closed feedwater heaters
- Second-law analysis of vapor power cycles
- Cogeneration
- Combined gas–vapor power cycles